2 Equipment in Power Systems

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Contents

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2.1 Introduction

Electricity is supplied to a large number of households, offices, and factories every day. Its availability has increased over the last 100 years since electricity has begun to be supplied in the late 1800s, and nowadays it is considered to be an essential 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 electrical energy generated in the power generation plants to the consumers in a safe and reliable way, no matter how far the power generation plants are located from the load. In most cases, alternating current (AC) technology is used for electrical energy transportation, and in a minority of the applications such as a point-to-point international connection and long-distance, large-capacity transportation, direct current (DC) is preferred. The advantage of an AC power system lies in the fact that the voltage can easily be brought to a higher level in order to reduce losses during energy transportation. Figure 2.1 shows a typical AC power system including power generators, power transformers, and substation equipment such as circuit breakers.

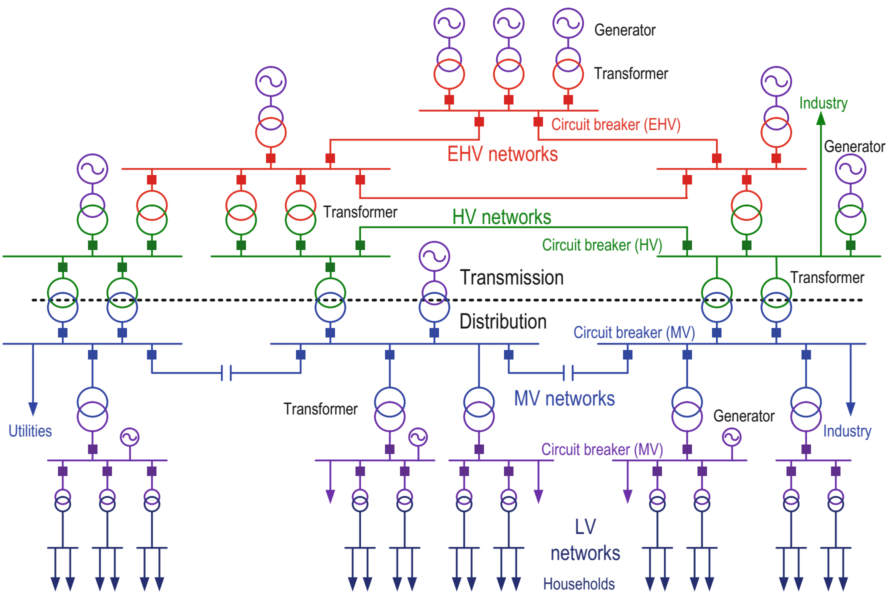


Fig. 2.1 Typical AC power system

Power generators can produce electricity taking care of the conversion of mechanical energy into electrical energy. Overhead lines suspended by a transmission tower comprised of aluminum and copper conductors, and underground cables are used to carry the current with minimum loss. Power transformers can bring the electrical energy to the appropriate voltage level at the load (demand) side. Society's dependence on this commodity has become extremely large, and the social impact of a failing power system is nowadays unacceptable. In fact the electrical power system is the backbone of modern society.

The power system generates, transports, and distributes electrical energy economically and in a reliable way to the consumers, with the constraint that both the voltage and frequency are kept constant, within narrow margins, at the load side. Power quality is a major issue these days, a nearly perfect sine wave of constant frequency and amplitude and always available. Electrical engineering started basically with the evolution of electrical power engineering at the turn of the nineteenth century, when the revolution in electrical engineering took place. In a rather short period of time, power transformers were invented, electric motors and power generators were designed, and the step from DC to AC transmission was made, making it possible to transport large amounts of electrical energy over long distances. Lighting, at first, but rapidly the versatile application of electrical power completely changed society. In this early period, small and independent operating power companies used different voltage levels and operated their system at various frequencies. There were no standards at that time, and electrical engineers were among the first to realize that international standardization would become necessary in the modern world.

Regarding DC versus AC transmission, there was a famous war of currents at the beginning of the power system. Tomas Edison started electricity supply in 1882 and provided DC 110 volts direct current to households in the United States. From the early 1880s on, AC distribution had been expanding with the development of transformers in Europe, and in the United States in 1885–1886, AC can transport electricity to very long distances through cheaper wires and easily step down the voltage at the load side. By the early 1890s, the technical benefits with AC had dominated the market, and the "War of Currents" would come to an end in 1892. Edison General Electric was renamed as General Electric that dominated the US power business and would go on to compete with Westinghouse for the AC supply.

Figure 2.2 shows a one-line diagram of the main substation including main power equipment. The substation has several functions to transform voltage from high to low, or the reverse, and switch off a circuit and on another circuit. For these purposes, the substation has power transformers, circuit breakers, and metal-oxide surge arresters which protect the system and equipment against the excessive overvoltages. Figure 2.3 shows a typical substation configuration.

In daily power system operation, switching is a rather normal action: the system needs to be reconfigured to facilitate the power flow from the generation to the load, a faulted part of the network has to be taken out of service, or a circuit is switched off for maintenance. Circuit breakers, disconnecting switches, and earthing switches are the components that carry out the switching actions. In this CIGRE Green Book, we will give background information on switching phenomena in the network and

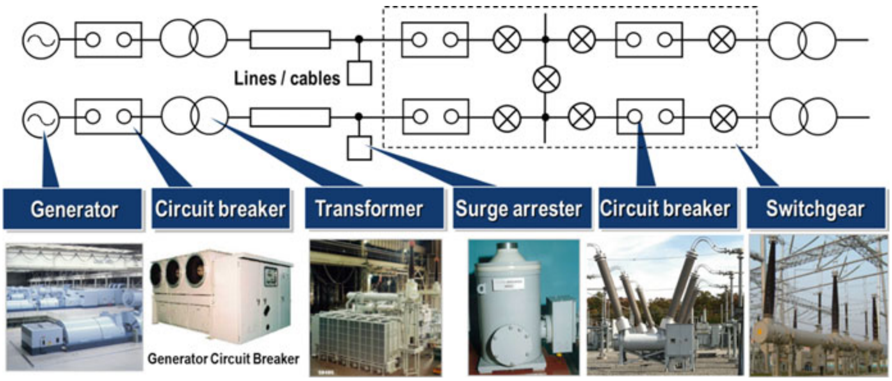


Fig. 2.2 Typical AC substation equipment

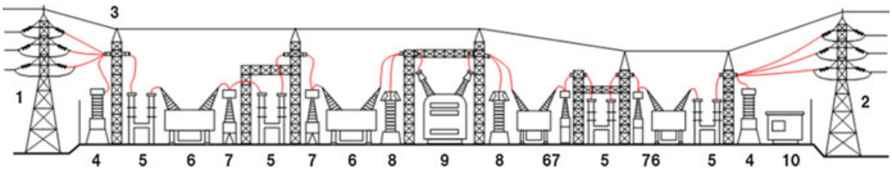


Fig. 2.3 Typical AC substation configuration. 1, incoming overhead line; 2, outgoing overhead line; 3, ground wire; 4, voltage transformer; 5, disconnecting switch; 6, circuit breaker; 7, current transformer; 8, surge arrester; 9, power transformer; 10, control cabinet with protective relay units. (Courtesy of Tokyo Electric Power)

describe the role, design, and constructive details of the various network components, and we will go through the historical development of the switching devices.

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 components or sections of the system, certain loads, or consumers. A typical example is the switching of shunt capacitor banks or shunt reactors, de-energization of cables and overhead lines, the reconnection of cables and overhead lines, transformer switching, 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 (or section of a substation) to another. Such operations occur when load current needs to be transferred without interruption, for example, in a substation, from one busbar to another.
- 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 are needed to limit the consequences of faults.

Switching in electrical power systems reconfigures the topology of an electrical network; it involves the making and breaking of currents and causes a disturbance of steady energy flow. Therefore, transients are expected to happen and are observed in the system during the change from the steady-state situation before, when the system was in a certain configuration to the new steady-state situation after switching when a new circuit topology is configured. Switching in the power system involves 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 and can exceed the withstanding capabilities of the equipment. Fundamentally in nature, any change of steady-state conditions generates transients.

The essential parameters in electrical circuits are current and voltage. During switching operations in power systems, transients can be observed in both. Regarding operations related to switching on (making or energization), the components of the system or the equipment 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, and sometimes the voltage stress can affect the insulation.

In a generalized concept, switching devices (dis)connect a source circuit to a load circuit. 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, the switching transients can be more easily understood.

When one speaks of electricity, one thinks of current flowing through the conductors from the generator to the load. This approach is valid because the physical dimensions of the power systems are large compared with the wavelength of the sinusoidal currents and voltages at the nominal frequency. For steady-state analysis of the power flow at the power frequency of 50 or 60 Hz, complex calculus with phasors representing voltages and currents in the frequency domain can be used successfully. Switching transients, however, involve much higher frequencies, up to kilohertz and megahertz, such that the complex calculus can no longer be applied. Now the differential equations describing the system phenomena in the time domain 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 winding turns to each other, and the grounded parts of the tank 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, in a more complex way.

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, which is not an easy task.

A transient occurs in the power system when the network changes from one steady-state condition into another. This can be, for instance, the case when lightning hits the earth in the vicinity of a HV overhead transmission line or when lightning hits a substation busbar or line directly. The majority of power-system transients are, however, the result of desired 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.

2.2 Definitions of Terminology

Power System/Electrical Power Network
Electrical power transmission and distribution networks are a power delivery system consisting of lines and cables that transports electrical power from the generation site to the demand users.

Alternating Current (AC)
AC refers to electrical current flow with positive and negative direction periodically. The waveform of the alternating current is normally a sine wave. In certain applications, different waveforms are used, such as triangular or square waves.

Direct Current (DC)
DC refers to electrical current flow with only one direction: positive or negative polarity. A common source of DC power is a battery cell or charged capacitor.

Medium Voltage (MV)
MV generally refers to the voltage levels up to and including 52 kV corresponding to distribution systems.

High Voltage (HV)
HV generally refers to the voltage levels higher than 52 kV corresponding to transmission systems.

Extra High Voltage (EHV)
EHV generally refers to the voltage levels around 230 kV (the value may differ in country) up to 800 kV. The rated voltages at trunk systems are, for example, 420/380 kV in Europe and in the Middle East, 550/800 kV in the US, Canada and Korea.

Ultrahigh Voltage (UHV)
UHV generally refers to the voltage levels exceeding 800 kV operating in China and testing in India and Japan.

Substation
A substation is a part of the power system consisting of electrical generation, transmission, and distribution system. Substations transform the voltage from high to low level or low to high level. There are various switching equipment to close a circuit or interrupt a nominal or a fault current along with measuring equipment and overvoltage protection units such as surge arresters.

Busbar
A conductor to which several circuits are commonly connected in the substation.

Generator
A rotating electric machine which is intended to convert mechanical energy into electrical energy.

Power Transformer
A static piece of apparatus with two or more windings which, by electromagnetic induction, transforms a system of alternating voltage and current into another system of voltage and current usually of different values and at the same frequency for the purpose of transmitting electrical power.

Overhead Line
An electric line whose conductors are supported above ground, generally by means of insulators and appropriate supports (transmission tower or electric pole).

Underground/Submarine Cable
An electric line with insulated conductors buried directly in the ground or laid in cable ducts, pipes, troughs, directly on the sea bottom, etc.

Gas-Insulated Line
An electric line whose conductors are contained in a metal enclosure and insulated with a compressed gas.

Surge Arrester
A surge protective device designed to limit the duration and frequently the amplitude of the voltage.

Switching Equipment
Equipment designed to make or break the current in one or more electric circuits.

Circuit Breaker
A circuit breaker is an electrical switch which has the function of opening and closing a circuit in order to protect other substation equipment in power systems

from damage caused by excessive currents, typically resulting from an overload or short-circuit conditions. When a fault occurs, circuit breakers quickly clear the fault to secure system stability. The circuit breaker is also required to carry a load current without excessive heating and withstand a system voltage during normal and abnormal conditions. Unlike a fuse, a circuit breaker can be reclosed either manually or automatically to resume normal operation.

Dead Tank Circuit Breaker
A circuit breaker with interrupters inside an earthed metal enclosure. The conductor applied with the system voltage is fed outside from the interrupters through the bushings.

Live Tank Circuit Breaker
A circuit breaker with interrupters inside a tank (composed of porcelain or composite insulators) insulated from earth. The conductor can be connected directly with a live part of the breaker terminals.

Oil Circuit Breaker
A circuit breaker in which the contacts open and close in mineral oil. The "bulk" or dead tank oil breaker has the contacts in the center of a large metal tank filled with oil. The oil serves as an extinguishing medium and provides the insulation to the tank. The live tank "minimum" oil breaker design has the contacts and arcing chamber inside a porcelain insulator filled with a small volume of oil compared to bulk-oil circuit breakers. The arc evaporates the surrounding oil and produces hydrogen and carbon compound. The process removes the heat from the arc and eventually interrupts the current at power-frequency current zero.

Air-Blast Circuit Breaker
A circuit breaker in which the contacts open and close in the air. Since the air interrupts and dielectric withstand capability at atmospheric pressure is limited, a compressed air to several MPa is required to high-voltage applications. The air relatively creates high arc voltage, which can decrease the fault current and assist thermal interruption capability.

Vacuum Circuit Breaker
A circuit breaker in which the contacts open and close within a highly evacuated vacuum enclosure. When the vacuum circuit breaker separates the contacts, an arc is generated by the metal vapor plasma released from the contact surface. The arc is quickly extinguished because the metallic vapor, electrons, and ions produced during arcing are diffused in a short time and condensed on the surfaces of the contacts, resulting in quick recovery of dielectric strength.

Sulfur Hexafluoride (SF_6) Circuit Breaker
A circuit breaker in which the contacts open and close in sulfur hexafluoride. Current interruption in a SF_6 circuit breaker is obtained by separating two contacts in sulfur hexafluoride having a pressure of several tenths of MPa. After contact separation, the

current is carried through an arc and is interrupted when this arc is cooled by a gas blast of sufficient intensity.

Disconnecting Switch
Switching equipment capable of opening and closing a circuit with either negligible/ leakage current is opened or made or without significant change in the voltage across the terminals of each of the poles of the disconnecting switch. It is also capable of carrying currents under normal circuit conditions and carrying for a specified time currents under abnormal conditions such as those of short circuit.

Earthing Switch
An earthing switch for the purpose of earthing/grounding and insulating a circuit.

Instrument Transformer
A transformer intended to generate an information signal to measuring instruments, meters, and protective or control devices. The term “instrument transformer” encompasses both current transformers and voltage transformers.

Current Transformer
An instrument transformer in which the secondary current, in normal conditions of use, is substantially proportional to the primary current and differs in phase from it by an angle which is approximately zero for an appropriate connection.

Voltage Transformer
An instrument transformer in which the secondary voltage, in normal conditions of use, is substantially proportional to the primary voltage and differs in phase from it by an angle which is approximately zero for an appropriate connection.

2.3 Abbreviations

AC	Alternating current
DC	Direct current
CB	Circuit breaker
MV	Medium voltage
HV	High voltage
EHV	Extra high voltage
UHV	Ultrahigh voltage
SIL	Surge impedance loading
GIL	Gas-insulated transmission line
EMF	Electromagnetic Field
atm	Standard atmosphere (a unit of pressure defined as 101,325 Pa)
rpm	Revolution per minute
MVA	Megavolt ampere (corresponds to MW)
Hz	Hertz (defined as one cycle per second)

2.4 Generation

The work horse for the generation of electricity is the synchronous machine. The bulk of electrical energy is produced by three-phase synchronous generators. Synchronous generators with power ratings of several hundred MVA are nowadays common; the biggest machines have a rating up to 1500 MVA. Under steady-state conditions, they operate at a speed fixed by the power system frequency, which is why they are called synchronous machines. As generators, synchronous machines operate in parallel in the larger power stations. A rating of 600 MVA for one generating unit is also quite common.

In a power generation plant, the shaft of the steam-, hydro- or wind-turbine is mounted in line with the shaft of the synchronous generator (Fig. 2.4). It is in the generator that the conversion from mechanical energy into electrical energy takes place. The two basic parts of the synchronous machine are the rotor and the armature (stator). The iron rotor is equipped with a DC-excited winding which acts as an electromagnet. When the rotor rotates and the rotor winding is excited by a DC source, a rotating magnetic field is present in the air gap between the rotor and the armature. The rotor excitation field is supplied from an auxiliary DC generator that can be placed on the shaft (on-shaft exciter) or outside the turbine-generator set. The armature has a three-phase winding in which a time-varying electromagnetic field (EMF) is generated by the rotating magnetic field.

Synchronous machines are built with two types of rotors: cylindrical rotors (in a horizontal position) which are driven by steam turbines at 3000 or 3600 rpm and salient-pole rotors that are usually driven by low-speed turbines, like hydroturbines as shown in Fig. 2.5. Salient-pole rotors are mostly mounted in a vertical position. In cylindrical rotors the field winding is placed in slots, cut axially along the rotor length. The diameter of the rotor is usually between 1 and 1.5 m which makes the machine suitable for operation at high angular velocities because of the rotational speed: 3000 or 3600 rpm. These generators are named turbogenerators. A

Fig. 2.4 1050 MW turbine generator, 2100 MW/2 units (Courtesy of J Power)

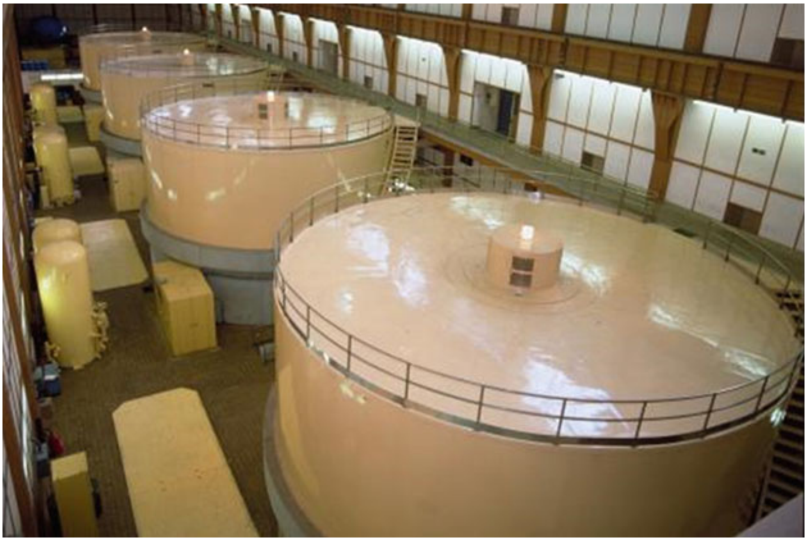


Fig. 2.5 87.5 MW salient-pole generator, 350 MW/4 units, 50/60 Hz dual frequencies. (Courtesy of J Power)

turbogenerator rotor has just one pair of poles. Salient-pole machines usually have more pairs of poles, so they can produce a 50 Hz or 60 Hz frequency, operating at a much lower rotational speed (like 50 to 100 rpm).

The energy efficiency of the generators is very important. Synchronous generators in power plants have an efficiency of 99% or even higher. This means that for a 600 MW generator, 6 MW heat is still produced, and therefore the machine has to be cooled in order to keep the temperature of the windings and the insulation material within speciation limits. Large turbogenerators are cooled with hydrogen or water. Hydrogen has 7 times the heat capacity of air and water 12 times. The hydrogen and/or water flows through the hollow stator windings. Cooling equalizes the temperature distribution in the generator, because temperature hot spots, when they occur, can greatly affect the life cycle of the electrical insulation and reduce the expected lifetime of generators.

2.5 Network Structures

The network structure is formed by the overhead lines, the underground cables, the transformers, and the buses between the points of power injection and power consumption. The number of voltage transformations from the highest voltage level to the lowest voltage level determines the principal network structure of a power system. Network structures can be distinguished in system parts with single-point feeding and with multiple-point feeding.

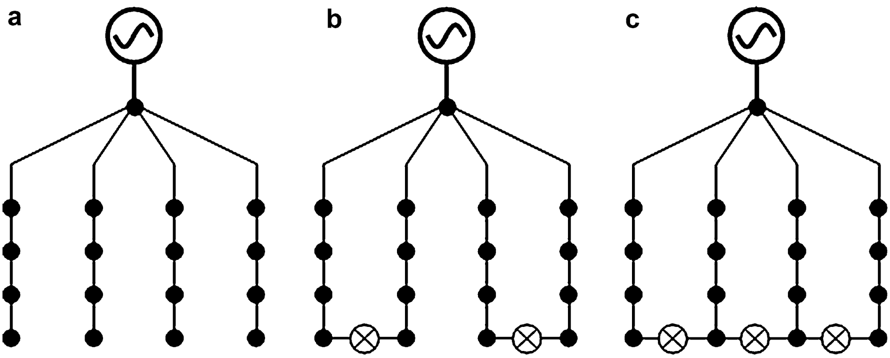


Fig. 2.6 Network structures with single-point feeding. (**a**) Radial structure; (**b**) loop structure; (**c**) multi-loop structure

A single-point feeding network can have three layouts, as depicted in Fig. 2.6:

- A radial structure, in which all substations (or consumers) are fed by lines or cables connected directly to one central supply; a network with a radial structure is less expensive to build.
- A loop structure, in which each and every substation (or consumer) within the system is fed from two directions; networks with a loop structure are more reliable but more expensive to build.
- A multi-loop structure, in which the substations (or consumers) are fed from the supply by more than two connections; networks with a multi-loop structure are very reliable in their operation but more costly.

In Fig. 2.6b and c, a bus-segregation switch is placed on positions where it is possible to open a loop in the grid. During operation, the system operator can decide to create “openings” in the grid, by means of switching devices, so that both the loop and multi-loop structures can be operated as radial networks. This is a common practice in the Dutch distribution networks (or in many countries); most of these networks have a (multi-) loop structure but are operated as radial networks as this keeps the protection of the network simple. After a fault situation, e.g., a short circuit that has been cleared, a grid opening can be “relocated” in order to change the network configuration and restore the energy supply as shown in Fig. 2.7.

A multiple-point feeding network nearly always has a multi-loop structure as shown in Fig. 2.8. Transmission networks are in general operated in a multi-loop structure, as the multi-loop network gives a rather high reliability of the power supply. In the case that a fault occurs in a multi-loop system, the power supply can (usually) be continued. Let’s imagine that the left feeder in Fig. 2.8 is short-circuited. The feeder will be isolated from the network (by the protective devices and the circuit breakers), which implies that the power supply from the left side is interrupted. However, we still have power supply from the right side, which feeds all the substations in the multi-loop structure.

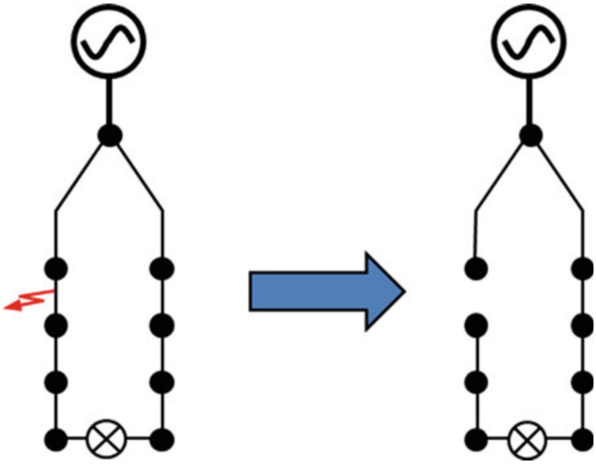


Fig. 2.7 Restoration of energy supply in a faulted, radially operated, system

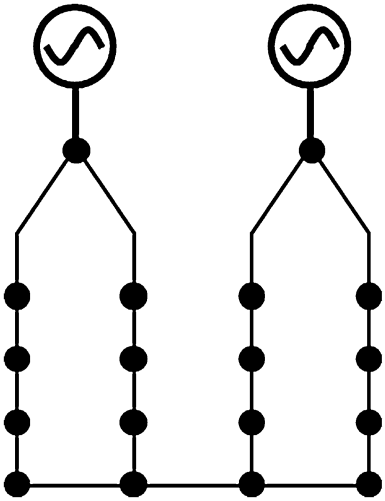


Fig. 2.8 Network structure with multiple-point feeding

2.6 Substation

The simplest way to look at the power system is to consider it as a collection of nodes, which we call substations, and connecting power carriers, such as overhead lines and underground cables. By means of substations as shown in Fig. 2.9, the power of a generating plant can be supplied to the system, the power can be divided over the connected lines, and the power can be distributed to the consumers. Furthermore, power transformers can be installed in the substations in order to interconnect different voltage levels. Substations play an important role in the protection of the power system, where

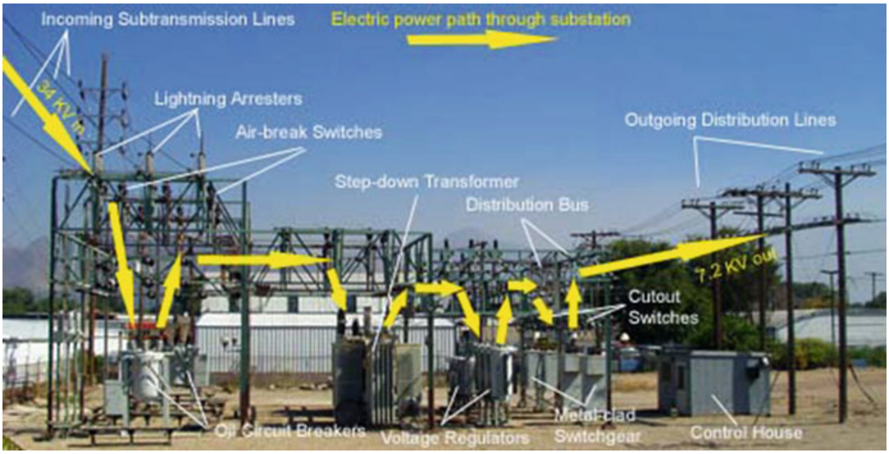


Fig. 2.9 Typical substation equipment. (Information downloaded from the website of Occupational Safety and Health Administration, United States Department of Labor: https://www.osha.gov)

the protection equipment (voltage transformers, current transformers, and protective relays) is installed together with the circuit breakers and disconnectors that perform the switching operations.

The system grounding is also established in the substations, and from the individual stations, measurement signals are guided to the control center. More detailed information is available in another CIGRE Green Book and documents published by Study Committee B3 dealing with substations.

2.7 Protection

With the increasing dependency of our society on electricity supply, the need to achieve an acceptable level of reliability, quality, and safety at an economic price becomes important to customers. The power system as such is well designed and also adequately maintained to minimize the number of faults that can occur.

Power system protection is a field in electrical power engineering dealing with protecting the equipment and the power infrastructure from faults by isolating the faulted components or circuits from the rest of the network. The objective of a protection scheme is to keep the network in a stable operating mode. More detailed information is available in another CIGRE documents published by Study Committee B5 dealing with protection and automation.

In normal operating conditions, a three-phase power system can be treated as a single-phase system when the loads, voltages, and currents are balanced. A fault brings the system to an abnormal and unbalanced condition. Short-circuit faults are especially of concern because they result in a switching action, which often results in transient overvoltages as a consequence of the operation of a circuit breaker.

Line-to-ground faults are faults in which an overhead transmission line touches the ground because of wind, ice loading, or a falling tree limb. A majority of transmission-line faults are single line-to-ground faults. Line-to-line faults are usually the result of galloping lines because of high winds or because of a line breaking and falling on a line below. Double line-to-ground faults result from causes similar to that of the single line-to-ground faults but are very rare. Three-phase faults, when all three lines touch each other or fall to the ground, occur in only a small percentage of the cases but are very severe faults for the system and its components. In the case of a symmetrical three-phase fault in a symmetrical system, one can still use a single-phase representation for short-circuit and transient analysis. However, for the majority of the fault situations, the power system has become unsymmetrical. Symmetrical components and, especially, sequence networks are an elegant way to analyze faults in unsymmetrical three-phase power systems because in many cases the unbalanced portion of the physical system can be isolated for study, the rest of the system being considered to be in balance. This is, for instance, the case for an unbalanced load or fault. In such cases, we attempt to find the symmetrical components of the voltages and the currents at the point of unbalance and connect the sequence networks, which are, in fact, copies of the balanced system at the point of unbalance (the fault point).

Protection systems are installed to clear faults, like short circuits, because short-circuit currents can damage the cables, lines, busbars, and transformers. The voltage and current transformers provide measured values of the actual voltage and current to the protective relay. The relay processes the data and determines, based on its settings, whether or not it needs to operate a circuit breaker in order to isolate faulted sections or components. The classic protective relay is an electromagnetic relay which is constructed with electrical, magnetic, and mechanical components. Nowadays computerized relays are taking over as they have many advantages: computerized relays can perform a self-diagnosis, they can record events and disturbances in a database, and they can be integrated in the communication, measurement, and control environment of modern substations.

A reliable protection is indispensable for a power system. When a fault or an abnormal system condition occurs (such as over−/undervoltage, over−/under-frequency, overcurrent, and so on), the related protective relay has to react in order to isolate the affected section while leaving the rest of the power system in service. The protection must be sensitive enough to operate when a fault occurs, but the protection should be stable enough not to operate when the system is operating at its maximum rated current. There are also faults of a transient nature, a lightning stroke on or in the vicinity of a transmission line, for instance, where it is undesirable that these faults would lead to a loss of supply. Therefore, the protective relays are usually equipped with auto-reclosure (auto-reclosing) functionality. Auto-reclosure implies that the protective relay, directly after having detected an abnormal situation leading to the opening of the contacts of the circuit breaker, commands the contacts of the circuit breaker to close again in order to check whether the abnormal situation is still there. In case of a fault of a transient nature, the normal situation is still there, the protective relay commands the circuit breaker to open its contacts again so that either the fault is cleared or consecutive

Fig. 2.10 Three single-phase independent operated gas circuit breakers. (Courtesy of TenneT TSO B.V)

auto-reclosure (C-O-C operation) sequences can follow. In most cases, the so-called backup protection is installed in order to improve the reliability of the protection system.

When protective relays and circuit breakers are not economically justifiable in certain parts of the grid, fuses can be applied. A fuse combines the "basic functionality" of the current transformer, relay, and circuit breaker in one very simple overcurrent protection device. The fuse element is directly heated by the current passing through and is destroyed when the current exceeds a certain value, thus leading to an isolation of the faulted sections or components. After the fault is repaired/removed, the fuse needs to be replaced so that the isolated grid section can be energized again.

A substation basically consists of a number of ingoing and outgoing power carriers that are connected to one or more common substation bus sections (busbars) by circuit breakers, disconnecting switches, and instrument transformers: the feeders. Figure 2.10 shows an example of a live tank gas circuit breaker installed in an open-air-insulated substation. A circuit breaker is a mechanical switching device, capable of making, conducting, and breaking currents under normal circuit conditions but also interrupting currents under abnormal conditions as in the case of a short circuit.

Disconnecting switches are primarily used to visualize whether a connection is open or closed. Figure 2.11 shows an example of a pantograph disconnecting switch. Different from circuit breakers, disconnectors do not have current-interrupting capability. Therefore, a disconnecting switch cannot be opened when it is conducting a current and when a recovery voltage builds up across the contacts after opening. A disconnecting switch can interrupt a small current when, after opening, a negligible voltage appears over the contacts. The instrument transformers in the substation, like voltage and current transformers, provide measured values of the actual voltage and current to the protective relay and the metering equipment. The protective relays have the task to detect and locate

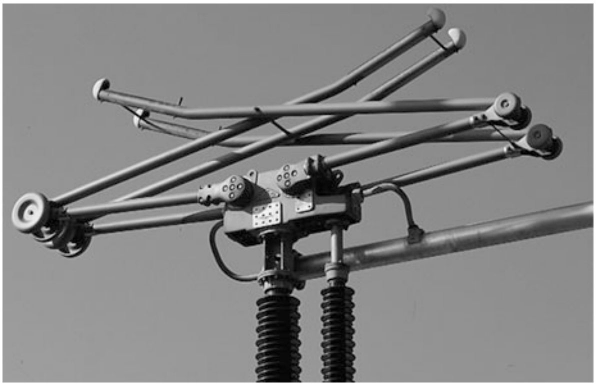


Fig. 2.11 Pantograph disconnecting switch in open position. (Courtesy of TenneT TSO B.V)

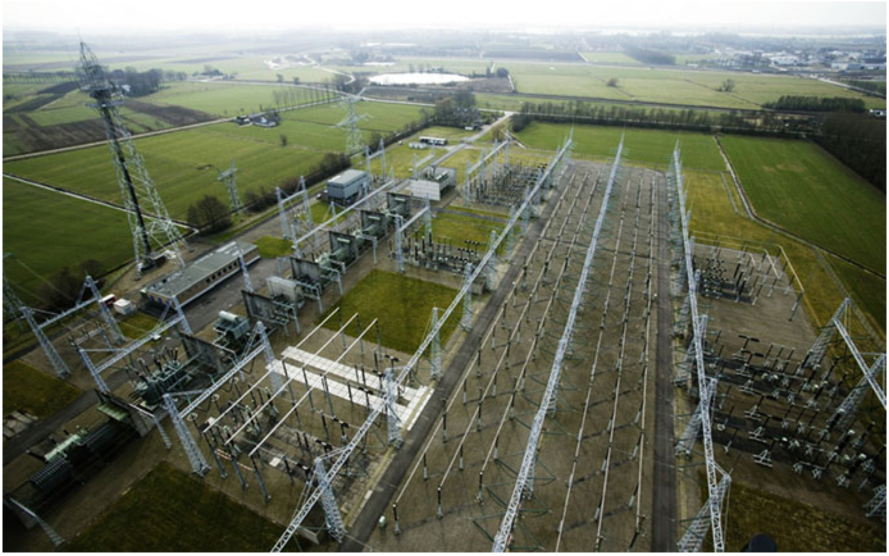


Fig. 2.12 Air-insulated substation. (Courtesy of TenneT TSO B.V)

disturbances in the system, such as short circuits, and to switch off only the faulted part of the network by opening the appropriate circuit breaker(s).

When space is available, substations are commonly erected in the open (an air-insulated substation, see Fig. 2.12). The ambient air serves as the insulating medium and insulators support the live parts. These open-air substations do require quite some space but offer advantages: quick assembly and easy repair and expansion and the possibility to install components of different manufacturers. When pollution is an issue, e.g., the substation is planned close to an industrial area or in a coastal region, the substation can be placed indoors. If the available space is limited, the choice is made for an SF_6 gas-insulated station (see Fig. 2.13). In such a gas-insulated station, the live parts are located inside an earthed metal enclosure.

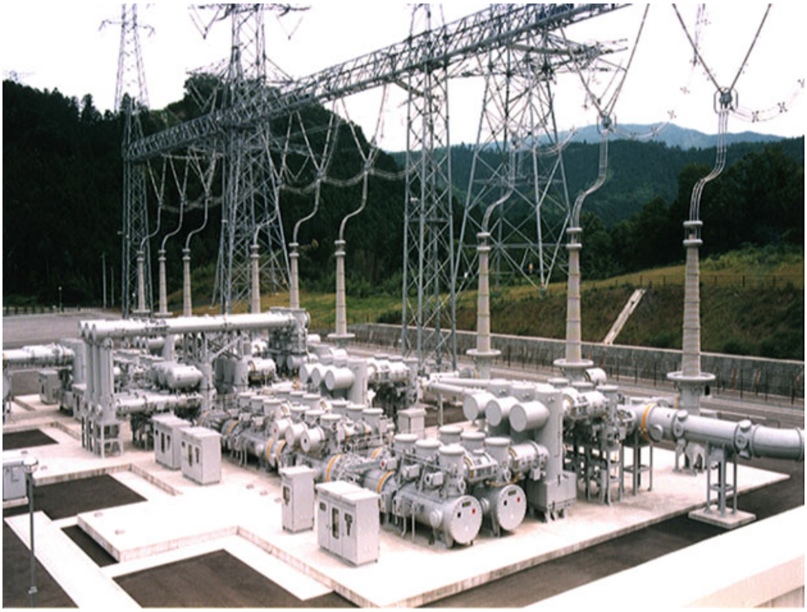


Fig. 2.13 Gas-insulated substation

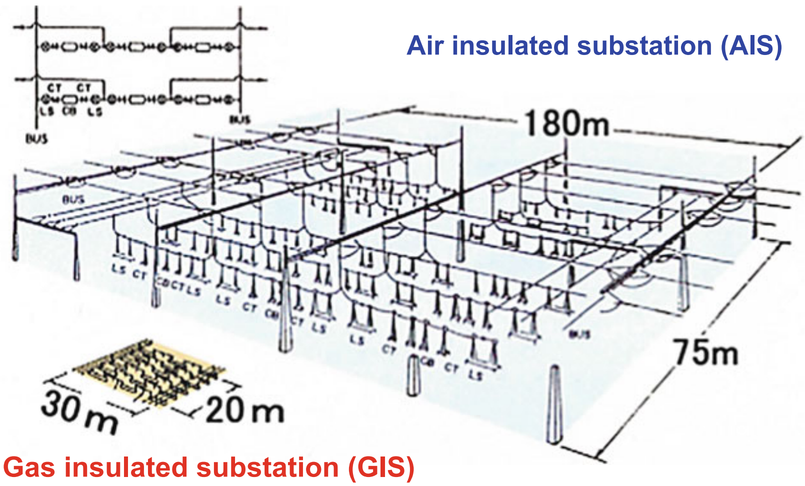


Fig. 2.14 Typical comparison of the installation areas between AIS and GIS

Pressurized SF_6 gas serves as an insulating medium in the enclosure. Pressurized SF_6 is a very good insulator that can be used with electric field strengths that (at a pressure of 5 atm) are about 12 times higher than in atmospheric air. A gas-insulated substation that is filled with SF_6 gas requires only 10–20% of the space of a comparable open-air substation as shown in Fig. 2.14.

2.8 Overhead Lines, Underground Cables, and Gas-Insulated Lines/Busbars

It is in principle an economical and an environmental issue whether to choose an overhead line or an underground cable for transmitting and distributing electrical power to densely populated areas. Underground systems are in general more reliable than overhead systems, because they are not exposed to wind, lightning, and vehicle damage. Underground systems do not disturb the environment, and they require less preventive maintenance. The main disadvantage, however, is its higher costs: for the same power rating, underground systems are in general six to ten times more expensive than overhead systems. In many populated countries, underground cables are commonly used in the MV and HV networks below 72 kV.

Transmission lines produce reactive power (capacitive behavior of the line), because of the electric field component, and consume reactive power (inductive behavior of the line) because of the magnetic field component. When the load of the transmission line is such that the capacitive reactive power and the inductive reactive power of the line are in balance, the operating condition of the line has a power factor equal to 1. We call this surge impedance loading (SIL) of the line. For a loading condition below the SIL point, the produced capacitive reactive power is larger than the consumed inductive reactive power, and the line delivers net capacitive reactive power to the system, and the voltage at the line end will increase. This can be compensated by shunt reactors. If the transmission line carries an amount of active power exceeding the SIL point, the capacitive reactive power is less than the consumed reactive power, so the line will absorb capacitive reactive power from the system resulting in a voltage drop at the end. More detailed information is available in another CIGRE Green Book and documents published by Study Committees B1 and B2, respectively, dealing with overhead lines and cables.

Figure 2.15 shows typical examples of transmission towers with a single circuit (a couple of three-phase lines) and double circuits (two couples of three-phase lines, six lines in total besides grounding wires located on the top of the tower). More detailed information is available in the CIGRE Green Book published by Study Committee B2 dealing with overhead lines.

Besides the existing technologies of overhead transmission lines and solid insulated underground cables, gas-insulated transmission lines (GIL) offer an additional solution for high-power transmission. GIL can be applied for voltages from 100 kV up to 800 kV. Most applications of the GIL are at 420 kV and 550 kV. The upper ranges of 800 kV find only a few applications in China. The gas-insulated transmission lines (GIL) used in the substation are mentioned as the gas-insulated busbars (GIB, see Fig. 2.16).

The GIL consist of a central aluminum conductor that rests on cast resin insulators, which center it within the outer enclosure. This enclosure is formed by a 400 to 600 mm diameter aluminum tube, which provides a solid mechanical and electrotechnical containment for the system. Figure 2.17 shows an example of 275 kV 6300 A GIL (pure SF_6 insulation) with length of 3 km installed in the underground tunnel. To meet up-to-date environmental and technical issues, in some applications, GIL are filled with an insulating gas mixture of mainly nitrogen and a smaller percentage of SF_6 of the line, and capacitor banks might be necessary to compensate for this.

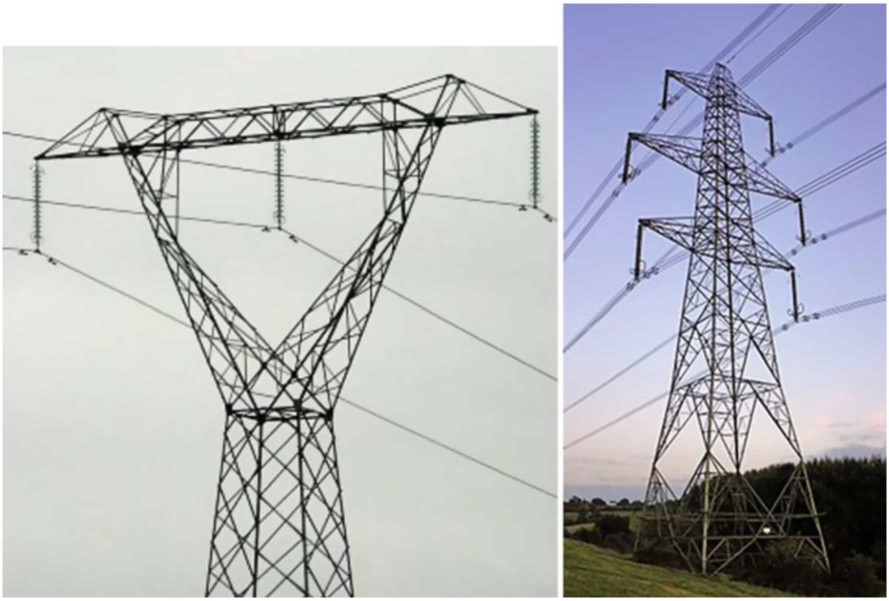


Fig. 2.15 Examples of overhead line with a single circuit and double circuits

Fig. 2.16 Gas-insulated busbar in 550 kV substation (GIB). (Courtesy of Kansai Electric Power)

2.9 Power Transformers

Power transformers are essential components in the AC power system as they make it possible to convert electrical energy to different voltage levels with an efficiency of more than 99%. That enables us to generate power at a relatively low voltage level (10–25 kV, limited by the insulation of the generator) and to transport it at high voltage levels (72/110 kV–420/550 kV and higher) to reduce the losses during transportation,

Fig. 2.17 275 kV 6300 A gas-insulated lines with length of 3 km. (Courtesy of Chubu Electric Power)

whereas domestic consumption can take place at a low and (more or less) safe voltage level (400 V and below). Transformers consist essentially of two coils on a common iron core. The iron core serves as the magnetic coupling between the two coils such that nearly all the magnetic flux from one coil links with the other coil.

The transformer ratio, under normal operating conditions, is given by the ratio of the number of turns of the primary winding and the secondary winding. Power transformers often have in addition to the primary and secondary winding another winding, the tertiary winding. This tertiary winding is either used for the electricity supply of the substation or for voltage regulation in the network. The tertiary winding is also called "regulating winding."

From the viewpoint of designs, power transformers are mainly classified into two different structures: core type and shell type. Figure 2.18 shows schematic drawings of coil arrangements for the core-type and the shell-type transformers. The core-type transformers used for power system commonly have a plurality of concentric coils, which are insulated with each other: low-voltage coils are arranged inside close to the core, and high-voltage coils are located outside. In contrary, the shell-type transformers typically have a multilayer rectangular shaped coils. The high-voltage rectangular hollow-shaped coils are clamped by the low-voltage rectangular hollow-shaped coils at both sides. Then both coils are clamped by the rectangular hollow-shaped core as shown in Fig. 2.19.

Figures 2.20 and 2.21 show examples of the core-type and the shell-type transformers.

2.10 Shunt Reactor

Transmission lines or underground cables, in particular for voltages of 72.5 kV and above, can produce a large amount of capacitive reactive power (for instance, when dispatch of variable renewable energy sources is low) which could cause the voltage profile of the network to exceed the maximum level.

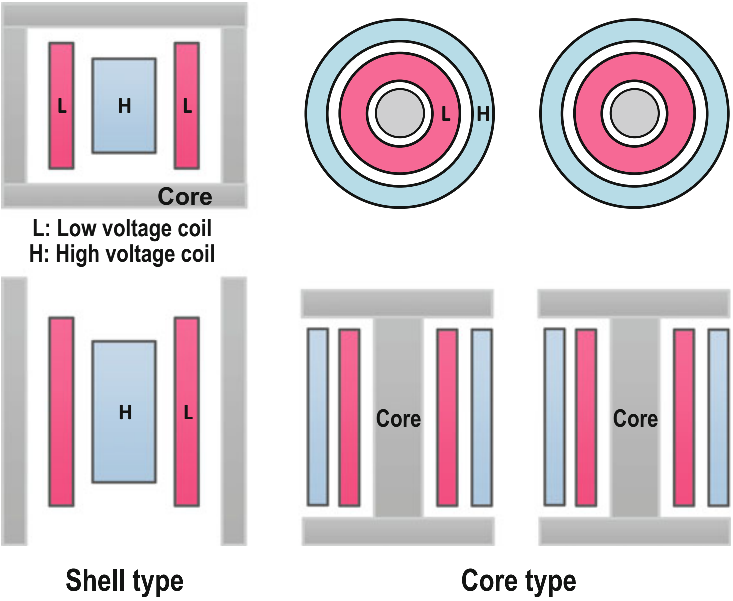
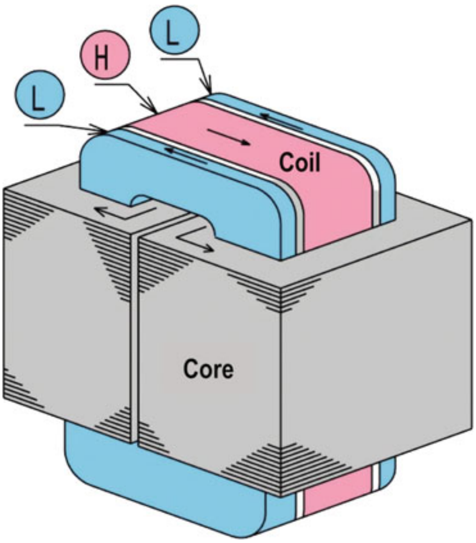


Fig. 2.18 Coil arrangements of shell-type and core-type transformers

Fig. 2.19 Coil and core arrangement of the shell-type transformer



Shunt reactors absorb reactive power and influence the voltage regulation by reduction of the voltage profile. The need of increasing and expanding the transmission system, in order to cope with the power transfer from large variable renewable energy sources, can lead to the necessity to install more shunt reactors at the

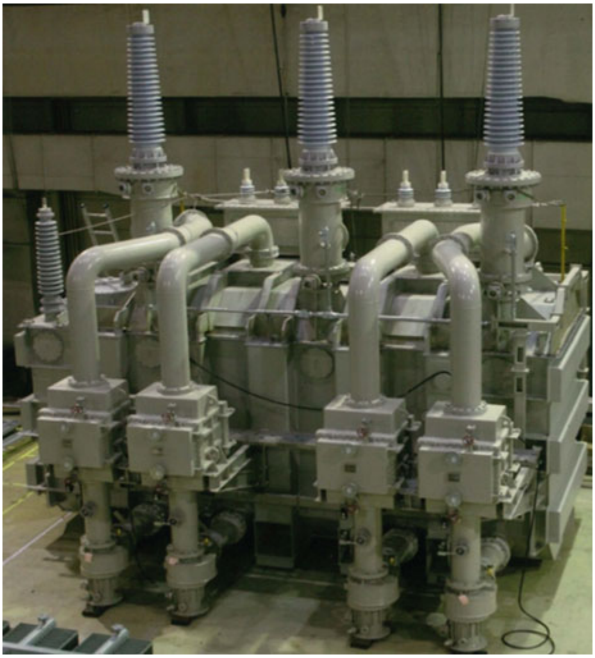


Fig. 2.20 132 kV 50 MVA SF_6 gas-insulated power transformer (core type)

Fig. 2.21 345 kV 750 MVA power transformer (shell type)

transmission level to control the increase of capacitive reactive power when the infeed of variable renewable energy sources is low (no wind for the wind farms, for instance). The transmission lines, when they do not carry a high amount of active power, have to deal with strong line-charging phenomena, as a result of the Ferranti effect. Shunt reactors keep the voltages within the desired margins.

Fig. 2.22 20 kV, 22.5 MVA shunt reactor bank. (Courtesy of J Power)

Shunt reactors can be installed as a three-phase unit or as three single-phase units. This depends on the rated reactive power, system voltage, or planning and design criteria. The shunt reactor can be permanently connected (fixed shunt reactor) or switched through a circuit breaker and can be installed at the transmission line terminals or connected to the substation busbar. Figure 2.22 shows an example of 20 kV shunt reactor which is a similar structure of power transformer with some cooling units.

Variable shunt reactors with a tap changer are applied when a precise and slow voltage regulation is required. For more coarse but flexible voltage regulation, switched shunt reactors are applied. For large reactive power ratings and high voltage levels, shunt reactors are of the gapped iron core oil-immersed type to minimize the losses and to reduce audible noise and vibrations. For the lower voltage levels and smaller reactive power ratings, the shunt reactors are dry-type reactors sometimes without an iron core to lower the cost.

2.11 Capacitor Banks

Capacitor banks produce reactive power to compensate for the inductive reactive power coming from transformers, from transmission lines that are loaded above their SIL level, or from inductive loads. The use of capacitor banks results in an increased transmission capacity and in a reduction of the losses because of the improved power factor and leads to a better voltage profile.

Fig. 2.23 23 kV, 22.5 MVA shunt capacitor bank. (Courtesy of J Power)

A capacitor bank consists of several capacitors of the same rating that are connected in a parallel/series arrangement (Fig. 2.23). Capacitor banks can be permanently connected (fixed capacitor bank) or switched through a circuit breaker and can be installed at the transmission-line terminals or at the substation busbar. For voltage ratings of 72.5 kV and higher, each bank has its own circuit breaker. The inrush or outrush currents can be kept under control in an active way (by controlled switching or with a pre-insertion impedance) or passive with series reactors.

Series reactors (also called damping reactors) can contribute to resonance in the network. The need of increasing and expanding the transmission system, in order to cope with the power transfer from large variable renewable energy sources, can lead to the necessity to install more capacitor banks at the transmission level to control the increase of inductive reactive power when the infeed of variable renewable energy sources is high (excessive wind for the wind farms, for instance).

2.12 Circuit Breaker

A high-voltage circuit breaker is an indispensable piece of equipment in the power system. The main task of a circuit breaker 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. The following requirements are also imposed on a circuit breaker:

- Excellent conductor to carry the nominal current in the closed position
- Excellent insulation to withstand overvoltages in the open position
- Rapid and reliable operation from closed to open position (and vice versa)
- No prominent overvoltages during switching operation

The need to perform all these tasks in a reliable way places circuit breakers among the most complex pieces of equipment installed in the power system. Circuit breakers are present at all voltage levels, in our household miniature circuit breakers (MCBs) protect our domestic apparatus and electronic equipment, at medium voltage they safeguard city quarters, and at the highest voltage levels, they protect the transmission corridors for bulk power.

High-voltage circuit breakers have to operate under very different climatic conditions, at high and extremely low temperatures; under high humidity, with ice load; in windy environments; and at high altitudes. They must be able to withstand seismic activity and function reliably in areas with high pollution as well.

Most circuit breakers are mechanical switching devices, driven by an operating mechanism, that in closed position continuously carry the rated current. However, when a protective relay sends a trip command, it has to operate in a very short period of time.

The first circuit breakers were built at the beginning of the twentieth century, and since then, the design, manufacturing, testing, and field application of circuit breakers have changed considerably. The worldwide experience with circuit breakers over the years, in a diversity of applications, and the exchange of this knowledge in Study Committee 13 and later in Study Committee A3 brought new insights that resulted in new medium- and high-voltage switching equipment.

Circuit breakers have to be capable of interrupting a wide range of currents, from rated nominal current to the maximum short-circuit current that they can handle. In addition, they have the task to energize and de-energize under normal service conditions shunt reactors, capacitor banks, transformers, generators, motors, cables, and transmission lines.

A circuit breaker consists of:

- The main contacts that carry the current under normal service condition
- The arcing contacts that facilitates the switching arc during current interruption
- The arcing chamber where hot gas is generated by the arc
- The operating mechanism that stores the energy to move the contacts apart
- Support insulators

For higher voltage levels, circuit breakers are sometimes equipped with pre-insertion resistors. The purpose of these resistors is to mitigate the transient recovery voltage after an opening operation or to reduce the inrush current after a closing operation. For transmission-line switching, the value of the pre-insertion resistor is typically between 200 and 600 Ω.

Nowadays controlled switching is widely used to reduce switching transients. Besides that modern SF_6 circuit breakers have better switching performance than their oil and air-blast predecessors which makes the use of pre-insertion resistors less necessary.

The electric arc is, except for power semiconductors, the only known element that is able to change from a conducting to a nonconducting state in a short period of time. In high-voltage circuit breakers, the electric arc is a high-pressure arc burning in oil, air, or sulfur hexafluoride (SF_6). In medium-voltage breakers, the low-pressure arc burning in the vacuum is more often applied to interrupt the current. The current interruption is performed by cooling the arc plasma so that the electric arc, which is formed between the breaker contacts after contact separation, disappears. This cooling process or arc-extinguishing can be done in different ways. Power circuit breakers are categorized according to the extinguishing medium in the interrupting chamber in which the arc is formed. That is the reason why we speak of oil, air-blast, SF_6, and vacuum circuit breakers.

In 1907, the first oil circuit breaker was patented by J. N. Kelman in the United States (Kleman 1907). The equipment was hardly more than a pair of contacts submersed in a tank filled with oil. It was the time of discovery by experiments, and most of the breaker design was done by trial and error in the power system itself. In 1956, the basic patent on circuit breakers employing SF_6 was issued to T. E. Browne, F. J. Lingal, and H. J. Hills (Lingal et al. 1956).

Presently the majority of the high-voltage circuit breakers use SF_6 as the extinguishing medium. J. Slepian (1929) has done much to clarify the nature of the circuit breaker problem, because the electric arc proved to be a highly intractable and complex phenomenon. Each new refinement in experimental technique threw up more theoretical problems. The practical development of circuit breakers was, especially in the beginning, somewhat pragmatic, and design was rarely possible as deduction from scientific principles. A lot of development testing was necessary in the high-power laboratory.

A great step forward in understanding arc-circuit interaction was made in 1939 when A. M. Cassie (1939; Cassie and Mason 1956) published the paper with his well-known equation for the dynamics of the arc and, then in 1943, O. Mayr (1943) followed with the supplement that takes care of the time interval around current zero. Much work was done afterward to refine the mathematics of those equations and to confirm their physical validity through practical measurements (CIGRE Working Group 13.01 1993, 1988). It becomes clear that current interruption by an electrical arc is a complex physical process when we realize that the interruption process takes place in microseconds, the plasma temperature in the high-current region is more than 10,000 K, and the temperature decay around current zero is about 2000 K per microsecond, while the gas movements are supersonic. The understanding of the current interruption process has led to SF_6 circuit breakers capable of interrupting 63 kA at 550 kV with a single interrupting element.

2.12.1 Oil Circuit Breaker

Circuit breakers built in the beginning of the twentieth century were mainly oil circuit breakers. Also water breakers have been developed, but maintaining proper dielectric insulation after a breaking operation was a too big challenge. In those days the breaking capacity of oil circuit breakers was sufficient to meet the required short-circuit level in the substations. Presently, oil and minimum-oil circuit breakers still do their job in various parts of the world, but they have left the scene of circuit breaker development. The first oil circuit breakers were of simple design, an air switch that was put in a tank filled with mineral oil. These oil circuit breakers were of the plain-break type, which means that they were not equipped with any sort of arc-quenching device. In 1901, J. N. Kelman of the United States (Kleman 1907) built an oil-water circuit breaker in this way, which was capable of interrupting 200–300 A at 40 kV. Kelman's breaker consisted of two open wooden barrels, each containing a plain-break switch. The two switches were connected in series and operated by one common handle. The wooden barrels contained a mixture of water and oil as the extinguishing medium (Fig. 2.24).

In the 1930s, the arcing chamber appeared on stage. The breaker, a metal explosion pot of some form, was fitted with an insulating arcing chamber through which the breaker contacts moved. The arcing chamber, filled with oil, fixes the arc, and the increase in pressure inside the arcing chamber improved the cooling effects on the arc considerably. Later, the design of the arcing chamber was further improved by pumping mechanisms, creating a cross flow of oil, giving extra cooling to the arc (Fig. 2.25).

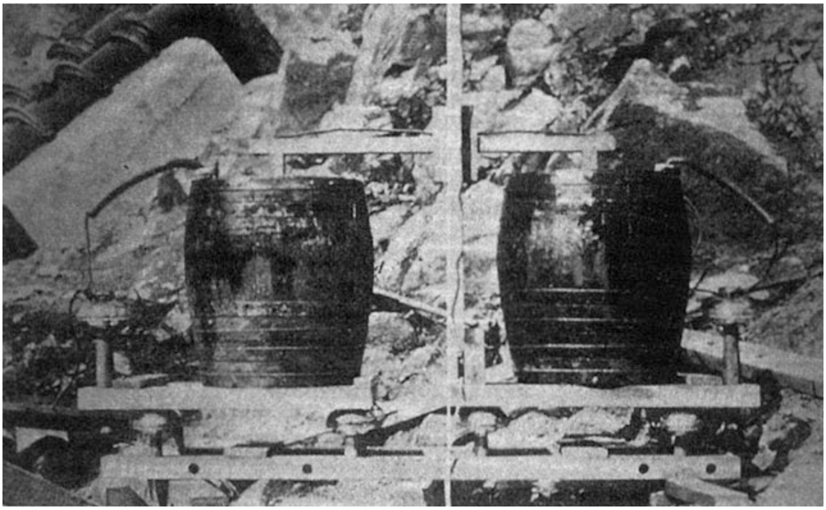


Fig. 2.24 Kelman's oil circuit breaker built in 1901 (40 kV, 300 A) (Wilkins and Crellin 1930)

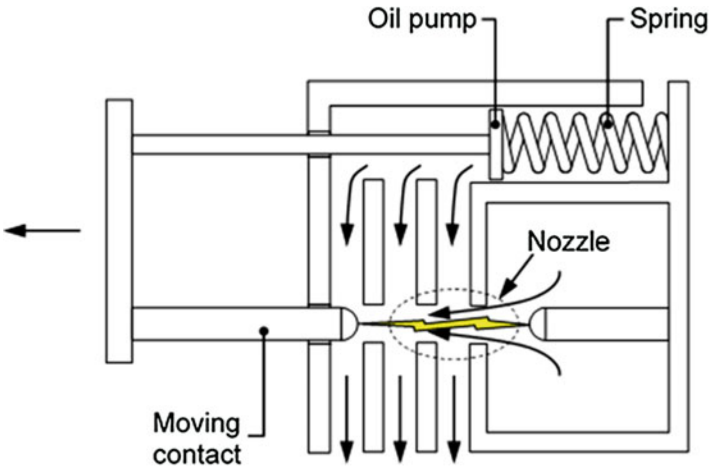


Fig. 2.25 Cross section of an oil circuit breaker assisted with pressurized oil

In the bulk-oil circuit breakers, the contacts were located in the center of a large metal tank filled with mineral oil. The oil serves as the extinguishing medium and provides the insulation to the tank. For current measurements current transformers were fit around the bushings of the breaker. Figure 2.26 shows an example of 168 kV bulk-oil dead tank circuit breaker.

A next step in the development of oil circuit breakers was the minimum-oil circuit breaker. The contacts and arcing chamber were placed into a porcelain insulator instead of in a bulky metal tank. Bulk-oil circuit breakers with their huge metal tank containing hundreds of liters of mineral oil have been popular in the United States. Minimum-oil circuit breakers conquered the market in Europe. Figure 2.27 shows an example of 245 kV 50 kA minimum-oil live tank circuit breaker produced in 1985.

The principle of arc extinction in oil breakers is based on the decomposition of oil in hydrogen and methane gas by the arc. Eighty percent of the gas is hydrogen which has excellent dielectric properties and a high specific heat constant. Minimum-oil breakers work best at higher currents that provoke a sharp rise in pressure and strong convection. The interruption of low currents, when the gas quantity released by the arc is lower, has always been a challenge for the design engineers. Minimum-oil breakers are sensitive for a dielectric reignition after the interruption of a capacitive current. Oil is a good electrical insulator, and when the breaker contacts are open, it isolates the grid voltage across the contacts.

2.12.2 Air-Blast Circuit Breaker

Air is used as an insulator in outdoor-type substations and for high-voltage transmission lines. Air can also be used as the extinguishing medium for current interruption. At atmospheric pressure, the interrupting capability, however, is limited to low-voltage

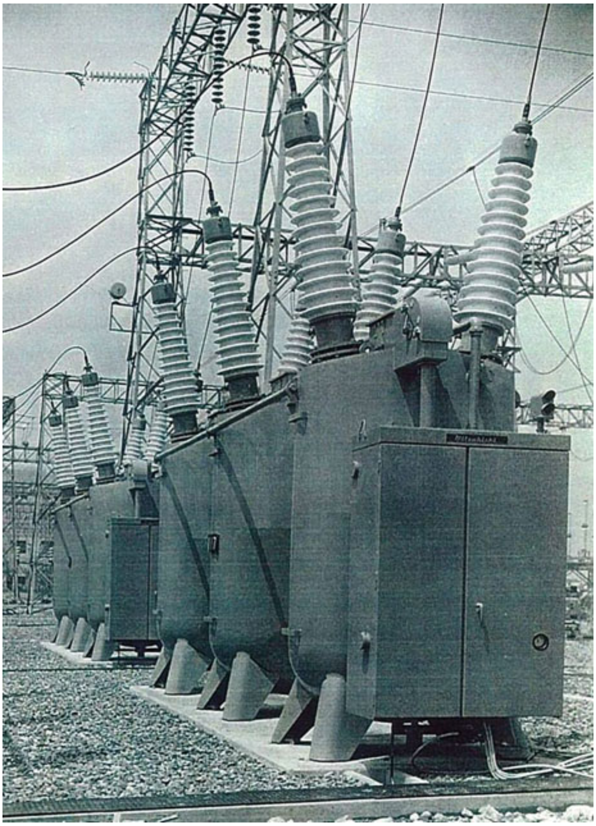


Fig. 2.26 168 kV bulk-oil, dead tank oil circuit breaker developed in 1959. (Courtesy of Mitsubishi Electric)

and medium-voltage only. For medium-voltage applications up to 50 kV, the breakers are mainly of the magnetic air-blast type in which the arc is blown into a segmented compartment by the magnetic field generated by the fault current. In this way, the arc length, the arc voltage, and the surface of the arc column are increased. The arc voltage decreases the fault current, and the larger arc column surface improves the cooling of the arc channel. Figure 2.28 shows 36 kV vintage air-blast circuit breaker.

At higher pressure, air has much more cooling power because the arc is cooled by convection as a result of the large pressure difference between the inside of the breaker and the ambient air outside. Air-blast breakers operating with compressed air can interrupt higher currents at considerably higher voltage levels. Air-blast breakers using compressed air can be of the axial-blast or the cross-blast type. The cross-blast type air-blast breaker operates similar to the magnetic-type breaker: compressed air blows the arc into a segmented arc-chute compartment. Because the arc voltage increases with the arc length, this is also called high-resistance interruption; it has the disadvantage that the energy dissipated during the interruption process is rather high. In the axial-blast design, which can be classified into the insulator nozzle type like the AEG design and the metal nozzle type employed in most other designs, the arc is

Fig. 2.27 245 kV 50 kA live tank oil circuit breaker. (Courtesy of ABB, product of ASEA in 1985)

cooled in the axial direction by the airflow. The current is interrupted when the ionization level is reduced around current zero. Because the arc voltage hardly increases, this is called low-resistance interruption. During operation, air-blast breakers make a lot of noise, especially when the arc is cooled in free air.

Air-blast circuit breakers were the preferred technology for extra high voltage (EHV) until the evolution and dissemination of SF_6 gas circuit breakers. Figure 2.29 shows an example of 800 kV air-blast circuit breaker. Due to the inherent high arc voltage of air, air-blast circuit breakers can provide technical advantages for rapid decaying of the DC component of an asymmetric fault current and a reduced period of the delayed current zero phenomenon (interval of missing current zero). However, higher cost and longer periods of maintenance work will limit its applications to specialized network conditions.

2.12.3 SF_6 Gas Circuit Breaker

The superior dielectric properties of SF_6 were discovered as early as 1920. SF_6 has molecular weight of 146, five times heavier than air. The dielectric strength is at

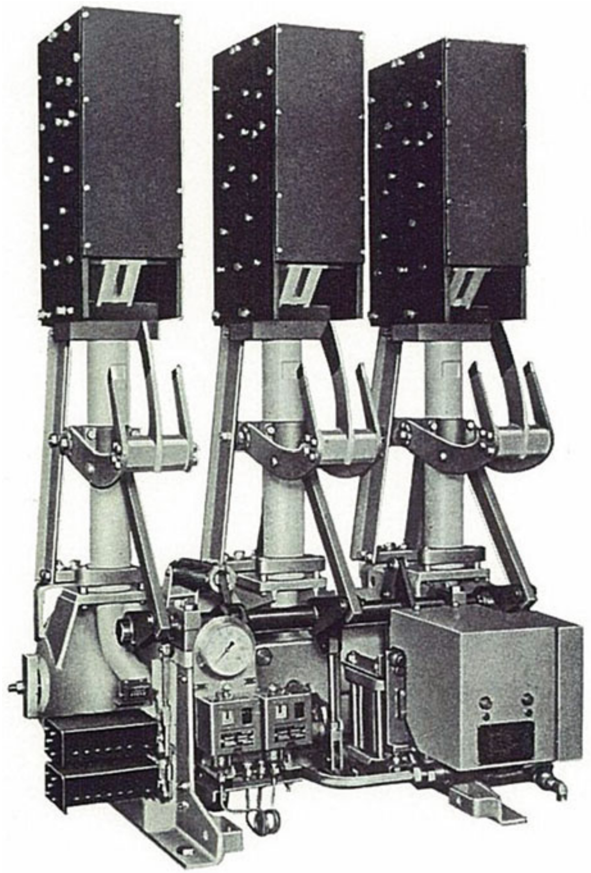


Fig. 2.28 36 kV air-blast circuit breaker developed in 1953. (Courtesy of Mitsubishi Electric)

atmospheric pressure three times better than that of air, and the dielectric strength increases rapidly with increased pressure. At a pressure of 2 atm (0.2 MPa), it has the same insulating properties as mineral oil. Contamination by air does not alter the insulating properties substantially. SF_6 is well suited for application in circuit breakers because it is an electronegative gas, therefore having an affinity for capturing free electrons, which gives rise to the formation of negative ions with reduced mobility. This property leads to rapid removal of electrons present in the plasma of an arc in SF_6, thus increasing the arc's conductance decrement rate when the current approaches current zero. SF_6 is an exceptionally stable and inert gas, but in the presence of an arc, it produces very toxic by-products such as SF_2 and SF_4 that recombine to form nontoxic products immediately after arc extinction. This reversible chemical reaction during arc generation and arc extinction processes is a unique feature of SF_6 to maintain its excellent interruption performance for a long period. The resulting main stable toxic products are metal fluorides that are deposited as white powder and are absorbed in an activated aluminum filter containing aluminum trioxide.

Fig. 2.29 Latest-generation 800 kV air-blast circuit breaker. (Courtesy of GE, produced by Alstom)

It took until the 1940s before the first development of SF_6 circuit breakers began, but it took till 1959 before the first SF_6 circuit breaker came to the market (Friedrich and Yechley 1959). These early designs were descendants of the axial-blast and air-blast circuit breakers, the contacts were mounted inside a tank filled with SF_6 gas, and during the current interruption process, the arc was cooled by compressed SF_6 gas from a separate reservoir. The liquefying temperature of SF_6 gas depends on the pressure but lies in the range of the ambient temperature of the breaker. This means that the SF_6 reservoir needed to be equipped with a heating element that introduced an extra failure possibility for the circuit breaker; when the heating element does not work, the breaker cannot operate. Therefore the puffer circuit breaker was developed, and the so-called double-pressure breaker disappeared from the market. Figure 2.30 shows an example of 240 kV double-pressure-type gas circuit breaker. In the single-pressure puffer circuit breakers of two generations with 245 kV 50 kA double breaks and with single break as shown in Fig. 2.31, the opening stroke made by the moving contacts moves a piston, compressing the gas in the puffer chamber and thus causing an axial gas flow along the arc channel. The nozzle must be able to withstand the high temperatures without deterioration and is made from Teflon. Presently, the SF_6 puffer circuit breaker is the breaker type used for the interruption of the highest short-circuit powers, up to 550 kV 63 kA per interrupters with live tank design and dead tank design as shown in Figs. 2.32 and 2.33.

Puffer circuit breakers require a rather strong operating mechanism because the SF_6 gas has to be compressed. When interrupting large currents, for instance, in the case of

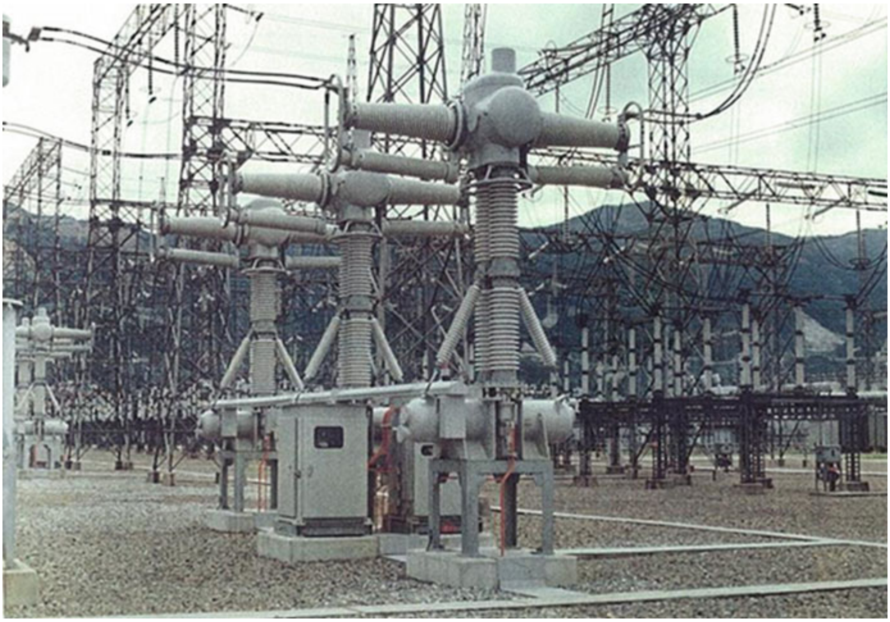


Fig. 2.30 240 kV double-pressure-type SF_6 puffer circuit breaker

a three-phase fault, the opening speed of the circuit breaker has a tendency to slow down by the thermally generated pressure, and the mechanism (often hydraulic or spring mechanisms) needs to have enough energy to keep the contacts moving apart. Strong and reliable operating mechanisms are costly and form a substantial part of the price of a breaker. For the lower-voltage range, self-blast circuit breakers are now on the market. Self-blast breakers use the thermal energy released by the arc to heat the gas and to increase its pressure. After the moving contacts are out of the arcing chamber, the heated gas is released along the arc to cool it down. The interruption of small currents can be critical because the developed arcing energy is in that case modest, and sometimes a small puffer is added to assist in the interrupting process.

In other designs, a coil, carrying the current to be interrupted, creates a magnetic field, which provides a driving force that rotates the arc around the contacts and thus provides additional cooling. This design is called the rotating-arc circuit breaker. Both self-blast breakers and rotating-arc breakers can be designed with less powerful (and therefore less expensive) mechanisms and are of a more compact design than puffer breakers.

2.12.4 Vacuum Circuit Breaker

Between the contacts of a vacuum circuit breaker, a vacuum arc takes care of the interruption process. As already discussed in the paragraph about the switching arc,

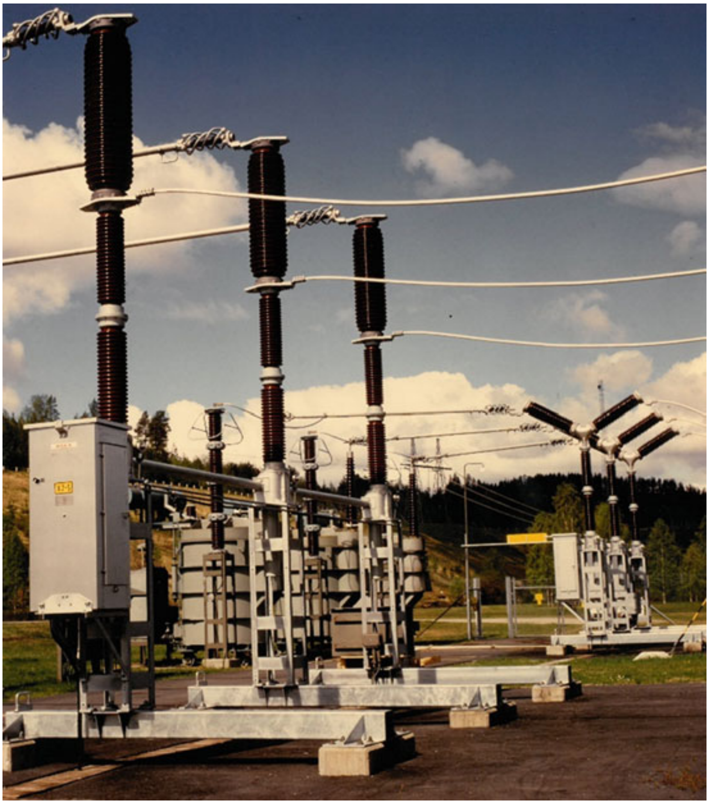


Fig. 2.31 245 kV 50 kA double-break and single-break SF_6 puffer circuit breakers. (Courtesy of ABB, ASEA products with double breaks in 1983 and with single break in 1985)

the vacuum arc differs from the high-pressure arc because the arc burns in the vacuum in the absence of an extinguishing medium. The behavior of the physical processes in the arc column of a vacuum arc is to be understood as a metal surface phenomenon rather than a phenomenon in an insulating medium. The arc is maintained by ions of metal material vaporized from the cathode. The density of this metal vapor is proportional with the current, and the plasma reduces when the current approaches current zero. At zero current the contact gap is rapidly deionized by condensation of the metal vapor on the electrodes. When the arc current goes to zero, it does so in discrete steps of a few amperes to 10 A, depending on the contact material. For the last current step to zero, this can cause a noticeable chopping of the current. This current chopping in turn can cause high overvoltages, in particular when the vacuum breaker interrupts a small inductive current, for example, when switching unloaded transformers or stalled motors. The absence of ions after current interruption gives the vacuum breaker a high dielectric withstand capability.

Fig. 2.32 550 kV live-tank SF_6 gas circuit breaker (Courtesy of Dominion Energy)

Fig. 2.33 550 kV 63 kA single-break SF_6 gas circuit breaker. (Courtesy of Chugoku Electric Power)

Fig. 2.34 24 kV 25 kA 1250 A vacuum circuit breaker. (Courtesy of Mitsubishi Electric)

The first experiments with vacuum interrupters had already taken place in 1926 (Sorensen and Mendenhall 1926), but it was not until the 1960s when metallurgical developments made it possible to manufacture gas-free electrodes that the first practical interrupters were built. In the 1970s, 36 kV vacuum interrupter was generally accepted as the unit voltage. The vacuum circuit breakers have been established as a reliable option for current interruption especially in MV networks. Figure 2.34 shows an example of 24 kV vacuum circuit breaker. Vacuum circuit breakers that continued to evolve and are gradually applied on a large scale in power networks up to 145 kV vacuum circuit breakers are available.

There are no mechanical ways to cool the vacuum arc, and the only possibility to influence the arc channel is by means of interaction with a magnetic field. The vacuum arc is the result of a metal-vapor/ion/electron emission phenomenon. To avoid uneven erosion of the surface of the arcing contacts (especially the surface of the cathode), the arc should be kept diffused or in a spiraling motion. The latter can be achieved by the electrodes with several spiral slits in the arcing contacts (see Fig. 2.35) or by applying horseshoe magnets as used in the vacuum interrupters (see Fig. 2.36). There is generally less energy required to separate the contacts of a vacuum circuit breaker, and the design of the operating mechanism usually results in reliable and maintenance-free breakers.

Vacuum breakers are produced for rated voltages up to 72.5 kV (some manufacturers also produce vacuum circuit breakers for 145 kV; see Fig. 2.37), and for the

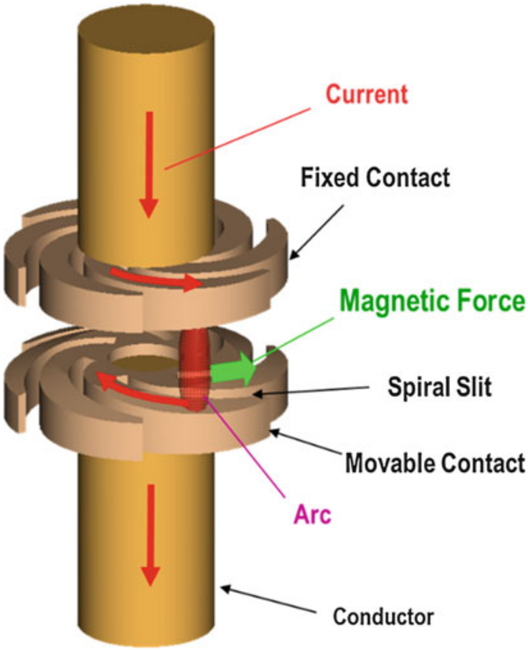


Fig. 2.35 Vacuum interrupter with spiral slits in the contacts to bring the arc in a spiraling motion

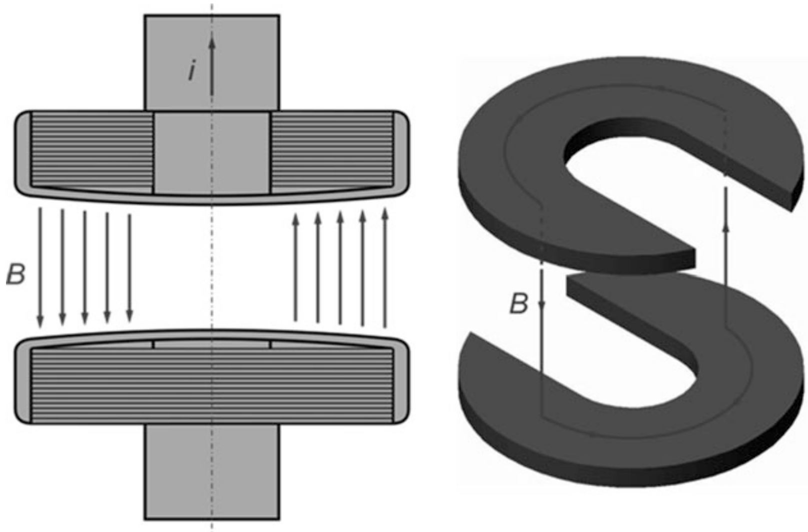


Fig. 2.36 Vacuum interrupter with horseshoe magnets. (Courtesy of Eaton Electric)

breaking current, the rating goes up to 31.5 kA. CIGRE WG A3.27 investigated several vacuum interrupters at transmission levels from 72 kV to 145/168 kV (CIGRE TB 589 2014). More detailed information is described in ▶ Chap. 7.

Fig. 2.37 Vacuum interrupters used at transmission levels (CIGRE TB 589 2014)

2.12.5 Generator Circuit Breaker

Generator circuit breakers are breakers applied at a rated voltage matching the rated voltage of a generator. They are located between the generator and the step-up transformer. When no generator circuit breaker is applied, an alternative solution is a circuit breaker at the high-voltage side of the step-up transformer. The advantage of this solution is the less complicated, simple high-current connection (generator bus duct) between the generator and transformer. The advantage of having a generator circuit breaker is the possibility to connect the auxiliary plant to the medium-voltage side of the (permanently energized) step-up transformer.

In the 1960s generator circuit breakers were developed for the higher power ratings. Air-blast technology was used, and the generator circuit breakers were equipped with an auxiliary switch and an opening resistor in parallel with the main interrupting chamber. The opening resistors were necessary to reduce the zero-crossing phenomenon and to decrease the rate of rise of the transient recovery voltage. In the late 1970s, generator circuit breakers with SF_6 technology came on the market. Figure 2.38 shows an example of 13.8 kV 100 kA SF_6 puffer-type generator circuit breaker. These breakers have no opening resistors and can be built more compactly.

The electrical and mechanical performances of a generator circuit breaker are very different from standard MV distribution switchgear. The common standard available worldwide that covers specifically the requirements for generator circuit breakers is IEC/IEEE 62271–37-013 (2015). Apart from the ratings and other relevant characteristics, this standard contains guidelines for the type testing of generator circuit breakers. Load currents for large generation units can be as high as 50 kA, which often makes forced cooling necessary.

2.13 Surge Arrester

Overvoltages, which stress a power system, can generally be classified into two categories regarding their origin:

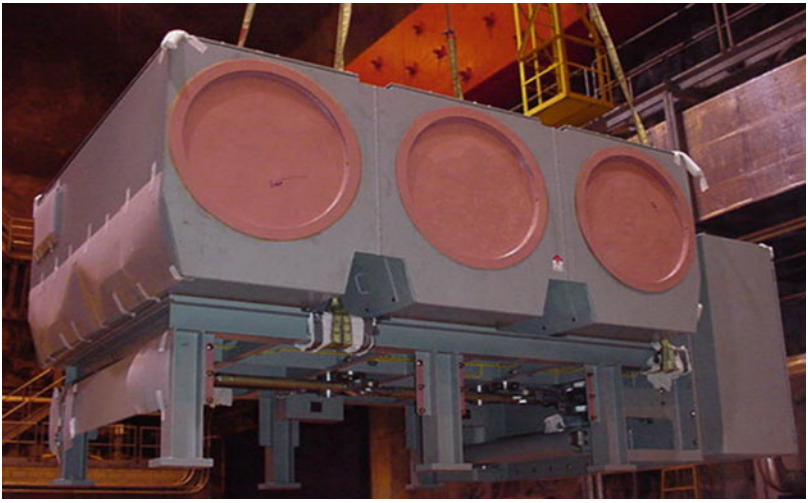


Fig. 2.38 13.8 kV 100 kA 12,000 A generator circuit breaker. (Courtesy of City of Tacoma, United States)

- External overvoltages, generated by lightning strokes, which are the most common and severe atmospheric disturbances
- Internal overvoltages, generated by changes in the operating conditions of the network, like switching

Surge arresters are placed in substations with the purpose to limit lightning-induced overvoltages and switching-induced overvoltages to a specified protection level, which is, in principle, below the withstand voltage of the equipment. The ideal surge arrester would be one that starts to conduct at a specified voltage level, at a certain margin above its rated voltage, holds that voltage level without variation for the duration of the overvoltage, and ceases to conduct as soon as the voltage across the surge arrester returns to a value below the specified voltage level. Therefore, such an arrester would only have to absorb the energy that is associated with the overvoltage.

The design and operation of surge arresters have radically changed over the last 30 years from valve or spark gap-type silicon carbide (SiC) surge arresters to the gapless metal-oxide (MO) or zinc-oxide (ZnO) surge arresters. Major steps in the development of surge arresters have been made, and modern surge arresters fulfil the present-day requirements (Fig. 2.39).

A metal-oxide surge arrester is essentially a collection of billions of microscopic junctions of metal-oxide grains that turn on and off in microseconds to create a current path from the top terminal to the earth terminal of the arrester. It can be regarded as a very fast-acting electronic switch, which is opened to operating voltages and closed to switching and lightning overvoltages. An important parameter of an arrester is the switching impulse protection level (SIPL) defined as the maximum permissible peak voltage on the terminals of a surge arrester subjected to switching impulses under specific conditions.

Fig. 2.39 Metal-oxide surge arresters (MOSA) in 550 kV substations. (Courtesy of Kansai Electric Power)

In order to keep the power supplied to a metal-oxide arrester at the system operating voltage small, the continuous operating voltage of the arrester has to be chosen such that the peak value of the resistive current component is well below 1 mA, and the capacitive current component is dominant. This means that the voltage distribution at operating voltage is capacitive and is thus influenced by stray capacitance. The voltage-current characteristic of the metal-oxide material offers the nonlinearity necessary to fulfil the mutually contradicting requirements of an adequate protection level at overvoltages and low current, i.e., low energy dissipation at the system operating voltage. Metal-oxide surge arresters are suitable for the protection against switching overvoltages at all operating voltages.

Traditionally, porcelain-housed metal-oxide surge arresters are used. For satisfactory performance, it is important that the units are hermetically sealed for the lifetime of the arrester discs. The sealing arrangement at each end of the arrester consists of a stainless steel plate with a rubber gasket. This plate exerts continuous pressure on the gasket, against the surface of the insulator. It also serves to fix the column of the metal-oxide discs in place by springs. The sealing plate is designed to act as an overpressure relief system. Should the arrester be stressed in excess of its design capability, an internal arc is established. The ionized gases cause a rapid increase of the internal pressure, which, in turn, causes the sealing plate to open and the gases to flow out through the venting ducts. Since the ducts are directed toward each other, it results in an external arc, thus relieving the internal pressure and preventing a violent shattering of the insulator.

However, porcelain-housed distribution arresters have tended to fail due to problems with sealing. The benefits of a leak-tight design, using polymers, have been generally accepted, leading to the changeover from porcelain to polymers. Polymer-housed arresters have a very reliable bond of the silicone rubber with the active parts. Hence, gaskets or sealing rings are not required. Should the arrester be electrically stressed in excess of its design capability, an internal arc is established, leading to rupture of the enclosure, instead of explosion. The arc will easily burn through the soft silicone material, permitting the resultant gases to escape quickly and directly. Hence, special pressure relief vents, with the aim of avoiding explosion of porcelain housing, are not required for this design. Moreover, polymer-housed distribution arresters are cheaper than porcelain-enclosed ones.

2.14 Switchgear at Distribution Levels

The roles of distribution networks are recently changing due to rapid increases of dispersed and intermittent wind and solar power generations. The dispersed power generations directly connected to distribution networks may cause a reversed load flow from the distribution to the transmission networks. Switchgears used at distribution levels are required to operate the distribution systems more reliably and efficiently.

CIGRE did not intensively investigate the switching phenomena and the requirements at distribution levels due to the lack of information on equipment performance in the field. SC A3 will increase the activities to investigate the equipment at distribution systems in the future (Fig. 2.40).

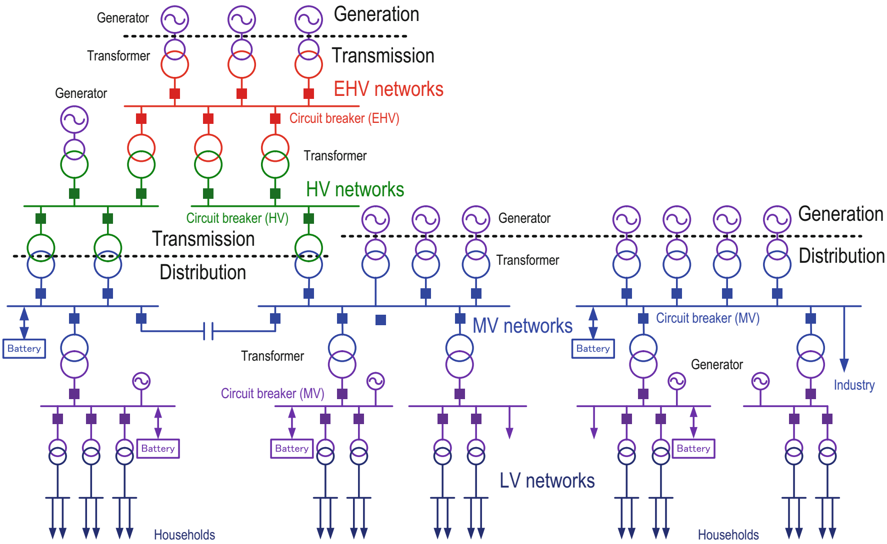


Fig. 2.40 Change of the roles of distribution system and equipment

MV switchgears are an essential part of the electrical power distribution system, contributing to its reliability and safety. It is typically installed on the power lines ranging from 1 kV up to 52 kV (IEC standards) or 38 kV (IEEE standards). The term switchgear is used to describe different types of equipment including electrical disconnecting switches, load break switches, reclosers, and circuit breakers. Their purpose is to control, protect, and isolate the equipment in distribution networks. They can be used to de-energize equipment to allow work to be done, to switch on/off the load, or to clear faults downstream.

As compared with HV switchgear, MV switchgear consists of two main components:

- Power-conducting components that conduct or interrupt the flow of electrical power
- Control systems such as control panels, current transformers, potential transformers, protective relays, and associated circuitry that monitor, control, and protect the power-conducting components

Ratings and specifications of MV switchgears must meet several different standards and requirements, including IEEE (Institute of Electrical and Electronics Engineers) and ANSI (American National Standards Institute) for North America and the IEC (International Electrotechnical Commission) standards around the world besides each national standard.

MV switchgears can be classified either by insulation type, by interrupter type, or by its construction below:

1. Classification by insulation: Most of MV switchgears available today use either gas or solid dielectric material for the insulation. While there was a strong penetration of solid dielectric insulation in the last two decades, the gas-insulated switchgears are still being produced utilizing air, SF_6, nitrogen, CO_2, and some gas mixtures. In recent years, there is a lot of research in the field of "alternative gases" to find a potential replacement for SF_6, and some new gases and gas mixtures are currently being evaluated.
2. Classification by interrupter technology
   (a) Air-insulated switchgears (AIS)
   (b) Gas-insulated switchgears (GIS)
   (c) Vacuum interrupter
3. Construction
   (a) Outdoor (must withstand the elements and large temp. range)
      (i) Pole top mount
      (ii) Pad mount (installed in a cabinet or a housing)
      (iii) Vault mount (installed in a wall)
   (b) Indoor
   (c) Live tank/dead tank
   (d) Metal clad/metal enclosed
   (e) Arc resistance

Fig. 2.41 Pole top recloser with solid dielectric insulation in accordance with IEEE C37.60/IEC 62271–111. (Courtesy of G&W Electric Company)

Reclosers are applied for overcurrent protection, mainly on overhead distribution systems in case of a temporary fault (not the case of a permanent failure). Reclosers help the network to self-recover itself and significantly improve reliability by isolating the smaller faulted sections and limiting customers' impacts due to outages. Typically, three-phase simultaneous operations are performed. However single-phase reclosing can be implemented on single-phase fault clearing to improve system reliability and availability. Fig. 2.41 shows an example of an independent pole-operated recloser with vacuum interrupters.

Reclosers are also used in substations as a circuit breaker. Dead tank designs allow reclosers to be used as a switch, a fault interrupter, or an intertie switch in pad-mount configurations. Site-ready designs with integrated lightning arresters and PTs allow customers to save installation time with a plug-and-play solution. Embedded voltage sensors on both sides of the vacuum interrupter permit the use of reclosers in distribution automation projects such as auto-transfer and loop-switching duties. Reclosers are tested in accordance to dual logo IEEE C37.60/IEC 62271–111 standard. The rating of the recloser shown in Fig. 2.42 is 27 kV, 12.5 kA, 800 A. The reclosers are typically used up to 40 kV, with the fault interrupting ratings up to 16 kA.

Load break, fused, and vacuum fault interrupting switches are commonly utilized in underground distribution systems for system reconfiguration and protection. Each switch may include one or more load break mechanisms which operate as an electric disconnect. These are often applied for system segmentation to separate a tie radial or a loop feeder. In addition, switches may be equipped with either fuses or vacuum interrupters for a load and/or system protection.

Medium-voltage distribution switches are available in both sealed and non-sealed designs. The sealed design shown in Fig. 2.42 utilizes SF_6 as the insulating medium

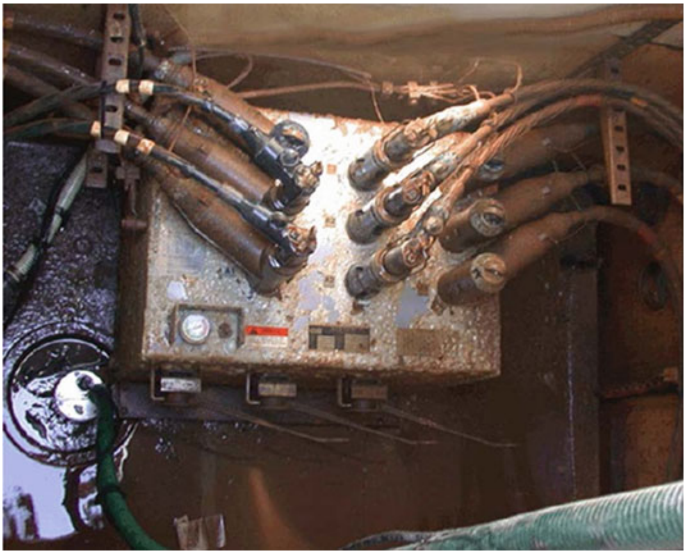


Fig. 2.42 27 kV 630 A SF_6 insulated dead tank switch. (Courtesy of G&W Electric Company)

Fig. 2.43 27 kV, 630 A solid dielectric insulated switchgears: dry vault (left) and pad-mounted (right) applications. (Courtesy of G&W Electric Company)

around the internal components and is designed and tested in accordance with the IEEE C37.74 standard for MV distribution applications up to 38 kV. Due to its dead tank design, it can be submerged and operated underwater, which is required for wet vaults that can operate in flooding.

Medium-voltage distribution switchgears with a variety of insulating mediums are available for a number of different applications. Figure 2.43 shows two different vacuum interrupter switches which use solid dielectric encapsulation for the insulation. These dry vaults are often applied for the inside of a building or above ground, inside of a pad-mount enclosure. Some types of switchgear are designed only for load break operations, while others are designed to cope with fault clearing as well.

They are tested in accordance to IEEE C37.74 standards and include ratings up to 38 kV, 630 A, and fault interrupting up to 25 kA.

Due to the permanent nature for this type of switchgear, each application has to consider a number of factors prior to the purchase and installation of the gear. These include:

- Load growth – How many loads will the switch need to protect and can the typical load value be increased over time?
- System changes – How will the switch be operated in the future and will that include remote or automated reconfiguration options?
- Total cost of ownership – As vault-style switchgear is typically difficult to remove or access for repair, the cost of replacement components and amount of expected maintenance must be included in the initial evaluation.

Figure 2.44 shows an example of air-insulated metal clad switchgear. It is constructed with grounded metal barriers to enclose all live parts. Typically, it has a removable (drawout type) circuit breaker, insulated bus, mechanical interlocks, voltage and current sensors, as well as a low-voltage control compartment isolated from the primary voltage areas in case of failures. It is used in a wide variety of applications including generation and distribution systems, industrial plants,

Fig. 2.44 36 kV, 2000 A, air-insulated metal clad switchgear. (Courtesy of Schneider)

Fig. 2.45 17.5 kV, 2000 A, 31.5 kA drawout circuit breaker with vacuum interrupters. (Courtesy of ABB)

commercial buildings, etc. This class of switchgear protects transformers, motors, generators, capacitors, distribution lines, and feeder circuits. It is tested in accordance to IEEE C37.20.2 standard.

Figure 2.45 shows an example of a 27 kV removable (drawout type) vacuum circuit breaker. The drawout circuit breaker is removable and can be separated from the power source in order to facilitate maintenance. It can be connected back to the power source using either a manual or motor-assisted racking capability.

Figure 2.46 shows an example of a ring main unit (RMU), which is a totally sealed, gas-insulated compact switchgear device, typically comprising of a circuit breaker, a disconnecting switch, and an earthing (grounding) switch. It is used on MV distribution lines in compact substations, small buildings, residential housing complexes, airports, wind power, etc. Since the gas tank is hermetically sealed, the environmental factors like moisture, dirt, and small insects are not affecting it. It enables connection, supply, and protection of transformers on an open ring or radial network. RMU is tested in accordance with IEC 62271–200 standard "AC Metal-Enclosed Switchgear and Controlgear for Rated Voltages Above 1 kV and up to 52 kV."

Figure 2.47 shows an example of arc resistance switchgear, which is a special type of switchgear designed to withstand the effects of an internal arcing fault as indicated by successfully meeting the test requirements. These requirements are specified in a number of national and international standards, including IEEE C37.20.7 "Guide for Testing Metal-Enclosed Switchgear Rated up to 38 kV for Internal Arcing Faults" and IEC 62271–200 "AC Metal-Enclosed Switchgear and

Fig. 2.46 24 kV, 630 A, gas-insulated ring main unit for secondary distribution. (Courtesy of Schneider)

Fig. 2.47 6.9 kV, 4000 A, 50 kA arc resistance switchgear tested per ANSI/IEEE C37.20.7. (Courtesy of Siemens)

Controlgear for Rated Voltages Above 1 kV and up to and Including 52 kV." Although the probability of the occurrence of an internal arc in MV switchgear during its life is very low, it can't be totally ignored. The causes of internal arcs

Fig. 2.48 29 kV, 900 A, 25 kA one-second short time and 42 kA peak fault closing. (Courtesy of S&C Electric Company)

include operational faults, system overvoltages, dielectric breakdown of material, and overstress of switches and circuit breakers, to name a few. The internal arc heats the surrounding gas resulting in an overpressure in the switchgear compartment. The hot gases may cause serious damage to the equipment and personnel in close proximity to the switchgear. In order to secure the safety of the operators, overpressure relief systems are integrated inside the switchgear to redirect the hazardous exhaust gases away from the areas where the operator might be working.

A circuit switcher is an economical equipment alternative to a circuit breaker. Figure 2.48 shows a circuit switcher unit utilizing interrupters that provide circuit interruption without external arc or flame. Arc extinction takes place within the SF_6 interrupters, which utilize a specially designed trailer and liner to create the necessary deionizing gases for efficient circuit interruption.

A circuit switcher is a mechanical switching device with an integral interrupter, suitable for making, carrying, and switching currents under normal circuit conditions. It is also suitable for interrupting specified primary-bus fault current and transformer-limited fault current that may be less than its rated short-circuit making current and rated short-time withstand current. A circuit switcher can also have an integral isolating disconnect. They are designed and built per IEEE C37.016 "Standard for AC High-Voltage Circuit Switcher Rated 15.5 kV Through 245 kV." The fault interrupting rating of a circuit switcher is somewhat lower from the corresponding circuit breaker, and the operating times are longer. Also, it is not rated for auto-reclosing; the operating sequence is only close-open operation. The primary applications for the circuit switcher are switching and protection of power transformers, shunt reactors, bus, and transmission lines.

2.15 Fuses

A fuse is the oldest and simplest protective device to perform overcurrent operation in an electrical circuit. The early pioneers, such as Michal Faraday, had observed that a wire could be fused by an electric current, and so the fuse was born. Primitive fuses consisted of an open wire between two terminals (Thomas Alva Edison, e.g., used a lead wire), but soon improvement was sought, and the wire was replaced by a strip, made of different materials, usually of lower melting point than copper, like zinc. But as the available power increased, the behavior of the fuse became increasingly violent until attempts were made to screen the fuse element by a tube, and fuse designers concentrated on how to limit the emission of flame from the ends of the tube. A useful degree of breaking capacity was achieved, but the introduction of the filled cartridge fuse marked the greatest advantage.

A fuse is a weak link in a circuit and as such has one important advantage over circuit breakers. Because the element in the fuse has a much smaller cross section than the cable it protects, the fuse element will reach its melting point before the cable. The larger the current, the quicker the fuse element melts. The fuse interrupts a very large current in a much shorter time than a circuit breaker does, so short in fact that the current will be cut off before it reaches its peak value, which in a 50 Hz system implies operation in less than 5 milliseconds, and serious overheating and electromechanical forces in the system are avoided. This current-limiting action is an important characteristic that has application in many industrial low-voltage installations. The single-shot feature of a fuse requires that a blown fuse has to be replaced before service can be restored. This means a delay, the need to have a spare fuse and qualified maintenance personnel who must go and replace the fuse in the field. In a three-phase circuit, a single-phase-to-ground fault will cause one phase to blow and the other two phases stay connected.

Fuses for high-voltage applications require a high breaking capacity. The cartridge is made of tough material, usually ceramic, and the cartridge contains, apart from the fuse element, a filler, such as powdered quartz, as is shown in Fig. 2.49. The purpose of the quartz filler is to condense as quickly as possible the metal vapor that is produced when a large overcurrent blows the fuse element. The filler prevents a dangerous pressure rise in the hermetically sealed enclosure. The filler should be neither too fine nor too coarse: an intermediate grain size provides the optimum cooling. The main classification of fuses is into current-limiting and non-current-limiting types.

Current-limiting fuses describe a class of fuses defined by the behavior that occurs when the current is so high that the fuse element melts before the peak of the fault current. The element is heated so rapidly that there is no time for heat loss to the surroundings; there is then a uniform temperature along the element, and all parts reach their melting temperature simultaneously. The wire thus becomes a liquid cylinder that becomes unstable and breaks up into a series of droplets. The fuse element has been replaced by a line of globules. The current is constrained to pass through them, because the surrounding filler has a nearly infinite resistance. In consequence the voltage drop at the beginning of arcing is considerable and causes rapid suppression of the current. The number of globules per centimeter is about

Fig. 2.49 7.2 kV fuse for industrial use rated current, 70 A; rated breaking current, 40 kA. (Courtesy of Mitsubishi Electric)

10–12, and as the voltage drop in a short arc is about 20 V, the voltage drop across the element is approximately 200–250 V per centimeter. The maximum voltage rise across a fuse depends on the length and the design of the fuse element. Upon melting, this type of fuse introduces resistance in the circuit so rapidly that the current stops rising and instead is forced quickly to zero, before a natural current zero would occur. The fuse limits the current in magnitude as well as in duration hence the name current-limiting. The current-limiting fuse introduces an overvoltage, called the fuse-switching voltage, into the system during the current-limiting action.

Non-current-limiting fuses or expulsion fuses melt under the same circumstances but add only a small resistance into the circuit, so that the current continues to about the same peak as would occur if the fuse had not melted. An expulsion action (that is where gas is generated by the arc and expelled along with ionized material) produces a physical gap such that, at natural current zero, the arc does not reignite and the current is interrupted. The expulsion fuse limits the duration of the fault current, but not its magnitude.

2.16 Summary

Chapter 2 introduced various equipment used in generation, transmission, and distribution networks. They include power generators, power transformers, circuit breakers, disconnecting switches, earthing switches, instrument transformers, and surge arresters.

Circuit breakers perform an important role to operate transmission and distribution systems efficiently and reliably. SF_6 gas circuit breakers have been applied to all system voltages up to UHV levels, and vacuum interrupters have penetrated into distribution systems and transmission systems up to 145 kV due to its excellent frequent operation capability with less maintenance work. Switchgear at the distribution voltages may change the requirements in changing network conditions due to rapid increases of dispersed and intermittent wind and solar power generations.

CIGRE SC A3 will continue to investigate the field experience with switching equipment in the changing network conditions and provide useful information for the experts in electrical industries.

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