1

Switching in Power Systems

1.1 Introduction

As electricity comes out of AC outlets every day, and has done so for more than 100 years, it is nowadays considered a commodity. It is a versatile and clean source of energy; it is rather cheap and ‘always available’.

The purpose of a power system is to transport and distribute the electric energy generated in the power plants to the consumers in a safe and reliable way. Generators take care of the conversion of mechanical energy into electric energy, aluminium and copper conductors are used to carry the current, and transformers bring the electric energy to the appropriate voltage level. Society’s dependence on this commodity has become extremely large and the social impact of a failing power system is unacceptable. The electrical power system is the backbone of modern society.

Switching operations in power systems are very common and must not jeopardize the system’s reliability and safety. Switching in power systems is necessary for the following reasons and duties:

- Taking into or out of service some sections of the system, certain loads, or consumers. A typical example is the switching of shunt capacitor banks or shunt reactors, de-energization of overhead lines, transformers, and so on. In industrial systems, this type of switching is by far the most common of all the switching operations.
- Transferring the flow of energy from one circuit to another. Such operations occur when load current needs to be transferred without interruption from one busbar to another, for example, in a substation.
- Isolating certain network components because of maintenance or replacement.
- Isolating faulted sections of the network in order to avoid damage and/or system instability. The most well-known example of this is the interruption of a short-circuit current. Faults cannot be avoided, but adequate switching devices in combination with a protection system need to limit the consequences of faults.

Figure 1.1 provides an overview in orders of magnitude of the power switched in electrical-engineering applications.

Switching in Electrical Transmission and Distribution Systems, First Edition.
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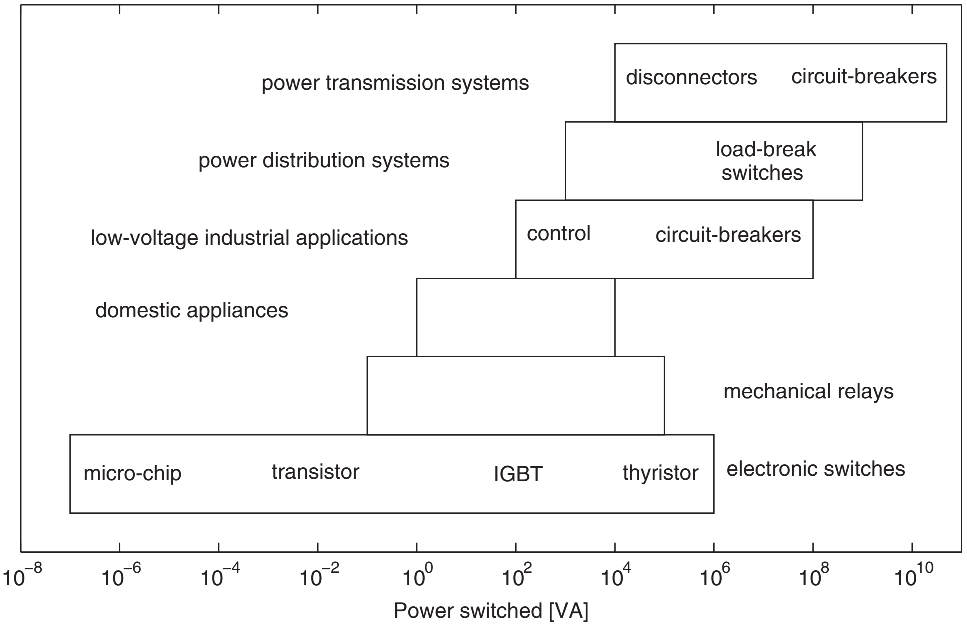

Figure 1.1 Overview of the power being switched in electrical-engineering applications.

Switching in electrical power systems re-configures the topology of an electrical network; it involves the making and breaking of circuits and causes a disturbance of steady energy flow. Therefore, transients have to be expected and are observed in the system during the change from the situation before to the situation after switching. Transients are abnormal patterns of current and voltage that have a limited duration. Attention should be paid to these phenomena because they very often exceed the values met during steady-state operation. Fundamentally in nature, any change of steady-state conditions generates transients.

The essential parameters in electrical systems are current and voltage. During switching operations, transients can be observed in both. Regarding operations related to switching-on (*making* or *energization*), the components of the system are mainly stressed by current-related transients. On the other hand, at switching-off operations (*breaking* or *de-energization*), voltage-related transients will especially stress the switching device performing the operation.

In a generalized concept, switching devices (dis)connect a source circuit to a load circuit (see Figure 1.2). Both circuits are a complicated combination of system components: lines, cables, busbars, transformers, generators, and so on. Through reduction of the complexity to relevant simple electrical elements, either lumped or distributed where necessary (refer to Section 1.3), the switching transients can be more easily understood.

1.2 Organization of this Book

The aim of this book is to describe and explain to technically interested and practically oriented readers the variety of switching processes and devices in electrical power systems, avoiding (as far as possible) deep physical details and formal mathematics – although both of these

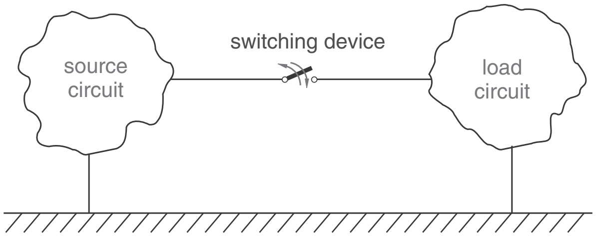

Figure 1.2 General concept of a switching device located between a source- and a load-circuit.

are in fact pillars in the resolution of problems encountered in the high-power switching technology. Numerous examples of measurements and observed effects have been selected from realistic tests of a wide variety of switchgear at the KEMA High-Power Laboratory of DNV GL – Energy, where real service conditions are simulated in powerful test-laboratories (see Section 14.2).

The book is divided roughly into two parts. The first part (Chapters 1 to 5) focuses on the switching phenomena and their description.

The second part (Chapters 6 to 14) describes the technology of the devices that must perform switching in all experienced varieties and their impact on the power system.

In Chapter 1, the necessary background on the practical aspects of switching is given. The origin and role of the two key phenomena governing the switching processes are described: the *switching arc* and the *transient recovery voltage* (TRV). Due to the nature of the transients that accompany switching, the general description must, in principle, be in terms of electromagnetic fields and travelling waves. However, at sufficiently low frequency, a simplification of the relevant circuits in terms of lumped elements can greatly facilitate mathematical formulation and calculation of the TRV characteristics in the majority of the practical cases.

Chapter 2 deals exclusively with faults in power systems. Essential transients of fault-current events are identified, together with their impact on network components. Data on fault statistics are summarized.

In Chapter 3, the switching of fault currents, correctly termed the *making* and *breaking operations*, resulting from various types of faults in power systems, is analysed. Since, in this case, the TRV plays a crucial role, the description of the TRV is given in terms of simplified *RLC* circuits[1] – either with lumped elements or in terms of travelling waves where necessary. A systematic approach is taken to represent every case by the minimum possible number of elements, in order to facilitate understanding.

Relevant characteristics of the switching arc are considered, showing its influence on the interruption process.

Chapter 4 deals with switching of loads: overhead lines, capacitor banks and shunt reactors operated under normal condition. Although the currents to cope with are much lower than at faults, it is explained that due to the reactive nature of capacitive and inductive loads, this type of switching is sometimes an onerous challenge. The main issue here is the description of transients generated by the switching process.

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[1] Oscillating circuits, each consisting of a single inductance L, capacitance C, and resistance R.

In Chapter 5, the calculation of the switching transients is treated. First, a formal analysis of the analytical solution of a few simplified circuits is given. Next, the background and the basics of some state-of-the-art numerical transient simulation programs are discussed.

Chapter 6 highlights the switching processes in gaseous media, such as air, the H_2 gas in oil circuit-breakers and SF_6 gas, the workhorse of present-day HV insulation and switching. Issues regarding health, safety and environment related to the ‘electrical’ use of SF_6 gas are treated in detail.

Chapter 7 focuses on the SF_6 circuit-breaker, the present-day technology of choice in HV systems. Technology and other relevant aspects of the circuit-breaker are described.

Chapter 8 describes the switching in vacuum, as presently applied on a large scale in distribution systems and slowly emerging in high-voltage systems as well.

Chapter 9 goes into the technology of the vacuum circuit-breaker. Recent information is added on the application of vacuum circuit-breakers for HV switchgear.

In Chapter 10, a variety of special switching situations and the technology of the appropriate devices are highlighted. A number of switching situations pose specific challenges to systems and switching devices. These are: generator circuit-breakers, switching with GIS- and air-break disconnectors, loop switching, switching in HV cable systems, the application of special by-pass switches in a series compensation capacitor bank, switching in the vicinity of shunt capacitor banks and switching in *ultra-high-voltage* (UHV) systems, high-speed earthing switches, *direct current* (DC) circuit-breakers and fuses.

Chapter 11 is devoted to switching overvoltages in systems. Practical values are given. Methods are discussed that enable reduction of the voltage stresses in particular situations. This is followed by an overview of controlled switching strategies that provide mitigation of unwanted transients.

Chapter 12 discusses the various investigations on reliability of circuit-breakers that have been conducted in the past 30 years. In addition, experiences regarding the endurance of switchgear against electrical and mechanical stresses are highlighted.

Chapter 13 deals with standardization and specification of switchgear. An explanation is given of the standardization framework for circuit-breakers that has been developed during the last half century in order to facilitate a system of quality assurance. In this chapter, as well as in other parts of the book, the worldwide accepted standardization system of the IEC (International Electrotechnical Commission)[2] will be followed mostly.

Chapter 14 describes the backgrounds of testing methods for circuit-breakers. A detailed analysis is given of the various possibilities and practices of testing of the switching and breaking capabilities of circuit-breakers.

Throughout the book, extensive reference is made to documents of the CIGRE (“Conférence International des Grands Réseaux Électriques” or “International Council on Large Electric Systems”)[3], a non-profit association for promoting collaboration with experts from all around the world by sharing knowledge and joining forces to improve the electric power systems of today and tomorrow. CIGRE has over 12 000 members from the electrical energy industry. More than 3500 experts from all around the world work actively together in structured *Working Groups* (WGs) coordinated by the CIGRE *Study Committees* (SCs). Their main objectives are

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[2] www.iec.ch

[3] www.cigre.org

to design and deploy the power system for the future, optimize existing equipment and power systems, respect the environment and facilitate access to information. For switching in power systems and its impact, the relevant study committees are A3 (High-Voltage Equipment), B4 (HVDC and Power Electronics), B5 (Protection and Automation) and C4 (System Technical Performance).

CIGRE documents can be accessed through www.e-cigre.org. A large volume of information is laid down in *Technical Brochures* (TB), the output documents of working groups, and in CIGRE meeting papers.

Another major source of reference is the IEEE ("Institute of Electrical and Electronics Engineers"). With more than 425 000 members IEEE is the world's largest professional association dedicated to advancing technological innovation.

IEEE has a number of societies. The one that is most closely related to the scope of this book is the PES ("Power and Energy Society") that covers planning, R&D, design, construction and operation of facilities systems for generation, transmission and distribution of electric energy. PES comprises 30 000 industry professionals, academics and students with a common interest in the electric power industry. It provides the world's largest forum for sharing the latest in technological developments in the electric power industry, for developing standards and for education.

Other societies related to switching technology are: the IAS ("Industry Applications Society"); the DEIS ("Dielectrics and Insulation Society") that deals with insulation materials and systems, dielectric phenomena and discharges in vacuum, gaseous, liquid and solid electrical materials; the IEEE PELS (Power Electronics Society), amongst others, on the development and practical application of power electronics technology; the NPSS (Nuclear and Plasma Sciences Society) that covers, amongst others, discharges in power switching devices.

IEEE documents are collected in the IEEE *Xplore*® Digital Library containing more than 3 million documents from IEEE and IEEE journals, transactions, magazines, letters, conference proceedings and active IEEE standards.

Within IEEE, the IEEE-SA (IEEE Standards Association) is developing and nurturing standards (see Chapter 13).

1.3 Power-System Analysis

Power-system analysis is a broad subject, too broad to be covered by a single textbook. Textbooks about the fundamentals of power-system analysis [1–4] give an overview of the structure of power systems (from the generation of electric energy, to the transmission and distribution to the customers) and take only the systems steady-state behaviour into account. This means that only the power-frequency phenomena are considered.

An interesting aspect of power systems is that the modelling of the system depends on the time scale that is being considered. In general, the time scales of interest are:

- Years, months, weeks, days, hours, minutes for steady-state analysis at power frequency (50 or 60) Hz. This is the time scale on which textbooks on the fundamentals of power-system analysis focus. The steady-state analysis covers a variety of topics, such as planning, design, economic optimisation, load flow / power flow computation, fault calculation, state estimation, protection, stability and steady-state control.
- Seconds for dynamic-behaviour analysis. The dynamic behaviour of electrical networks and their components is important in order to predict whether the system, or a major

part of it, remains in a stable state after a disturbance, for example, after a switching operation occurring at initiation or removal of a fault. The stability of power systems depends particularly on the ability of the installed control equipment to damp the electromechanical disturbances of the synchronous generators.

- Tens of microseconds to milliseconds for transients related to switching (kilohertz to tens of kilohertz). The insight into the transient behaviour of systems is important for understanding the effects of switching events (i.e. connection/disconnection of loads or fault clearing).
- Microseconds or less for disturbances having a disruptive origin (tens of kilohertz to several megahertz) like the effects of atmospheric disturbances (lightning strokes), breakdown phenomena causing excessive voltages and currents. Physically, the impact of these fast transients is mostly limited to the part of the system where the disturbance originates, that is, most often the affected part or component of the system itself and its immediate vicinity.

Although the power system itself remains unchanged when different time scales are considered, the components in the power system should be modelled in accordance with the appropriate time frame.

An illustrating example is the modelling of an overhead transmission line. For steady-state consideration at the power frequency of 50 Hz, the wavelength of the sinusoidal voltages and currents is 6000 km:

$$\lambda = \frac{c}{f} = \frac{3 \times 10^8}{50} = 6 \times 10^6 \text{ m} = 6\ 000 \text{ km} \tag{1.1}$$

λ is the wavelength [m];
c is the speed of light $\approx 3 \times 10^8$ m s^{-1};
f is the frequency [Hz = 1/s].

Thus, the transmission line is essentially of electrically small dimensions compared with the wavelength of the voltage or current. The generally valid Maxwell equations can therefore be approximated considering a quasi-static approach, and the transmission line can be rather accurately modelled by lumped elements. Kirchhoff's laws can be fruitfully used to compute the voltages and currents.

In contrast, when the effects of a lightning stroke have to be analysed, frequencies of 1 MHz and higher occur, and the typical wavelength of the voltage and current wave is 300 m or less. In this case, the transmission line is far from being electrically small, and it is no longer justified to use the lumped-element approximation. The distributed nature of the parameters of the transmission lines has to be taken into account, and has to be dealt with by travelling waves [5, 6].

Despite the fact that mainly lumped-element models are used in modelling, it is important to realize that the energy is mainly stored in the electromagnetic field surrounding the conductors with almost none in the conductors themselves. The Poynting vector, being the vector product of the electric field intensity vector $\boldsymbol{E}$ and the magnetic field intensity vector $\boldsymbol{H}$, indicates the direction and intensity of the electromagnetic power flow.

$$\boldsymbol{S} = \boldsymbol{E} \times \boldsymbol{H} \tag{1.2}$$

$\boldsymbol{S}$ is the Poynting vector [W m^{-2}];
$\boldsymbol{E}$ is the electric field intensity vector [V m^{-1}];
$\boldsymbol{H}$ is the magnetic field intensity vector [A m^{-1}].

Due to the finite conductivity of the conductor material and the finite permeability of the transformer-core material, a small electric field component is present inside the conductor and a small magnetic field component results in the transformer core:

$$\boldsymbol{E} = \frac{\boldsymbol{J}}{\sigma} \tag{1.3}$$

$\boldsymbol{J}$ is the current density vector [A m^{-2}];
σ is the conductivity [S m^{-1}].

$$\boldsymbol{H} = \frac{\boldsymbol{B}}{\mu} \tag{1.4}$$

$\boldsymbol{B}$ is the magnetic flux density vector [T = AH m^{-2} = Vs m^{-2}];
μ is the permeability [H m^{-1}].

When one speaks of *electricity*, one thinks of current flowing through the conductors from generator to load. This approach is valid because the physical dimensions of the power systems are large compared with the wavelength of the currents and voltages. For steady-state analysis of the power flow at the power frequency 50 or 60 Hz, complex calculus with phasors representing voltages and currents can be used successfully. Switching transients, however, involve much higher frequencies, up to kilohertz and megahertz, and the complex calculus can no longer be applied. Now the differential equations describing the system phenomena have to be solved. In addition, lumped-element modelling of the system components has to be done with care if Kirchhoff's voltage and current laws are used.

In the case of a power transformer under normal power-frequency conditions, the transformer ratio is given by the ratio of the number of turns of the primary and the secondary winding. However, for a lightning-induced voltage wave or a fast switching transient, the stray capacitance of the windings and the stray capacitance between the primary and secondary coil determine the transformer ratio. In these two situations, the power transformer has to be modelled differently. When one cannot get away with a lumped-element representation, wherein the inductance represents the magnetic field, the capacitance represents the electric field, and the resistance represents the losses, travelling wave analysis must be used. The correct 'translation' of the physical power system and its components into suitable models for the analysis and calculation of power-system transients requires insight into the basic physical phenomena. Therefore, it requires careful consideration and is not easy [7].

A transient occurs in the power system when the network changes from one steady state into another. This can be, for instance, the case when lightning hits the earth in the vicinity of a HV transmission line or when lightning hits a substation directly.

The majority of power-system transients are, however, the result of switching actions. Load-break switches and disconnectors switch off and on parts of the network under load and no-load conditions, respectively. Fuses and circuit-breakers interrupt higher currents and clear short-circuit currents in faulted parts of the system. The time period when transient voltage and current oscillations occur is in the range of microseconds to milliseconds. On this time scale, the presence of a short-circuit current during a system fault can be regarded as a steady-state situation, wherein the energy is mainly in the magnetic fields, and, after the fault current interruption, the system is transferred into another steady-state situation, wherein the energy is predominantly in the electric fields.

1.4 Purpose of Switching

1.4.1 Isolation and Earthing

Isolation of components from energized sections of the system is the simplest (no-load) switching operation. Isolation is usually necessary for safe maintenance, repair, and replacement of power-system components. Only after isolation and earthing, can personnel approach the equipment. In many countries, a visible break between live and workable parts is required.

To reduce the probability of breakdown to the absolute minimum, a very large contact distance, to be achieved with the switching device, is necessary. Such switching devices are commonly called *disconnectors* or *disconnecting switches*. These devices can operate in open air (such as in outdoor substations) or in an SF_6 (sulfur hexafluoride) environment, such as in *gas-insulated switchgear* (GIS) where the conductors and switchgear are insulated by pressurized SF_6 gas contained in metal tubes.

The no-load switching, that is, only isolation from energized sections, might seem to be an easy, straightforward operation. Nevertheless, due to the stray capacitance of the power system, a very small current always flows in energized systems. Because of this, disconnector switching is also associated with the extinction of an electric arc (see Section 1.5). Disconnector switching is discussed in detail in Section 10.3.2.

Earthing is the switching operation that connects a previously live part of the system to earth. In normal earthing operation, the section to be earthed is de-energized. In a faulty situation, when earthing is performed with energized sections or components of the power system, large currents can result, depending on earthing of the neutral of the power system. In any case, earthing switches must be capable of conducting the fault current, while special fast- and high-speed earthing switches have to perform the earthing operation under all (including faulty) conditions, see Section 10.4.2.

1.4.2 Busbar-Transfer Switching

For reliable operation of power systems many components and connections are installed in a redundant way. Busbars in substations are usually in a double arrangement. In cases when the flow of current has to be maintained but diverted (or commutated) from one busbar to another, switching devices, such as disconnectors are used to transfer the load current to the parallel busbar. Thus, the net load current will continue to flow uninterrupted. Because of the presence of the parallel busbar, current transfer up to a significant load current is relatively straightforward.

Bus transfer switching is treated in detail in Section 10.3.3.

1.4.3 Load Switching

Loads are regularly switched in power systems. For industrial systems, *contactors* are designed to switch normal loads, such as motors, pumps, furnaces, and so on, very frequently. In utility power systems, load-break switches and circuit switchers are the devices that can interrupt the load current – but not the (full) fault current. The frequency of normal-load switching in utility systems is usually very low. This is not the case for reactive-power installations, such as shunt capacitors and shunt reactors that are switched very frequently, often twice daily.

Unlike normal loads that mostly have a power factor close to one, shunt-reactor currents and capacitive currents have a phase angle of 90 electrical degrees between current and voltage. This has severe implication for the switching of these devices, as will be explained in Sections 4.2 and 4.3. Reactors can store energy in their magnetic field and capacitors store electric charge, the energy of which is released when the de-energization operation fails. The release of this energy in the system may have detrimental effects for the installed switchgear and other components.

1.4.4 Fault-Current Interruption

When a fault occurs in the power system, the associated short-circuit current is detected by protective relays which initiate circuit-breaker operation in order to interrupt the fault current (see also Section 2.1). The event is also known as *fault clearing*. The protective relays continuously monitor currents and voltages, collecting the information from the instrument transformers, that is, current and voltage transformers.

The time between the occurrence of a fault and its detection by the protection system, the *relay time*, is usually of the order of one to three half-cycles of the power-frequency of 50 or 60 Hz. The protection system issues a tripping command to the circuit-breaker(s) that should isolate the faulted section from the rest of the network. The tripping command activates the operating mechanism and through its kinematic chain makes the contacts in the circuit-breaker separate. After a certain *opening time*, the circuit-breaker arcing contacts will open in all three poles; this is usually referred to as *contact parting* or *contact separation*.

The pole of a circuit-breaker, or more generally of a switching device, is the part of the device that is located in one of the phases of the network, so there are three poles in a three-phase device.[4] A switching device is called single-pole if it has only one pole. If it has more than one pole, it may be called multi-pole (two-pole, three-pole, etc.) provided the poles are or can be coupled in such a manner as to operate together. The part of the pole in which the actual current is to be interrupted is generally called the *interrupter* or *interruption chamber*. It consists of contact system(s), a mechanical device supporting the arc-extinction process, and insulation. Depending on the rated voltage, a pole can consist of two or more interrupters placed in series in order to share the voltage. *Grading capacitors* across each interrupter have to take care of an equal voltage distribution across each interrupter.

So, a circuit-breaker may be designed as three single-pole switching devices or as a three-pole switching device and each pole will contain one or more interrupters. A three-pole device will be equipped with a single operating mechanism while single-pole devices will have one operating mechanism per pole or, at the highest system voltages, even several operating mechanisms per pole.

The electric arc in a circuit-breaker plays a key role in the interruption process and is therefore often called a *switching arc*. Upon contact separation, an arc is formed in the interrupter(s) of each pole. Actual interruption must wait for a zero crossing of the current. The arc is in essence resistive and therefore the arc voltage and the current reach the zero crossing at the

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[4] Definition of *pole of a switching device*: *"The portion of a switching device associated exclusively with one electrically separated conducting path of its main circuit and excluding those portions which provide a means for mounting and operating all poles together"* (IEC 60050-441, "International Electrotechnical Vocabulary").

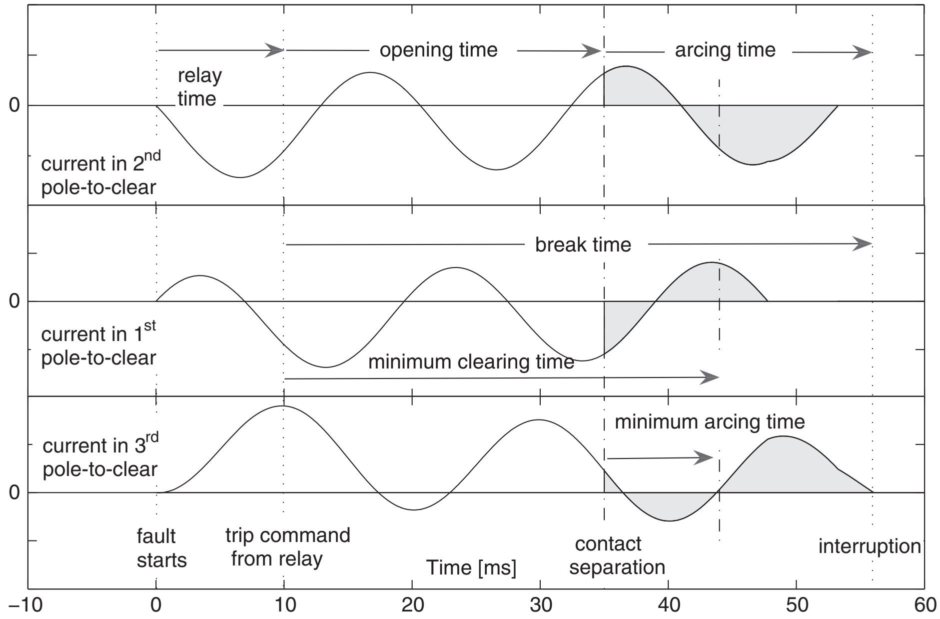


Figure 1.3 Circuit-breaker opening in a three-phase circuit and the IEC definitions of relevant times.

same instant. Around current zero (see Section 1.5), the energy input in the arc channel is rather low (at current zero there is even no energy input), and if the circuit-breaker design is such that the cooling by the extinction medium is adequate, the current can be interrupted. Depending on the type of circuit-breaker, the device may not be ready to interrupt at the first occurring current zero after contact separation. It takes a certain *minimum arcing time* before the circuit-breaker can actually interrupt the current, because sufficient cooling pressure of the extinction medium must be available and/or sufficient contact distance must be reached.

Then, after the minimum arcing time has elapsed, the current can be interrupted at the first following current zero. Current interruption will take place at the respective current zero of each of the three phases. When all the poles have interrupted, the fault has been cleared. The time between the instant of energizing the trip coil of the circuit-breaker and the current interruption in all phases is called the *break time*.

All relevant times are displayed in Figure 1.3 showing a three-phase-fault interruption sequence in an effectively earthed neutral system (see Section 3.3.2).

In the standard IEEE C37.04 [8], the rated interrupting time (i.e. the time between energization of the trip circuit and interruption in all phases) is expressed by the number of power-frequency cycles. A three-cycle breaker thus needs three power-frequency cycles to clear a fault.

1.5 The Switching Arc

When current flows through a circuit-breaker and the contacts of the breaker separate, the current continues to flow through the arc that starts at contact separation. Just before contact separation, the circuit-breaker contacts touch each other at a very small surface area, the contact bridge, and the resulting high current density makes the contact material melt. The melting contact material virtually explodes and this leads to a gas discharge in the surrounding medium, that is, air, oil, or SF_6.

The matter changes from a *solid state* to a *liquid state*. When more energy is added and the temperature increases, the matter changes from a liquid state to a *gaseous state*. A further increase in temperature gives the individual molecules so much energy that they dissociate into separate atoms, and if the thermal energy level is increased even further, the electrons in the outer shell(s) of the atoms acquire sufficient energy to become free electrons, leaving positive ions behind. The mixture of free electrons and ions is called the *plasma state*: a state of matter in which a certain portion of the particles is ionized. Because of the presence of free electrons and the heavier positive ions in the high-temperature plasma channel, the plasma channel is highly conductive and the current continues to flow through the arc plasma after contact separation. The electric arc is the plasma channel between the circuit-breaker contacts, a high-current electrical discharge in the extinction medium.

When considering current interruption, it is important to realize that an electric arc is always drawn at contact separation, and it appears immediately, automatically, and inevitably.

The electric arc is the only known element, apart from power semiconductors, that is able to change from a conducting to a non-conducting state in a short period. In HV circuit-breakers, the electric arc is a high-pressure arc burning in oil, air, or SF_6 (see Chapter 6). In medium-voltage (MV) circuit-breakers, the arc exists in vacuum or, more correctly, in the metal vapour released from the contacts (see Chapter 8).

Current interruption is performed by cooling the arc plasma so that it disappears at its most critical period of existence around the current zero.

Interruption of a short-circuit current is a very important function of a circuit-breaker. This function is verified in an extensive system of test-duties, set up by standardizing bodies, such as IEC and IEEE (see Section 13.1).

To understand the inevitability but also the advantage of an electric arc, consider a simple 50 Hz circuit with the r.m.s. inductive current $I = 100$ A at line-to-line voltage $U_r = 10$ kV (Figure 1.4).

Assume the hypothetical case that this current is interrupted immediately at contact separation without an arc at an instantaneous ‘chopped’ value of $i_{ch} = 100$ A as depicted in Figure 1.5.

The value of the inductance L can be calculated straightforwardly from the r.m.s. values of the current and voltage:

$$L = \frac{U_r}{\sqrt{3} I \omega} = 0.184 \text{ H} \tag{1.5}$$

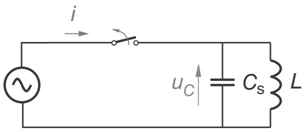


Figure 1.4 Equivalent circuit diagram for inductive-current interruption.

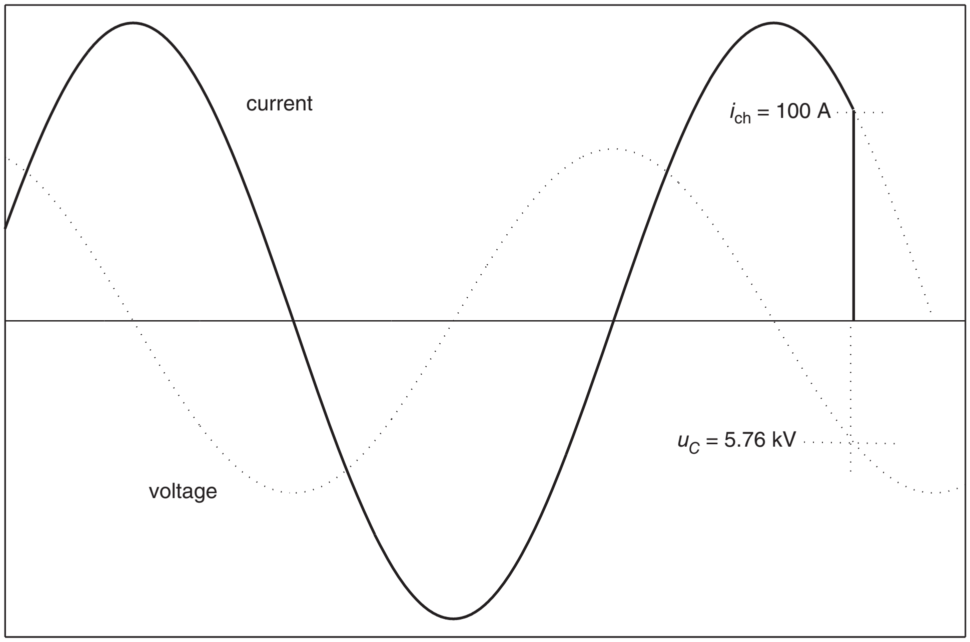


Figure 1.5 Current and voltage at current interruption without arc.

At the moment of interruption, the instantaneous voltage across the load u_C is given by:

$$u_C = U_r\sqrt{\frac{2}{3}}\cos\left\{\arcsin\left(\frac{i_{ch}}{I\sqrt{2}}\right)\right\} = 5.76\ \text{kV} \tag{1.6}$$

In practice, the load reactance will always possess a certain stray capacitance C_s, which is taken in this example as a lumped stray capacitance $C_s = 5$ nF. The stray capacitance represents in fact the energy storage in the electric field caused by the voltage at the terminals of the load. At current interruption, this capacitance remains charged at the voltage u_C. Now the situation is that the reactor stores magnetic energy because of the current i_{ch}, and the capacitor stores electric energy because of its voltage u_C. In terms of energy, the magnetic energy stored in the disconnected load reactor is:

$$E_m = \frac{1}{2}L \cdot i_{ch}^2 = 920\ \text{J} \tag{1.7}$$

whereas the electric energy stored in the capacitor is:

$$E_e = \frac{1}{2}C_s \cdot u_C^2 = 0.08\ \text{J} \tag{1.8}$$

Since the circuit-breaker is assumed to have disconnected the load from the source, the stored energy cannot transfer back to the source and remains in the load. The energy in the reactor and in the capacitor varies widely, and there is an exchange of the energy between the two components tending to reach a state of balance. The exchange results in an oscillation. As a consequence, the total energy $E_\mathrm{m} + E_\mathrm{e}$ at a certain moment will be present only in the capacitor with zero current and energy in the reactor. At that moment, the voltage across the capacitor $u_{C,\max}$ can be calculated as:

$$E_\mathrm{m} + E_\mathrm{e} = \frac{1}{2} C_\mathrm{s} \cdot u_{C,\max}^2 \tag{1.9}$$

from which it results that $u_{C,\max} = 607$ kV.

This is of course a rather unrealistic situation since 607 kV is a voltage unimaginable in a 10 kV system. The voltage cannot reach this value because a breakdown will occur at the dielectrically weakest location in the circuit. This location is the contact gap of the switching device.

The arc (*electric arc discharge*) will start because conducting plasma is created by the melting, evaporation and ionization of the metal originating from the last contact bridge through which all current is passing (see Section 1.4.4). Every time when the arc has a tendency to extinguish, for example when the current is too small to maintain the arc, there is still substantial energy trapped in the reactor and, consequently, the voltage appearing immediately across the contact gap will re-ignite the arc and re-create the conducting arc channel.

Therefore, in an inductive circuit, the arc is a continuously surviving discharge, lasting until the magnetic energy stored in the load reactor is released back to the source. Only at the instant of current zero ($i = 0$) is there no magnetic energy in the reactor and the arc disappears.

This shows the big advantage of the arc interruption over a sudden interruption: the arc allows a natural transfer of load energy back to the source, thus avoiding excessive overvoltages.

In AC systems, current zero crossings occur every half-cycle and all HV AC power switching devices interrupt the current at one of those current zeros.

Switching arcs are normally not visible in HV switching devices because they appear in a hermetically sealed interrupter. In simpler switching devices, however, the arc and its consequences can be observed. Figure 1.6 shows a switching arc in a load-break switch (see Section 1.4.3). In this example, a current of 700 A is interrupted in a 12 kV test circuit, which is a normal action at load-current switching. The impact of the arc can be seen: the pressure rise in the interruption chamber between open contacts in the atmospheric air causes a plasma jet to eject ionized gas to the outside, together with the debris from molten material of the contacts and the interruption-chamber walls. The interruption principle of confining the arc into a chamber with walls that release evaporation material that contributes to the cooling of the arc is sometimes referred to as the “deion principle” (see Section 6.2.3).

Figure 1.6 Switching arc of a load-break switch interrupting 700 A in a 12 kV test circuit.

From this example it is clear that arcs created in the largest single-interrupter circuit-breakers capable of breaking 63 kA in 550 kV systems, that is, having 4125 times greater apparent switching power than the load-break switch, are hugely violent phenomena.

Although current zero is the only opportunity for a switching device to interrupt a current, this does not imply that every current interruption is finally successful. The arc being present between the contacts may have disappeared, but the hot remnants, for example, ionized gases in SF_6 circuit-breakers and metal vapour in vacuum breakers, will reduce the dielectric strength, thus influencing the ability of the circuit-breaker to withstand the *transient recovery voltage* (TRV). The transient recovery voltage is the voltage that appears across the gap immediately following current interruption, as a reaction of the network to the new situation. A re-ignition may occur followed by another loop of power-frequency current. Eventually, after several unsuccessful attempts, the device may not be capable of interrupting the current and will explode, causing a short-circuit by itself.

1.6 Transient Recovery Voltage (TRV)

1.6.1 TRV Description

The TRV is the voltage across the open circuit-breaker contacts immediately after current interruption. The TRV, that is, u_{ab}, appears as the difference between the voltage-to-earth at the source side and the voltage u_{bn} at the load side (see Figure 1.9):

$$u_{\mathrm{ab}} = u_{\mathrm{an}} - u_{\mathrm{bn}} \tag{1.10}$$

Thus, a TRV always consists of two components: a source-side component u_{an} and a load-side component u_{bn}. In all cases, the TRV starts from zero at current zero, makes an excursion to the momentary power-frequency voltage, overshoots in a damped oscillatory manner, and continues to oscillate until a steady-state condition is reached. This steady-state situation is a power-frequency voltage, called the *recovery voltage* (RV).

The complete interruption process is outlined schematically in Figure 1.7. In this case the RV is equal to the source voltage.

The frequency of the TRV is determined by the relevant inductance and capacitance. The peak value in the undamped case is two times the peak source voltage; in practice, the peak value of the TRV is lower due to damping.

The TRV affects the interruption for two reasons:

- Determined by the oscillation frequency, the *rate-of-rise of recovery voltage* (RRRV) can be very high. This implies that very shortly after extinction of the arc, a high voltage appears across the contact gap. If there are still ionized, hot residues of the arc remaining to a certain degree, the arc will be re-established (will *re-ignite*) due to the impact of the TRV. In Section 13.1.2 it will be described that the standardized RRRV corresponds to the slope of the tangential line of the TRV wave shape, a value not necessarily equal to the highest value of the derivative of the TRV ($\mathrm{d}u/\mathrm{d}t$), see Figure 1.8.
- The peak value of the TRV can be very high. In testing and standardization, the damping is expressed by the *amplitude factor* k_{af}, defined as the ratio between the transient peak value and the steady-state value; in Figure 1.8 the steady state voltage is the peak of the power-frequency voltage. The value of k_{af} is in the range $1 < k_{\mathrm{af}} \leq 2$.

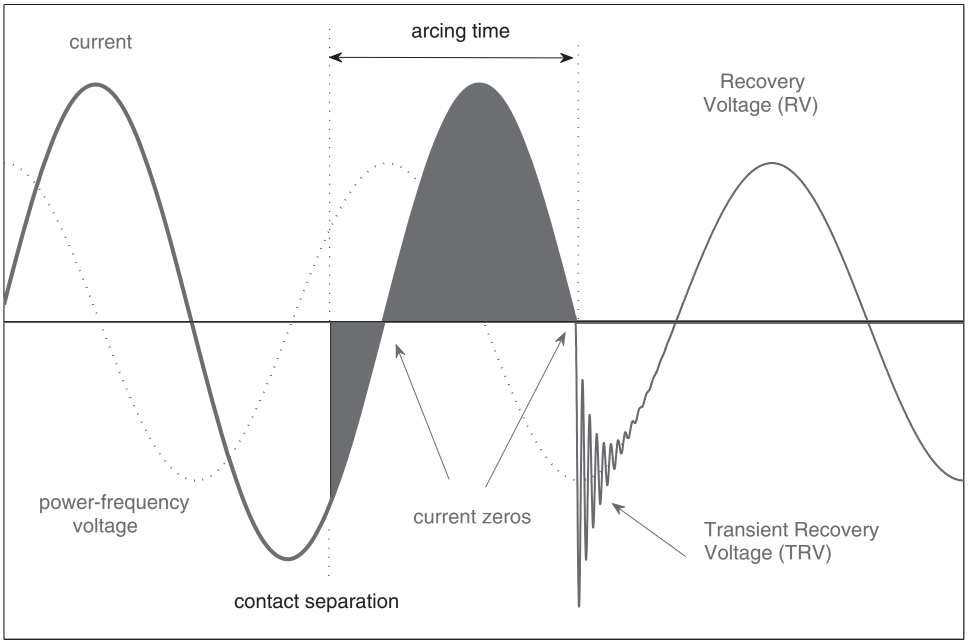


Figure 1.7 Current-interruption in a purely inductive AC circuit.

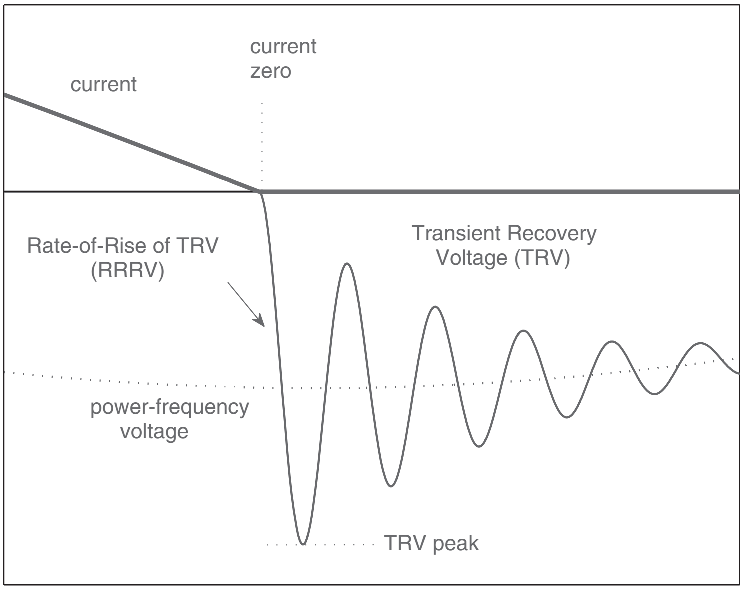


Figure 1.8 Current zero and transient recovery voltage in an inductive AC circuit.

Representative values of k_{af} are very difficult to calculate, because resistances depend strongly on frequency. Due to the skin-effect, the effective conduction takes place in a surface layer, the thickness of which is smaller at higher frequencies, leading to a rapid increase in damping resistance at higher frequencies.

The technology of circuit-breakers must be able to:

- Withstand the high thermal energy of the arc before current zero.
- Rapidly remove the remnants of the arc after current zero in order to withstand the TRV. In gas/oil breakers, this is achieved by a forced gas flow through the former arc path, removing the ionized medium. In vacuum interrupters, the natural diffusion of the metal vapour plasma towards the very low background pressure enables fast recovery of the gap.

Background information on the awareness of TRV over the years and its standardized description can be found in Section 13.1.1.

Circuits subjected to a short-circuit are mainly inductive. This is because the current value is limited by the reactance ($X = \omega L$), rather than by the resistance R. In other words, $R \ll \omega L$. This causes the short-circuit current to lag approximately 90° with respect to voltage. In 50 Hz circuits the ratio is standardized: $X/R = 14.14$ and the phase lag of the current with respect to the voltage is 85.9° (electrical degrees). In medium voltage cable networks the phase lag is smaller, which results in a less onerous interruption regarding TRV.

1.6.2 TRV Composed of Load- and Source-Side Contributions

In practical cases, there will be more parts of the network involved in the TRV wave shape than just the single LC elements of the circuit described in the example above. Consequently, the TRV often comprises multiple-frequency components decisive for its RRRV and peak value.

As an example, the case is considered of a fault some distance away from the circuit-breaker. A simplified single-phase equivalent circuit is shown in Figure 1.9. It comprises two separate LC circuits, one with C_S and L_S at the source side and one with C_L and L_L at the load side. After interruption of the current – which is lower than the terminal-fault current because of the load-side impedance – the two parts of the circuit are disconnected completely and have no electrical interaction.

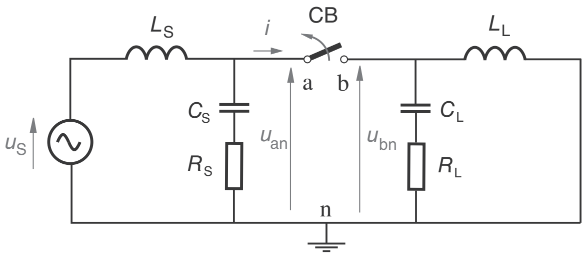


Figure 1.9 Equivalent circuit diagram for multi-frequency TRV.

The transients in both circuit parts behave independently and, in the construction of TRV, understanding of the initial, intermediate, and final conditions is very helpful:

- Initial condition (at current zero):

  Both transients start at the same voltage level:

$$u_{\mathrm{an}}(0) = u_{\mathrm{bn}}(0) = \frac{L_{\mathrm{L}}}{L_{\mathrm{S}} + L_{\mathrm{L}}}\hat{U} \tag{1.11}$$

  This is the voltage to earth at current zero; in the simple-circuit case it is the voltage across the capacitors C_{S} and C_{L} that are charged to equal voltage at current zero.
- Oscillation interval from current zero to the decay of the transients after which only power-frequency recovery voltage remains:

  The TRV component at the source side u_{an} has an amplitude

$$u_{0,\mathrm{S}} = \hat{U} - u_{\mathrm{an}}(0) = \frac{L_{\mathrm{S}}}{L_{\mathrm{S}} + L_{\mathrm{L}}}\hat{U} \text{ and frequency } f_{\mathrm{S}} = \frac{1}{2\pi}\cdot\frac{1}{\sqrt{L_{\mathrm{S}}C_{\mathrm{S}}}} \tag{1.12}$$

  The TRV component at the load side u_{bn} has an amplitude

$$u_{0,\mathrm{L}} = u_{\mathrm{bn}}(0) = \frac{L_{\mathrm{L}}}{L_{\mathrm{S}} + L_{\mathrm{L}}}\hat{U} \text{ and frequency } f_{\mathrm{L}} = \frac{1}{2\pi}\cdot\frac{1}{\sqrt{L_{\mathrm{L}}C_{\mathrm{L}}}} \tag{1.13}$$

- Final condition after decay of transient components:

  The TRV component at the source side $u_{\mathrm{an}}(t)$ will oscillate from the initial voltage $u_{\mathrm{an}}(0)$ to the power-frequency voltage of the source $\hat{U}\cdot\cos(\omega t)$, ignoring the voltage drop across the capacitance, because $1/(\omega C_{\mathrm{S}}) > \omega L_{\mathrm{S}}$.

  The TRV component at the load side $u_{\mathrm{bn}}(t)$ will oscillate from the initial voltage $u_{\mathrm{bn}}(0)$ to zero (in the absence of an active source and/or a charge-storing element).

  Keeping these simple and clear rules in mind, understanding TRV in various situations is straightforward.

Considering the fact that in practical cases the frequency of the source- and load-side TRV component is much higher than the power frequency, the transient components can be treated independently from the power-frequency voltage.

In practical cases, in circuits with power factor close to zero, the equation of the TRV reads as follows:

$$u_{\mathrm{ab}}(t) = \hat{U}\left[\cos(\omega t) - \frac{L_{\mathrm{S}}}{L_{\mathrm{S}} + L_{\mathrm{L}}}\exp(-\beta_{\mathrm{S}}t)\cos(\omega_{0\mathrm{S}}t) - \frac{L_{\mathrm{L}}}{L_{\mathrm{S}} + L_{\mathrm{L}}}\exp(-\beta_{\mathrm{L}}t)\cos(\omega_{0\mathrm{L}}t)\right] \tag{1.14}$$

with β_{S} and β_{L} being the damping in the source- and load-side circuit:

$$\beta_{\mathrm{S}} = \frac{R_{\mathrm{S}}}{2L_{\mathrm{S}}} \qquad \beta_{\mathrm{L}} = \frac{R_{\mathrm{L}}}{2L_{\mathrm{L}}} \tag{1.15}$$

and $\omega_{0\mathrm{S}} = 2\pi f_{\mathrm{S}}$ and $\omega_{0\mathrm{L}} = 2\pi f_{\mathrm{L}}$ the respective angular frequencies.

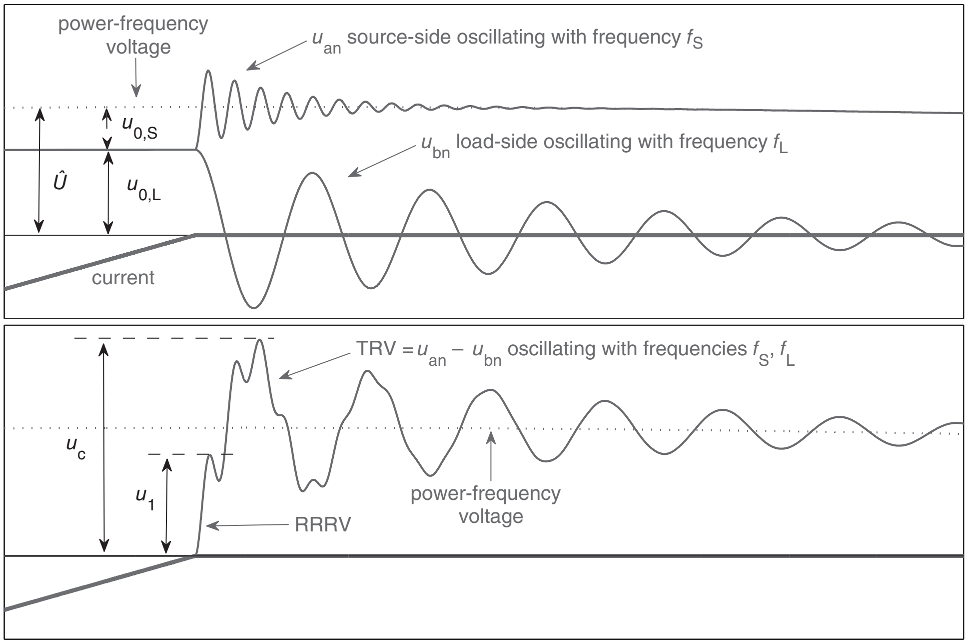


Figure 1.10 Double-frequency TRV with the source-side and load-side components.

The formal mathematical derivation of this generalized TRV equation can be found in Section 5.1.3.

Because of the presence of two frequencies, there is now a first local maximum value u_1 and a global maximum u_c.

The effect of the double-frequency nature of the TRV is twofold:

- The peak value u_c is reduced (with respect to a single-frequency TRV) because the amplitude of each of the oscillations is smaller than $\hat{U}$;
- The rate-of-rise of TRV (RRRV) may increase because of a second component having a higher frequency.

In Figure 1.10, the transients at the load and source sides are given for different load and source impedances ($L_S = 0.5\,L_L$). Both transients contribute to the TRV. As can be seen in this example, the initial rate-of-rise of TRV (RRRV) is determined by the TRV component of the highest frequency (here the source side), whereas its peak value will usually be determined by the oscillation having the largest amplitude (the load side in Figure 1.9). This is normally the circuit part experiencing the largest voltage drop.

A clear distinction can be made between a fault- and load-current interruption as detailed in Chapters 3 and 4 respectively:

1. In fault-current breaking, the current to be interrupted is mainly determined by the source impedance: $X_S \gg X_L$, as shown in Figure 1.11. Then, the TRV amplitude is mainly contributed by the source-side circuit ($u_{0,S} \gg u_{0,L}$).

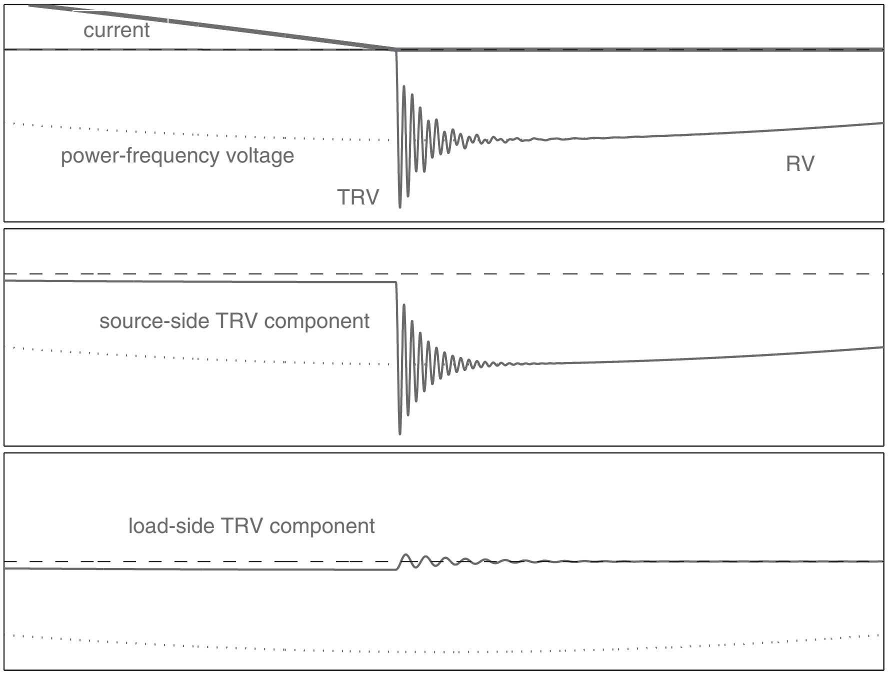


Figure 1.11 Double-frequency TRV fault switching with current mainly determined by the source reactance ($X_L = 0.1X_S$ and $C_L = 300$ nF).

2. In load switching, the current is clearly determined by the load impedance, thus $X_S \ll X_L$ and $u_{0,S} \ll u_{0,L}$, leading to the situation in Figure 1.12 where the load oscillation is dominating the TRV wave shape.

Clearly, the TRV components originating from various parts of the circuit must be taken into account.

1.7 Switching Devices

Switching devices are devices designed to make and/or break the current in one or more electric circuits. Depending on their specific switching duty, a large number of devices can be identified, most of which will be treated in detail in this book.

When combined with their secondary equipment, switching devices are called *switchgear*, which is *"a general term covering switching devices and their combination with associated control, measuring, protective, and regulating equipment, also assemblies of such devices and equipment with associated interconnections, accessories, enclosures, and supporting structures, intended in principle for use in connection with generation, transmission, distribution, and conversion of electric energy"* (definition by IEC [9]).

The most widely applied switching device is the *switch* that is defined as: *"A mechanical switching device capable of making, carrying and breaking currents under normal circuit*

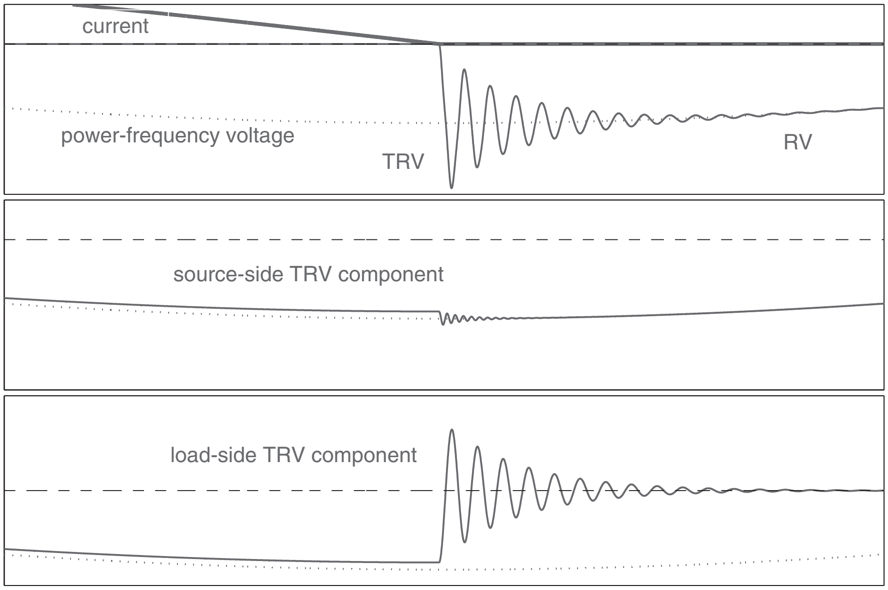


Figure 1.12 Double-frequency TRV load switching with current mainly determined by the load reactance ($X_L = 10X_S$ and $C_L = 30$ nF).

conditions which may include specified operating overload conditions and also carrying for a specified time currents under specified abnormal circuit conditions such as those of short circuit. Note: A switch may be capable of making but not breaking short-circuit currents" (definition by IEC [9]).

Circuit-breakers are indispensable switching devices in the power system. Their main task is to interrupt fault currents and to isolate faulted parts of the system. Besides short-circuit currents, a circuit-breaker must also be able to interrupt a wide variety of other currents at system voltage, such as capacitive currents, small inductive currents, and load currents. They are defined as *"mechanical switching devices, capable of making, carrying and breaking currents under normal circuit conditions and also making, carrying for a specified time and breaking currents under specified abnormal circuit conditions, such as those of short circuit"* (definition by IEC [9]).

Circuit-breakers are the only switching devices able to interrupt (break) fault currents in electrical power systems up to the highest short-circuit current levels [10–16, 21]. At present, in distribution networks operated at voltages below 72.5 kV, these short-circuit currents can go up to 63 kA in standard applications and up to 300 kA in generator applications; generator circuit-breakers are situated between the generator and the step-up transformer, in power stations (see Section 10.1). In transmission systems, generally operated at a voltage of 72.5 kV and above, a short-circuit current can arise up to 80 kA. In contrast to fuses and other fault current limiting devices, as discussed in Sections 10.12 and 10.12.1, after fault clearing, circuit-breakers are required to be ready for service again and even fulfil an operating sequence of several short-circuit current breaking and making operations.

Faults in power systems cannot be avoided. A wide-scale international survey on fault statistics shows that most faults occur on overhead lines, with several faults per 100 km overhead line per year [17] (see details in Section 2.4).

The general basic characteristics and requirements of circuit-breakers are the following:

- A good conductor when closed. In order to minimize energy losses during normal operation, the contact system must be designed to have very low resistance. In addition, during conduction of short-circuit current (when not called upon to interrupt), excessive generation of heat or other malfunction must not occur.
- A good insulator in open position. This requirement involves withstanding of high overvoltages due to switching and/or lightning overvoltages. Circuit-breakers in the open position do not have a safety insulating function, a feature achieved by disconnectors that are specified to withstand higher overvoltages across the open contacts.
- The transition from conductor to insulator (and vice versa) must occur sufficiently fast. The breaker must be able to act very quickly after being tripped, in order to minimize damage due to a short-circuit. In Section 1.5, the sequence of events is sketched during this transition.

  Interruption of any current (from very small transformer magnetizing currents up to massive terminal fault currents) must be assured. In addition, making (energizing a circuit) is a requirement. A making operation under short-circuit is not straightforward, it can cause damage to the contact system.
- The switching should not generate unacceptable transients in the network. The arc, initiated in the interruption chamber at contact separation, allows the release of the energy of the load back to the source (see Section 1.5).
- The breaker must be able to switch often without too much erosion. The arc is an intensive heat source and potentially damages the internal parts. This causes loss of material (erosion) from contacts and hot gas guiding elements (*nozzles* in gas circuit-breakers). Withstanding against repeated electrical arcing is called *electrical endurance*, refer to Section 12.2. Generally, the higher the current, the higher the erosion.
- The breaker must operate immediately, even after long idle time and in all possible climatic conditions.
- The breaker must be able to handle a large number of switching operations, all not necessarily with current. This capability is called *mechanical endurance* – refer to Section 12.2. It requires very high reliability of the mechanical components of the circuit-breaker. From international studies it is concluded that this requirement is very severe: most major and minor failures in switchgear have a mechanical rather than an electrical origin, refer to Section 12.1.3 [18].

Even though real HV circuit-breakers never realize the ideal transition from perfect conductor to perfect insulator instantaneously, it can be expected that the conductivity of their contact gap decreases by 13 to 15 orders of magnitude during a very short period of time, (10^{-5} to 10^{-6}) s, at the instant of the current interruption. At present, except for semiconductors, the only known medium that has the capability of such rapid change in conductivity is the arc plasma, after a change in temperature of only 1 to 2 orders of magnitude.

The highest technical requirements in terms of breaking current and rated voltage are set for HV transmission-line circuit-breakers. They must

- carry (without exceeding the temperature limits of their components) the normal rated current of up to 4 kA – at the highest system voltages even larger values; generator circuit-breakers in nuclear power stations even up to 40 kA;
- withstand (up to 3 s) high short-time currents $I_k \leq 100$ kA with the corresponding peak withstand currents $I_p \leq 250$ kA;
- switch all currents from several amperes to (80 to 100) kA short-circuit currents at rated voltages up to 1200 kV with a maximum break time of few cycles, which is necessary for reasons of system stability.

Circuit-breakers are often located in outdoor substations and exposed to all kinds of climates, from tropical heat with extreme humidity to arctic cold, down to –55 °C. They can also be exposed to extreme pollution. HV circuit-breakers may also be required to withstand earthquake stresses.

In the case of a short-circuit somewhere in the network, circuit-breakers are the last link in the chain of power-system protection and the only means of protecting the network. Therefore, they must comply with extremely high demands for operational reliability.

Unlike other components, circuit-breakers actively intervene in the flow of energy in electrical power systems and, therefore, not only cause but also have to withstand the electrical (and mechanical) stresses that arise due to their action.

An extended set of tests intended to verify all these requirements is defined and used in the industry. These tests, specifically designed to verify circuit-breaker performance, are collected in IEC 62271-100 [19] and IEEE C37-09 [20] (see Chapter 13).

1.8 Classification of Circuit-Breakers

Circuit-breakers can be classified by many different criteria, such as rated voltage class, type of installation, structural design, arc-extinction principle, extinction medium, and so on.

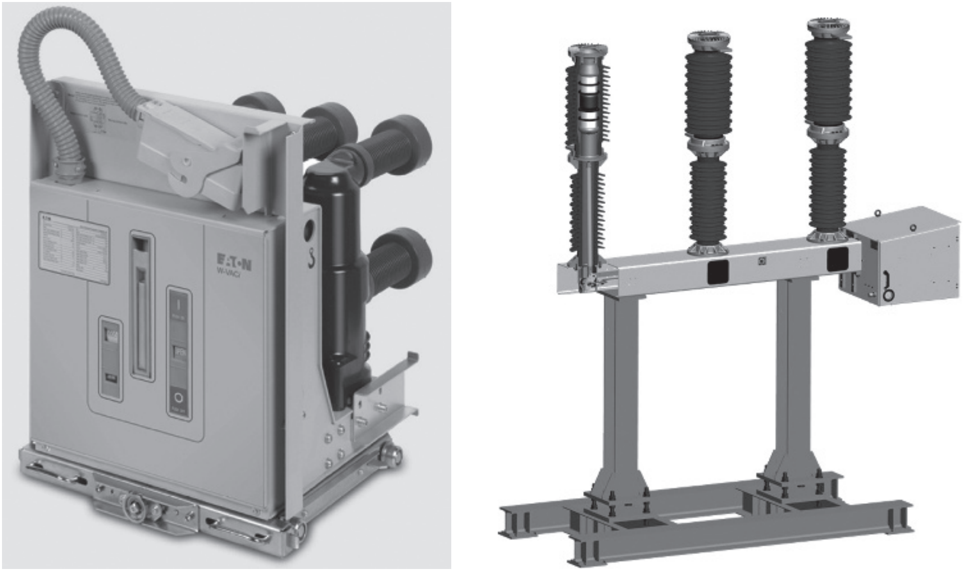
The basic classification of circuit-breakers relates to the voltage level for which they are designed. By this criterion, circuit-breakers are classified by IEC into two main groups:

- LV (low-voltage) circuit-breakers with rated voltages below 1000 V; and
- HV circuit-breakers with rated voltages 1000 V or more.

This classification of circuit-breakers is currently being used by both IEC and IEEE/ANSI standards.

In addition, the terms medium voltage (MV) for the range (1 to 52) kV, extra-high voltage (EHV) ranging (245 to 800) kV and ultra-high voltage (UHV) for rated voltages above 800 kV are in common use, though not defined in the standards.

HV circuit-breakers can be designed for either indoor or outdoor installation. Indoor circuit-breakers can be used only inside buildings or weather-resistant enclosures. MV indoor circuit-breakers are often designed for use inside a metal-clad switchgear enclosure. The essential differences between indoor and outdoor circuit-breakers are the external packaging and the



(a) (b)

Figure 1.13 Vacuum circuit-breakers: (a) 24 kV indoor circuit-breaker (reproduced with permission of Eaton Electric); (b) live-tank 72.5 kV vacuum circuit-breaker (reproduced with permission of Siemens AG).

enclosure materials that are used, as illustrated in Figure 1.13. In many cases, the interruption chambers and the operating mechanism are the same for both indoor and outdoor circuit-breakers. Therefore, they have identical or very similar switching capabilities.

There are two types of outdoor circuit-breakers, based on their structural design (Figure 1.14): dead-tank circuit-breakers and live-tank circuit-breakers.

Dead-tank type circuit-breakers are characterized by the following advantages over live-tank circuit-breakers:

- they have a lower centre of gravity with a high seismic withstand capability;
- multiple instrument transformers can be installed at both sides of the circuit-breaker at low potential; and
- they can be shipped completely assembled with factory-made adjustments.

Live-tank type circuit-breakers have the interrupter housing at a high potential above earth. They also have certain advantages over dead-tank circuit-breakers:

- lower cost, except for the current transformers;
- less technically complicated because the interrupter is far away from earth;
- smaller space requirements for the installation; and
- a smaller quantity of isolating medium (oil or gas) is required.

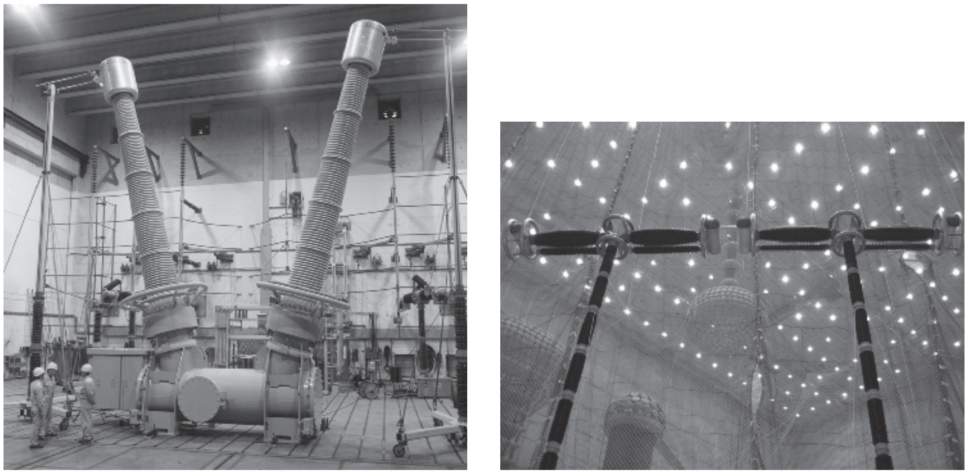

(a) (b)

Figure 1.14 (a) 550 kV dead-tank single break type circuit-breaker in KEMA test-laboratory (reproduced with permission of Hitachi); (b) EHV-UHV four-break live-tank circuit-breaker (reproduced with permission of Alstom Grid).

Another important classification of circuit-breakers is by the medium for insulation and arc extinction. The evolution of circuit-breaker technology has been strongly related to the appearance of new media.

Oil and air were used during the early decades of electrification and they were prevalent throughout the first half of the twentieth century. Very reliable designs were developed, many of which are still in service today. They were manufactured until the 1980s when they were supplanted by circuit-breakers using vacuum and sulfur hexafluoride (SF_6) gas.

Vacuum and SF_6 made their appearance at about the same time – in the second half of the twentieth century. Today, they are absolutely dominant and leading technologies: vacuum for medium voltages and SF_6 for high voltages. For that reason, this book concentrates predominantly on these two technologies, on which all present-day products are based.

In Figure 1.15 an overview is provided of the various media and principles that were and are used in power switching devices.

HV circuit-breakers can also be classified by their operational arrangements. There are three-pole-operated circuit-breakers and single-pole-operated circuit-breakers, as illustrated in Figure 1.16.

A three-pole-operated circuit-breaker operates the interrupters for all three phases simultaneously with one operating mechanism. Such designs are normally used at medium voltages and are predominant up to ratings of 245 kV. The prevalence towards three-pole operation at lower rated voltages is primarily cost driven, as it requires only one operating mechanism for all three poles. Single-pole operated circuit-breakers at these voltages are used only if a single-phase auto-reclosure of transmission lines is required. Due to the mechanical coupling of all three poles, this type of circuit-breaker ensures better synchronism between poles during both closing and opening.

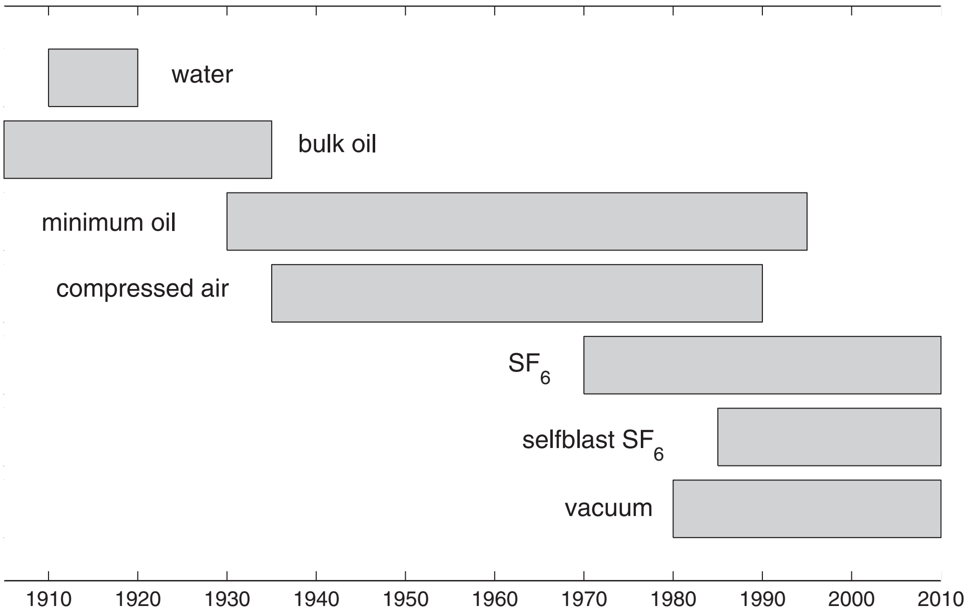
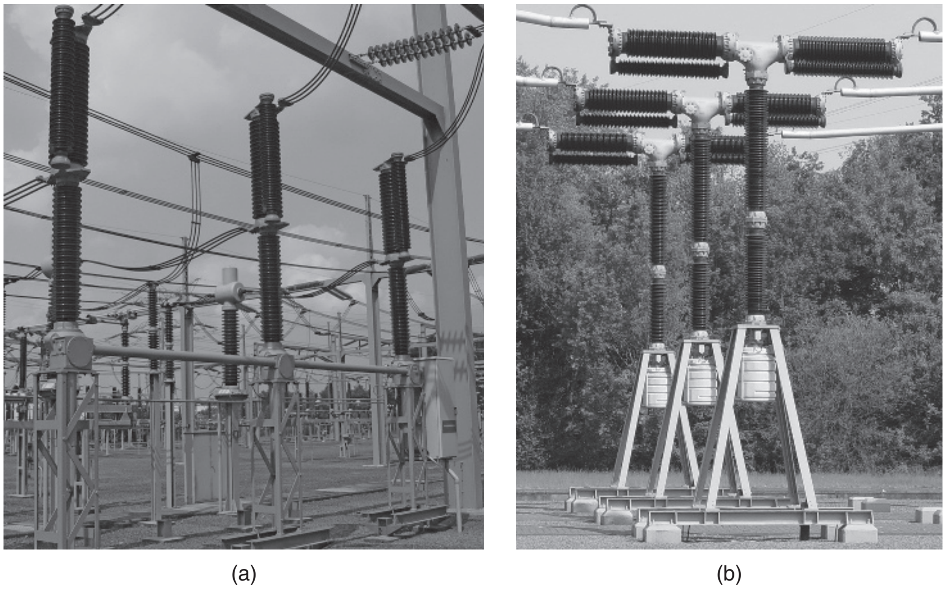


Figure 1.15 Use of arc-extinction media in switching devices over the years.


(a)

(b)

Figure 1.16 (a) Three-pole-operated single-break 170 kV live-tank SF_6 circuit-breaker; (b) single-pole-operated double-break 420 kV live-tank SF_6 circuit-breaker.

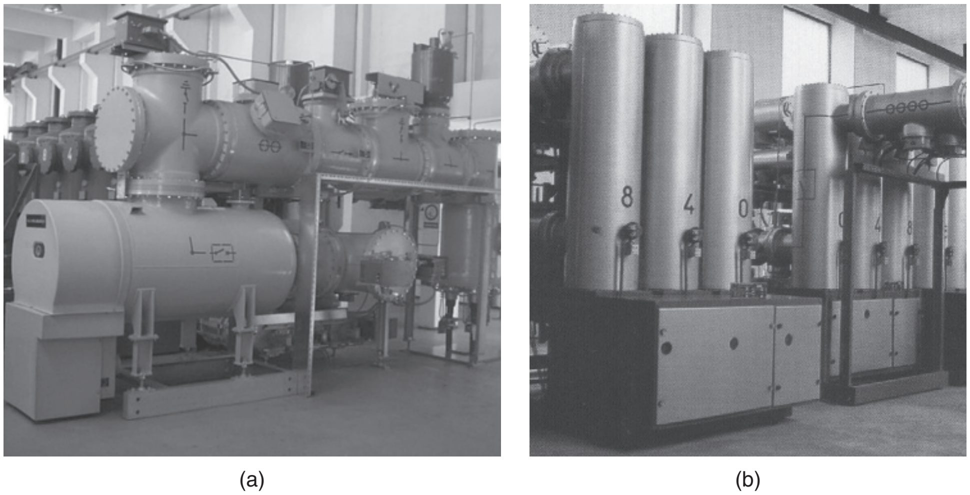


Figure 1.17 (a) Three-phase-enclosed 123 kV GIS SF_6 circuit-breaker; (b) single-phase-enclosed 123 kV GIS SF_6 circuit-breaker.

Single-pole-operated circuit-breakers use three separate operating mechanisms to control each of the three phases separately. Such designs are used predominantly at voltages above 245 kV, mainly due to constraints of the physical size, the associated operating energies and forces involved in such large circuit-breakers.

Circuit-breakers for metal-enclosed SF_6 g*as-insulated switchgear* (GIS) represent a separate group of HV circuit-breakers. The distinctive advantages of GIS are:

- small size and therefore very small space requirements, which is particularly important in urban environments;
- extra safety for operating personnel protecting them from contact with live parts, since all live parts of the switchgear are contained in an earthed metal enclosure;
- full protection of HV parts against pollution, unaffected by weather, including higher altitudes;
- wide range of possible locations for installation and aesthetic compatibility with its surroundings;
- short on-site erection time, owing to extensive prefabrication and factory testing of complete bays;
- compact and modular design.

Two main enclosure-design principles are applied to the GIS circuit-breakers: three-phase enclosed and single-phase enclosed (Figure 1.17).

Single-phase enclosures are used, with few exceptions, for rated voltages above 170 kV, otherwise the diameter of the enclosures becomes too large. Up to ratings of 170 kV, the three-phase enclosures have certain advantages compared with single-phase enclosures:

- the total number of the enclosures is reduced to one-third;
- the bay width and floor area are considerably reduced;

- three-phase-enclosed GIS practically does not suffer from eddy currents and therefore electrical losses in the enclosure are negligibly small;
- larger gas zones ensure a slower rise of pressure in case of an internal fault;
- burn-through of the enclosure, in the case of an internal fault, is much less probable because a phase-to-earth fault usually turns into phase-to-phase arcing within several tens of milliseconds; and
- the probability of gas leakage is smaller due to the reduced number of gas zones and fewer compartments.

References

[1] van der Sluis, L. and Schavemaker, P. (2001) *Electrical Power Systems Essentials*, John Wiley & Sons Ltd, Chichester, England, ISBN 978-0470-51027-8.

[2] Grainger, J.J. and Stevenson, W.D. Jr. (1994) *Power System Analysis*, Chapters 4, and 5, McGraw-Hill, New York, ISBN 0-07-061293-5.

[3] Duncan, J.D. (1993) *Power System Analysis and Design*, PWS Publishing Co., Boston, ISBN 0-53493-960-0.

[4] El-Hawary, M. (1995) *Electrical Power Systems*, IEEE Power System Engineering Series, IEEE, ISBN 0-7803-1140-X.

[5] Bewley, L.V. (1963) *Travelling Waves on Transmission Systems*, 2nd edn, Chapters 1–4, Dover Publications, Mineola, New York.

[6] Rüdenberg, R. (1962) *Elektrische Wanderwellen*, 4th edn, Parts I, II, IV, Chapters 1, 6, and 17, Springer-Verlag, Berlin.

[7] Rüdenberg, R. (1968) *Electrical Shock Waves in Power Systems*, Parts I, II, and IV, Chapters 1, 6, and 17, Harvard University Press, Cambridge, Massachusetts.

[8] IEEE Std C37.04-1999 (1999) IEEE Standard Rating Structure for AC High-Voltage Circuit Breakers.

[9] IEC 60050-441 (1984) International Electrotechnical Vocabulary – Chapter 441: Switchgear, controlgear and fuses.

[10] Browne, T.E. Jr. (1984) *Circuit Interruption*, Chapter 3, Marcel Dekker, New York, ISBN 0-824771-77-X.

[11] Garzon, R.D. (1997) *High-Voltage Circuit-Breakers*, Chapter 3, Marcel Dekker, New York, ISBN 0-8247442-76.

[12] Nakanishi, K. (ed.) (1991) *Switching Phenomena in High-Voltage Circuit-Breakers*, Marcel Dekker, New York, ISBN 0-8247-8543-6.

[13] Ragaller, K. (1977) *Current Interruption in High-Voltage Networks*, Plenum Press, ISBN 0-306-40007-3.

[14] Flurscheim, C.H. (ed.) (1975) *Power Circuit-Breakers*, Peter Peregrinus Ltd., ISBN 0-901233-62-X.

[15] Jones, G.R., Seeger, M. and Spencer, J.W. (2013) Chapter: Gas-filled interrupters - fundamentals, in *High-Voltage Engineering and Testing*, 3rd edn (ed. H.M. Ryan), IET, Stevenage, UK, ISBN 978-1-84919-263-7.

[16] Blower, E.A. (ed.) (1986) *Distribution Switchgear*, Collins, London, ISBN 0-00-383126-4.

[17] CIGRE Working Group 13.08 (2000) Life Management of Circuit-Breakers, Technical Brochure 165.

[18] CIGRE Working Group A3.06 (2012) Final Report of 2004-2007 International Enquiry on Reliability of High Voltage Equipment, Part 2 – Reliability of High Voltage SF_6 Circuit-Breakers, Technical Brochure 510.

[19] IEC 62271-100 (2012) High-voltage switchgear and controlgear – Part 100: Alternating-current circuit-breakers, Ed. 2.1.

[20] IEEE C37.09 (1999) IEEE Standard Test Procedure for AC High-Voltage Circuit-Breakers Rated on a Symmetrical Current Basis.

[21] Kapetanović, M. (2011) *High Voltage Circuit-Breakers*, ETF – Faculty of Electrotechnical Engineering, Sarajevo, ISBN 978-9958-629-39-6.