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Technical Application Papers No. 26

Medium voltage switching devices: technologies and applications

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1. Introduction

This publication illustrates the basic operating principles of switching apparatus in relation to the different techniques used to date for monitoring and protecting medium voltage electrical installations.

1.1 General principles

First, the definitions provided by the Standards:
- Circuit breaker (IEC 60050 441-14-20): “Mechanical switching device capable of making, carrying and breaking currents under normal circuit conditions and also making, carrying for a specified duration and breaking currents under specified abnormal circuit conditions, such as those of short-circuit.”
- (Mechanical) switch (IEC 60050 441-14-10): “Mechanical switching device capable of making, carrying and breaking currents under normal circuit conditions which may include specified operating overload conditions and also carrying for a specified time currents under specified abnormal circuit conditions such as those of short-circuit.”

Thus the main functions of a circuit breaker in relation to the current to be interrupted are:
- switching the load current (the same as its rated current or less), which the circuit breaker must be capable of carrying continuously
- making, carrying and breaking overload currents
- making, carrying and breaking short-circuit currents following a fault in the electrical installation.

The switch, on the other hand, is unable to break short-circuit currents. It is only capable of supporting them for a certain time and making them at most. If the switch is also a disconnector, it must provide, in the open position, the insulating requirements of a disconnector.
- Contactor: (IEC 60050 441-14-33): "Mechanical switching device having only one position of rest, operated otherwise than by hand, capable of making, carrying and breaking currents under normal circuit conditions including operating overload conditions". Contacts are not capable of switching and withstanding short-circuit currents and must therefore be adequately protected.

Thus the circuit breaker is the only device designed to break short-circuit currents. A circuit breaker basically consists of two contacts (which are separated when the electrical circuit is open) and the relative actuating drive. The electric current is not interrupted immediately after the contacts have separated since an electric arc strikes between them and allows the current to keep flowing for a certain time.
In short, the operating principle of a circuit breaker is high-speed separation of the contacts so as to extinguish the electric arc and interrupt the current, at natural zero crossing of the alternating current. In addition, the voltage generated between the two contacts (Transient Recovery Voltage), imposed by the circuit in which breaking occurs, must be lower than that capable of restriking the arc (re-ignition voltage). This is why the arc quenching dielectric medium between the electrodes is so important and why it must possess high dielectric strength, considering the high temperature and ionizing state of the volume surrounding the arc.
Whichever the current that needs to be broken and the type of switching (opening or closing), the electric energy or mechanical impact that could occur or the effect on the insulation also depend on the type of breaking technology used.

1.2 A brief history

The first circuit breakers were used by Hanz Christian Oersted, Andre Marie Ampere and Michael Faraday for their experiments and consisted of two terminals in a bowl of mercury from which they were removed in order to break the current. The first circuit breakers of a more industrial type only appeared at the beginning of the twentieth century. They consisted of two large oil-filled wooden barrels containing contacts. The barrels were connected in series and were operated separately. The maximum operating voltage was around 40 kV.

One of these circuit breakers in service in 1901 is illustrated in fig. 1.1.

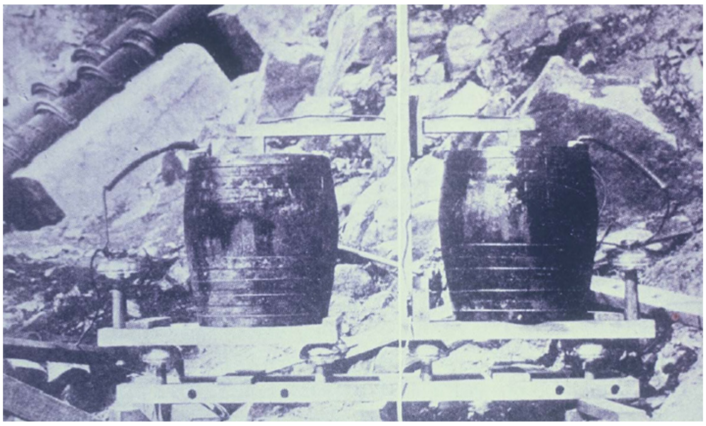


Fig. 1.1

One of the first circuit breakers designed in 1898 by L. L. Elden and installed in the Electric Light Company (fig. 1.2).

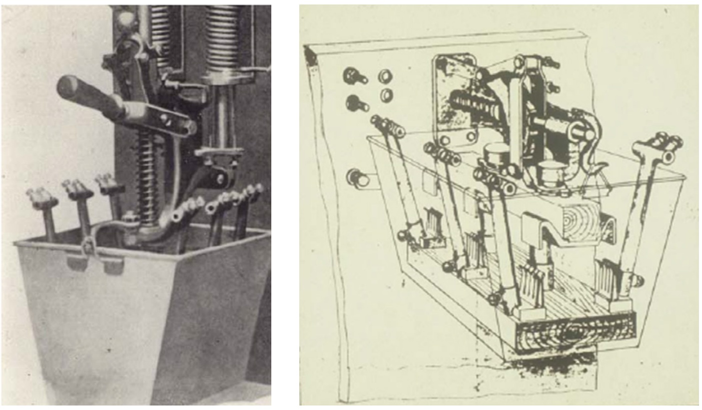


Fig. 1.2

From that moment on, the developments proceeded at a rapid pace since decidedly more industrialized 70 kV circuit breakers in closed tanks (one tank per phase) were already available in 1910 (fig. 1.3).

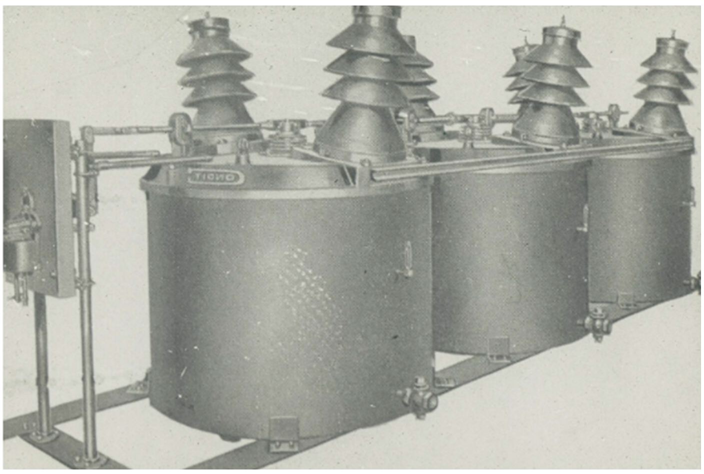


Fig. 1.3

The following photos (fig. 1.4 a,b,c) illustrate the sequences of a test performed on a Condit Elec. Mfg. Company 24 kV circuit breaker, which took place in Pittsburg in 1926 with a 10.5 kA opening-closing cycle.

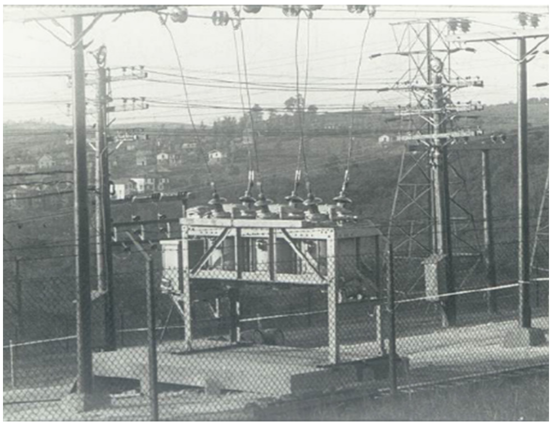


Fig. 1.4 a

Fig. 1.4 b

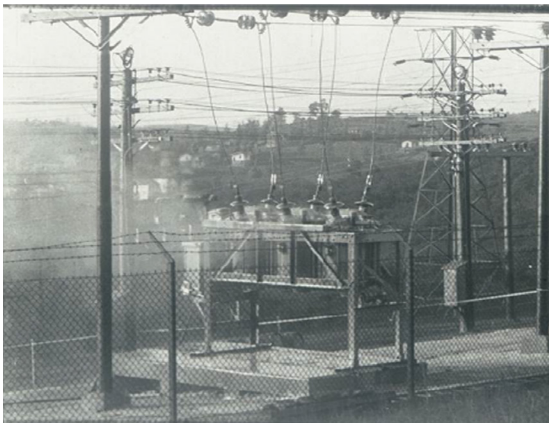


Fig. 1.4 c

1. Introduction

These circuit breakers, which contained a large amount of oil, were mainly used in the United States and were replaced in Europe at the beginning of the ’50's by breakers containing less oil.

Fig. 1.5

Fig. 1.5 shows one of the SACE MPR minimum oil content circuit breaker installed at the Dalmine steelworks (now Gruppo Tenaris), where it operated from 1958 to 1998. Fig. 1.6 shows the MR type as it appeared in the catalog in 1968.

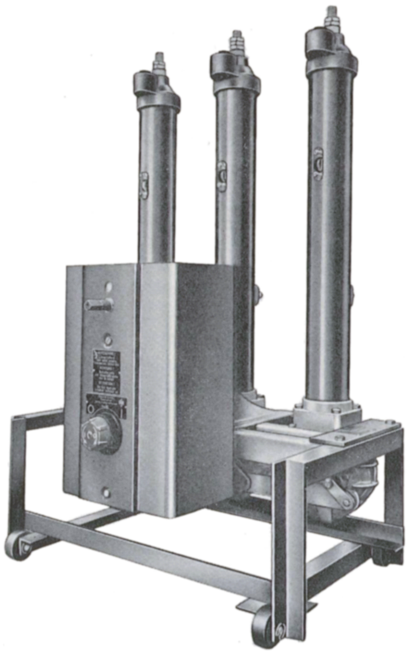


Fig. 1.6

Air circuit breakers were developed in Europe, first in 1926 by Whitney and Wedmore of the British Electrical Research Association, while successive developments mainly took place in Germany and Switzerland in the ’30's and ’40's. Development of air circuit breakers was at its highest peak in the ’60's after which this type of apparatus was progressively replaced by SF_6 circuit breakers. Fig. 1.7 illustrates a SACE air circuit breaker in the ’60's.

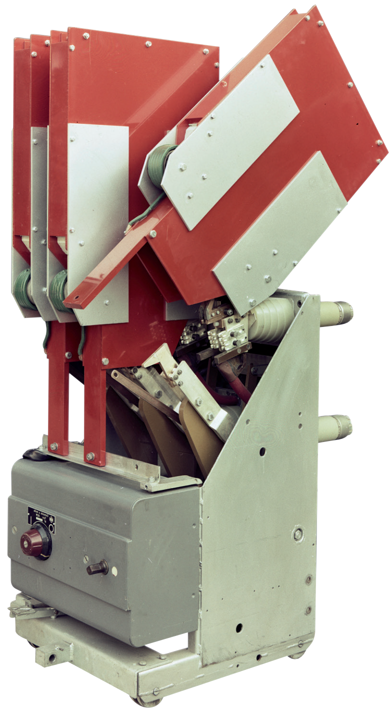


Fig. 1.7

The benefits of using SF_6 gas in electrical applications had already been evident in the ’30's, but it was only towards the end of the ’50's that the first circuit breaker for high voltage (HV) was developed. This led to the development, a few years later, of the first SF_6 circuit breaker for medium voltage. This circuit breaker was initially designed according to the same construction principles as the HV air circuit breaker with double pressure, where the pressurized SF_6 was blown axially onto the contacts. This type was short-lived and already by the end of the ’60's, it was being replaced by the present day SF_6 circuit breakers built according to different, more innovative principles (puffer and self-blast).

Mod. SFA, shown in fig. 1.8, was one of the first SACE SF_6 breakers.

Fig. 1.8

That vacuum was one of the ideal current breaking techniques had already been recognized around 1890, when the first patent was filed. However, certain technical difficulties limited its development for many decades. Initially used in HV systems, vacuum circuit breakers have now become the predominant technology in medium voltage installations (MV).

One of the first SACE vacuum circuit breakers, mod. Viarc, can be seen in fig. 1.9.

Fig. 1.9

All the different breaking techniques continued to be used for many years, especially between the ’60's and ’70's when they were all available on the market, one or the other being employed depending on customary habit or the type of application (fig. 1.10).

But the two dominant technologies, vacuum and SF_6, are not identical and the correct choice depends on the real characteristics of the installation that needs protecting, such as its age and size, the type and nominal characteristics of the machines and the type of process.

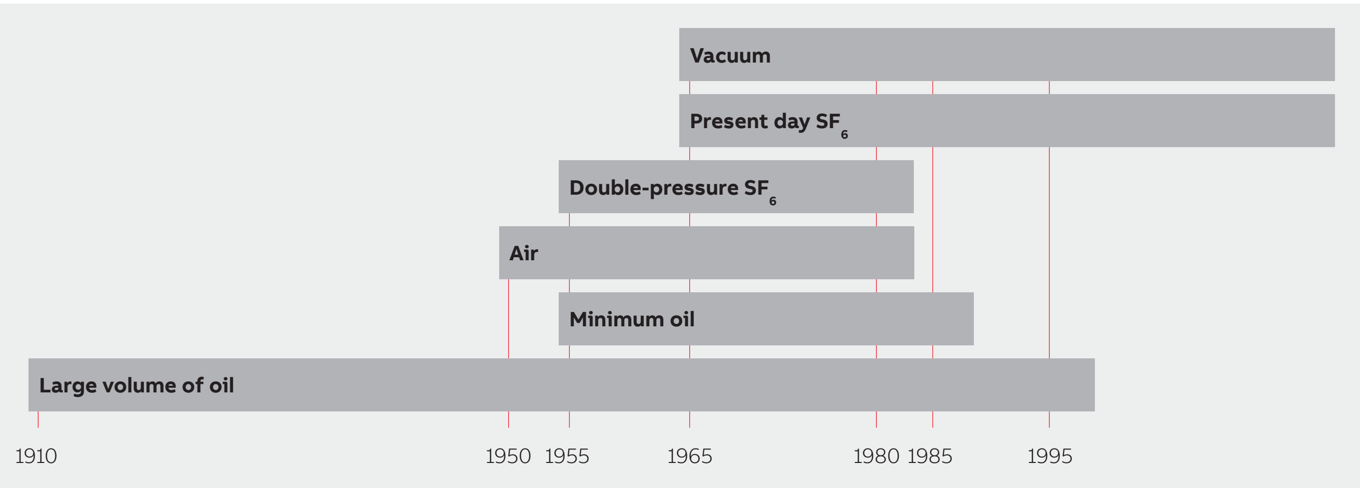


Fig. 1.10

2. The electric arc and its extinction

2.1 The electric arc

In a normal inductive electric circuit (fig. 2.1) one assumes that there is an ideal circuit breaker capable of instantaneously breaking the current, i.e. of switching in zero time from the state of conductor to the state of insulator.
If breaking occurs when the current crosses zero, the energy accumulated in the circuit ½ Li^2 at that moment is null, as is the consequent overvoltage, which equals L di/dt.

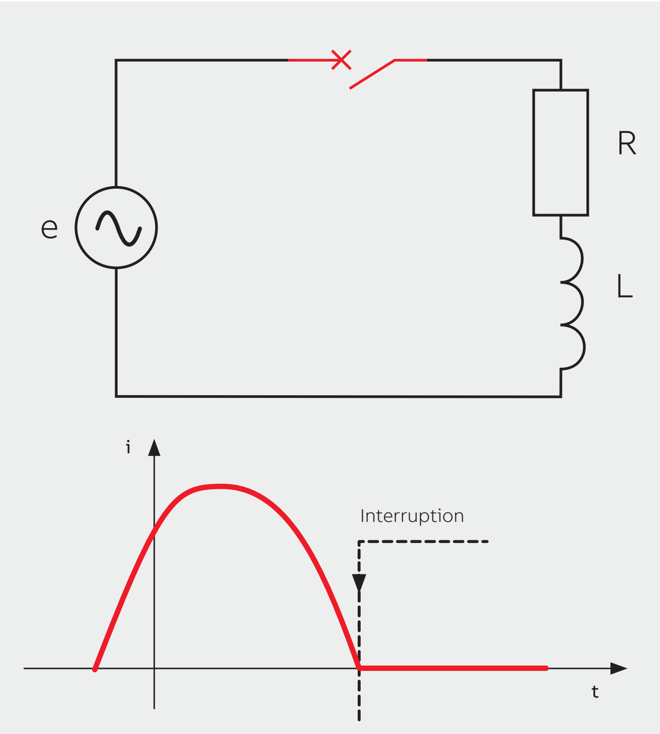


Fig. 2.1

However, breaking can occur in any point of the current wave. Thus there is energy other than zero which must be dissipated in the circuit. An overvoltage is also generated. The sharper the current interruption the higher the overvoltage, theoretically infinite in the case of instananeous interruption.
Again considering an ideal case, since the voltage is out-of-phase in relation to the current, grid voltage (called recovery voltage) appears between the contacts of the circuit breaker. Thus, if breaking were instantaneous, the rate of rise of this voltage dV/dt would also be very high, limited only by the parasitic capacitances of the grid, making definitive current breaking difficult if not impossible.
In actual fact, separation of the contacts in circuit breakers generates an electric arc owing to the energy that has accumulated in the circuit. This allows the current to continue to flow, thus current breaking is not instantaneous. Comprehending the electric arc phenomenon and analyzing what happens during arc quenching is the key to understanding how a circuit breaker functions.

When voltage is applied to two electrodes, the consequent electric field exercises a force on the electric charges in the medium in between. This force obliges the positive ions to move towards the cathode and the electrons towards the anode. When the electric charges hit the electrode, they yield the charge and actually produce a current which flows into the gaseous medium. Obviously, the current is only able to keep flowing if the yielded electric charges are continually replaced. This normally occurs due to ionizing processes, such as photoelectric or thermionic emisions. Initially, there is only a small current, which tends to increase as the voltage applied to the electrodes increases and, consequently, as the production of electric charges grows. Stable current, called saturation current, is obtained when a balance between produced charges and yielded charges is achieved.
This balance depends on the ionization intensity, and on the volume and pressure of the gas between the electrodes. This current does not self-supply itself since it depends on external ionization phenomena.
The effect of electrostatic forces due to the opposite polarity of the electrodes is a concentration of electric charges near the actual electrodes, which alters the original homogeneity of the electric charges themselves. Concentrations of electric charges near electrodes are called space-charge regions. A concentration of charges in the two regions leads to a localized increase in the electric field and, vice versa, to a diminution of the field in the intermediate region. These potential drops are known as anodic and cathodic potential drops (fig. 2.2).

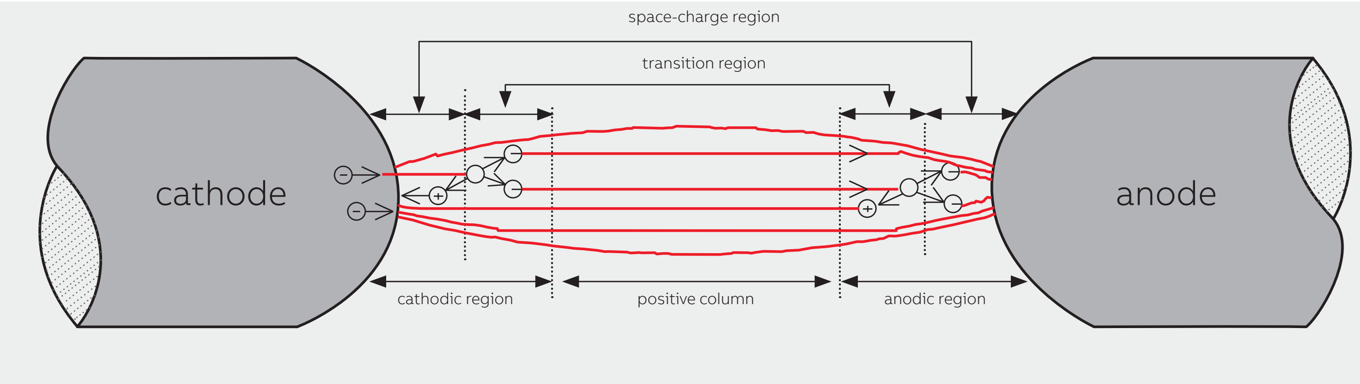


Fig. 2.2

If it is true that, once it has reached saturation value, current no longer increases as the voltage increases, then it is also true that when it is more intense, an electrical field leads to an increase in the speed at which the electric charges move towards the electrodes. Thus it is reasonable to expect that when the kinetic energy of the ions and electrons increases, collisions lead to the collisional emission of other charges or, in any case, bring the atoms to an excited state so that less energy is required for ionizing when the next collision occurs. So much so, the phenomenon could quickly be able to self-supply itself in the form of glow discharge.
The colour of glow discharge depends on the type of gas. In air, for example, the central region is pale blue in colour while the regions near the electrodes are salmon pink (fig. 2.3).
The cathodic region becomes thinner as the current increases. This means that a larger number of ions of increasing energy is able to collide with the cathode, thereby raising the temperature and leading to thermionic emission with a consequent further current increase and a rapid drop in discharging voltage.
The phenomenon now evolves rapidly from glow discharge into a true electric arc.
Electric arcs can carry high currents and electrically behave as non-linear resistors. The gases and vapors that supply the ions required for conduction come from the surrounding environment and/or from the electrodes themselves.

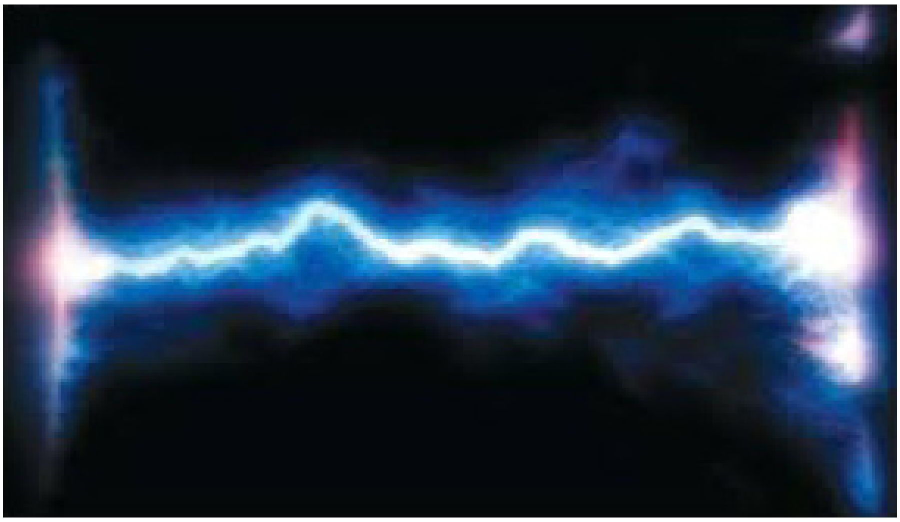


Fig. 2.3

2. The electric arc and its extinction

A further division between high pressure electric arc and low pressure electric arc is given in literature. The high pressure arc features an extremely luminous column formed by the ionized gas that conducts the electric current. The temperature is very high, with a consequently high degree of gas dissociation. The electric arc is characterized by a high current density in the plasma (hundreds of A/cm^2) and on the electrodes (thousands or millions of A/cm^2) and by a high temperature plasma (5000-20000 ºC).
The arc voltage between the two electrodes is not distributed in a linear way and three zones can be distinguished: two in the vicinity of the contacts (anodic and cathodic region) and the intermediate positive column.
The voltage is independent of the current value in the first two zones. Most of the voltage drop concentrates near the cathodic region. Its value is typically 10 to 25 V and it is substantially a function of the electrode material. The voltage drop in the anodic region is lower, generally between 5 and 10 V. The voltage in the positive column mainly depends on the type of gas, its pressure, the value of the arc current and the length of the arc itself. Since the voltage drop diminishes as the current intensity increases, an electric arc is similar to a non-linear conductor, thus Ohm's law does not apply. The typical positive column voltage vary values from a few Volts per centimeter to hundreds of Volts per centimeter.
Ayrton's equation can be used to calculate overall arc voltage U_a between anode and cathode:

$$U_a = A + Bl + \frac{C + Dl}{i}$$

where l is the length of the arc, i is the current and A, B, C, D are experimental coefficients. For copper air electrodes the values are: A=19, B=11.4, C=21.4, D=3.
All this shows how different breaking techniques have different arc voltage values since these latter depend on the characteristics of the materials and the geometry of the circuit breaker.

The arc is also influenced by the presence of a magnetic field or by fluid flowing at high pressure. The positive column of the arc is in thermal balance and, from the physical viewpoint, can be considered to be a hot gas conductor column subject to the laws of thermodynamics and electromagnetism, in any case strongly temperature-dependent.
Lastly, the current density of the cathode is strongly dependent on the material of the electrode.
The current density for some materials, among which copper, is in the order of $10^6 – 10^7$ A/cm^2.
This high current density also corresponds to a low boiling point of the material, which is a different phenomenon from the sublimation that affects refractory materials like graphite. Loss of material in metals like copper occurs to a much greater degree than in refractory materials and this is a further parameter to consider when choosing the contacts of a circuit breaker.
In the case of low pressure arcs or even vacuum arcs, the main difference compared to the high pressure arc is that the positive column is only influenced by the electrode material, since ionized gas is not present, and is thus composed of metal vapors. Arc voltage typically ranges from 40 V to 100 V and is therefore much lower than that of gas arcs. The typical arc voltage values are given in fig. 2.4 for various dielectric materials.

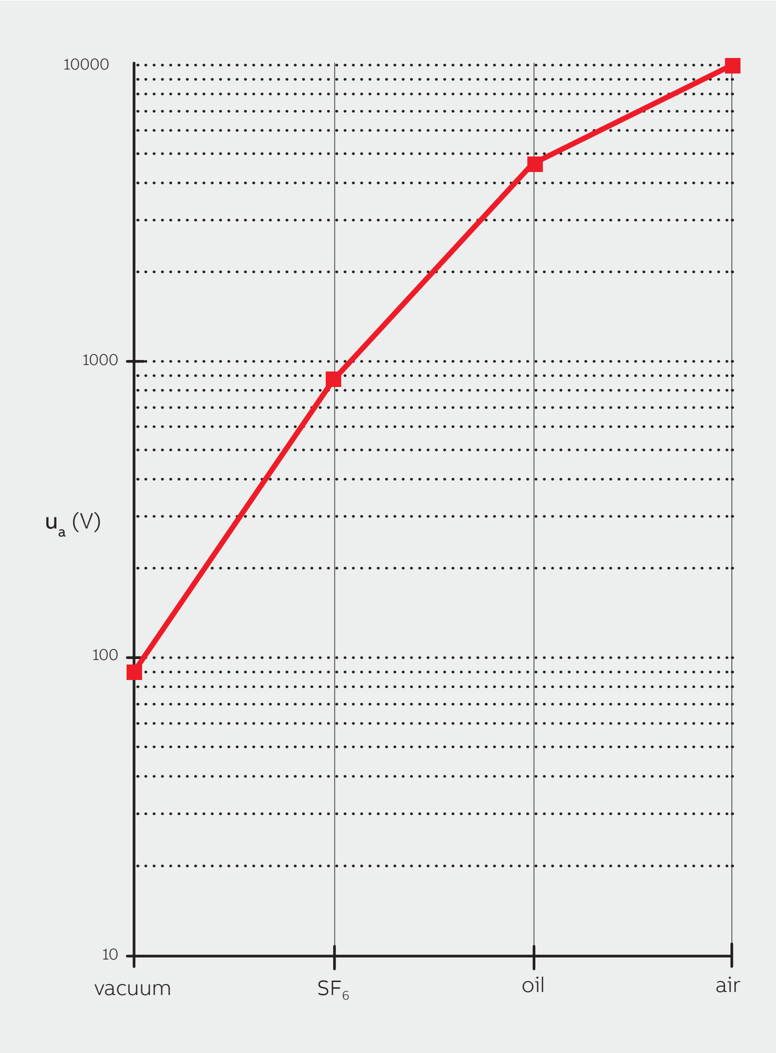


Fig. 2.4

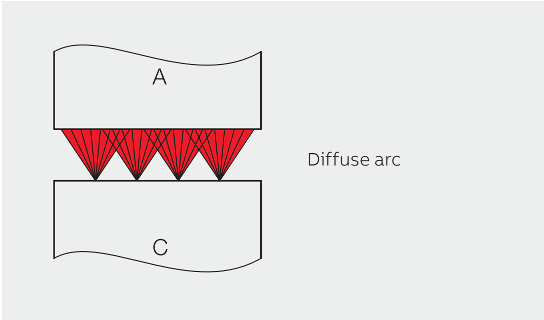


Fig. 2.5

In the diffuse mode, the arc, in relation to the cathode, takes the form of points of concentration which move rapidly and from which a multitude of parallel arcs depart (fig. 2.5).

As the current increases and beyond a certain limit (which depends on the contact material), the arc concentrates in a single region with respect to the anode while there will be very close and movable concentration points at the cathode (fig. 2.6).

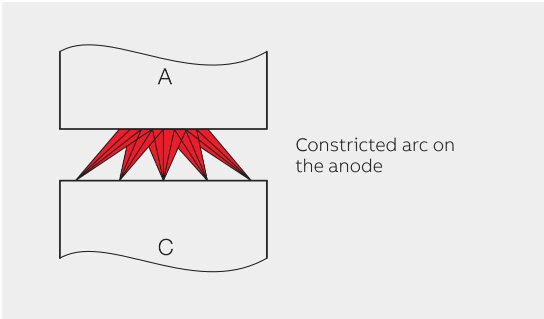


Fig. 2.6

Lastly, if the current increases to a further extent, the arc will concentrate in a single point on both the anode and cathode (fig. 2.7).

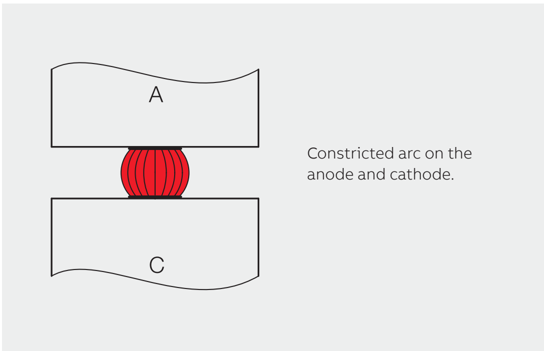


Fig. 2.7

The crossover point between difuse arc and constricted arc depends on the material and shape of the contacts. The typical value is around 15 kA of current.

2. The electric arc and its extinction

In the case of an alternating current short-circuit fault it is therefore logical to expect the arc to switch from a diffuse state to a constricted state before crossing natural zero.

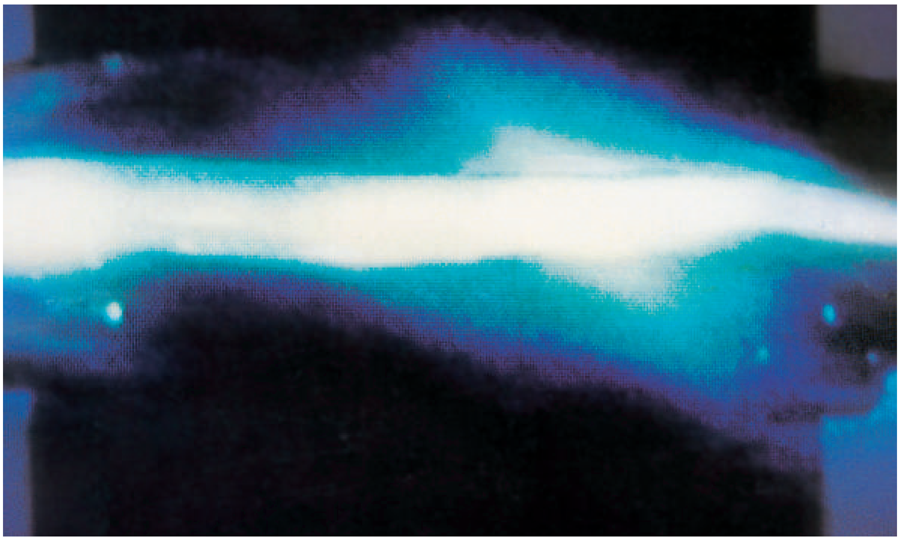


Fig. 2.8: vacuum arc between contacts

If one analyzes the behaviour of the alternating current arc, the current will be seen to decrease after having reached the peak. The level of ionization will also decrease as a consequence while the resistance of the arc itself will increase. Just before natural current zero crossing, the arc will therefore extinguish and then restrike when the current starts flowing in the opposite direction. The time between quenching and restriking depends on the dielectric medium in between and the characteristics of the external circuit. In terms of energy, the arc is supported by the energy supplied by the external circuit (½ Li²), while energy is dissipated by conduction (by means of the contacts), by convection (by means of the dielectric, thus not in the case of vacuum) and by radiation. The arc quenches at current zero crossing since energy is no longer supplied. There will be a peak arc voltage u_a, called peak extinction voltage, during the current zeroing phase (fig. 2.9). This voltage opposes immediate arc restriking, thus there is a period of time during which current does not flow. Deionization due to loss of heat begins since energy is not supplied during this period of time. This means that the voltage required to restrike the arc will be higher, certainly more than the voltage required to support it after it strikes. After a restrike, the current increases and the arc voltage decreases until it reaches the minimum value, which remains constant for most of the current half-cycle. The time between current zero and arc restriking depends on the recovery voltage slope and the deionizing speed of the medium between the contacts.

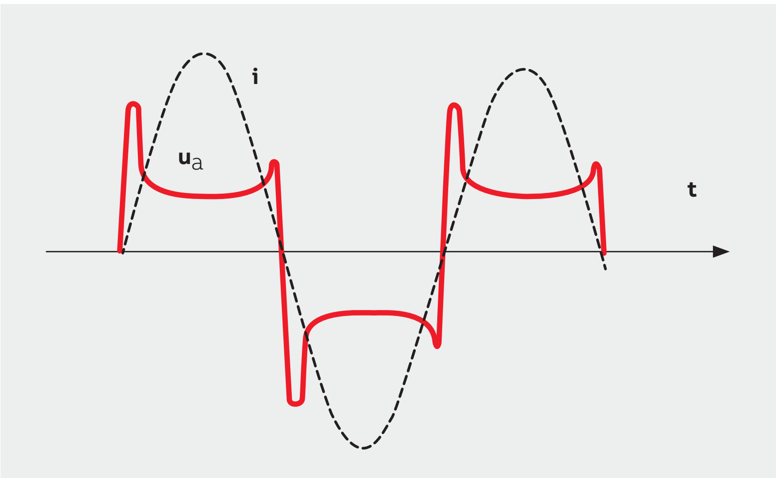


Fig. 2.9: voltage and arc current trends.

The energy dissipated by the arc can be expressed as a function of the current considering, with good approximation, u_a constant for a given breaking technique:

$$\int_{to}^{ta} Ua\ idt$$

where t_0 is the arc striking moment and t_a the quenching moment. Thus, considering the typical arc voltage values, current being equal, the energy issue will be less important for a vacuum circuit breaker and, vice versa, of maximum importance for an air circuit breaker. Whichever the case, the energy dissipated by the arc will have an impact on the design of a circuit breaker, which must also be able to withstand interruption from the thermal aspect.

2.2 Alternating current breaking

Since, in alternating current installations, the current value crosses zero twice at each cycle, it may seem sufficient to wait for natural deionization of the gap between contacts to obtain arc extinction and to prevent the restriking. In fact the section of the arc diminishes very quickly in the last part of the current half-wave. The dielectric medium near the contacts tends to cool rapidly and, while the electrons migrate towards the anode, the cathode forms, in about 1 µs, a layer of positive charges able to maintain a voltage value of 100 to 1000 V. During the first instants, the withstand function is entirely provided by this layer since ionization does not disappear instantly, but gradually, while the dielectric medium tends to regain its dielectric strength. Lastly, conductivity vanishes below a certain temperature and the voltage spreads evenly over the entire distance between the contacts. The energy balance within the first 100 µs from extinction is fundamental to the success of breaking.
Thus the duration of the phenomenon is of crucial importance in the breaking process (arc hysteresis). At the frequencies normally used in power plants (50-60 Hz), current zero time may not be sufficient to reduce arc conductivity, that is, for the deionizing effect to be significant, and to thus prevent the arc from restriking. On the other hand (as illustrated in fig. 2.10 showing the arc voltage curve for an alternating current), current direction reversal helps as it generates a peak given by the sum of the extinction voltage of the previous half-wave and the peak of the re-ignition voltage of the successive half-wave with opposite polarity.

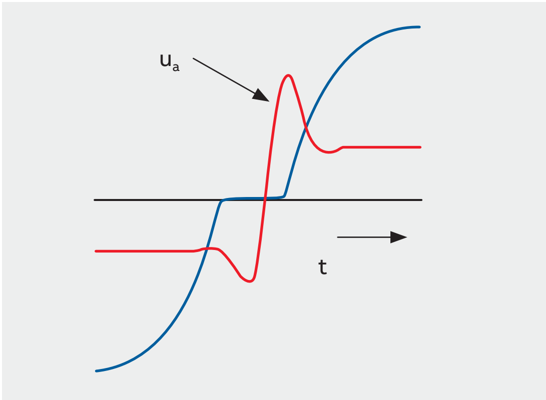


Fig. 2.10

Getting back to the way a circuit breaker functions, re-ignition voltage V_d, i.e. the voltage required to re-strike the arc, rapidly increases in relation to the opening speed of the contacts and the dielectric characteristics (fig. 2.11). Distance between contacts being equal, the voltage thus depends on the physical and chemical behavior of the dielectric medium. This means that when it comes to designing a circuit breaker, the better the characteristics of the dielectric medium the shorter will be the distance between contacts required to quench the arc and the less energy will be required by the drive.

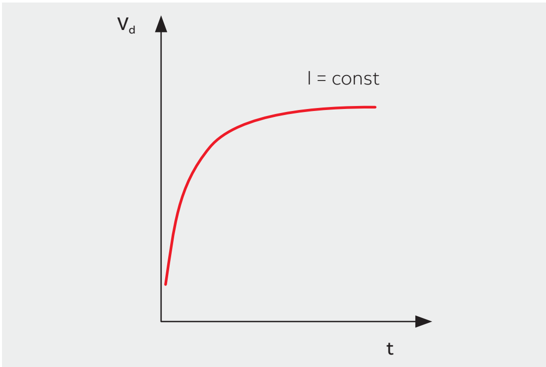


Fig. 2.11

2. The electric arc and its extinction

That being said, the other variable to consider is the recovery voltage imposed by the electric circuit which is generated at the circuit breaker contacts. In short, if one examines the trend over time of re-ignition voltage V_d and Transient Recovery Voltage V_r (TRV) one can affirm that a restrike will occur whenever $V_r(t) \geq V_d(t)$ for the entire period of time that elapses from extinction until the contacts have completely opened (fig. 2.12).

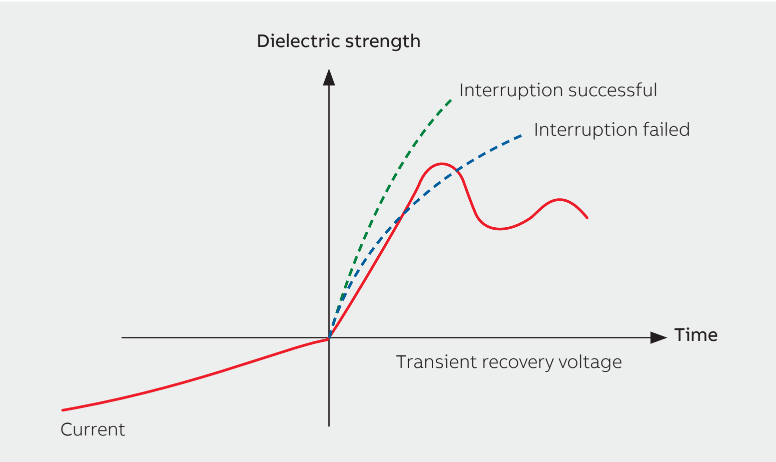


Fig. 2.12

TRV is therefore a crucial factor for the success of the breaking action by the circuit breaker, but it largely depends on the characteristics of the electrical installation. However, it can only be determined by simulating the behavior of the installation in transient conditions using software tools called EMTP (Electro Magnetic Transients Program).
Evidently, the most favorable case is when the voltage is at its minimum when the current crosses zero, that is, when the voltage and current are in phase, thus in the case of a resistive load.
However, the situations in installations are very different and, depending on the loads, the current can be inductive or capacitive, which makes current breaking more complex. These conditions are examined in chapters 4 and 5.
Interruption of a short-circuit current, which can be considered purely inductive, is illustrated in fig. 2.13 by way of example.

Since plasma consists of electrically charged particles, the magnetic field can affect the position of the arc by lengthening it, by moving it to certain positions where it can be more easily quenched or for the purpose of achieving a more uniform wear on the contacts. Using the magnetic field generated by the actual current, studying specific geometries for the contacts or breaking chamber, are solutions used in almost all the breaking techniques.
As for the curve over time of the arc voltage in alternating current, note that the voltage is in phase with the current. Thus it is normally considered to be like a resistance.

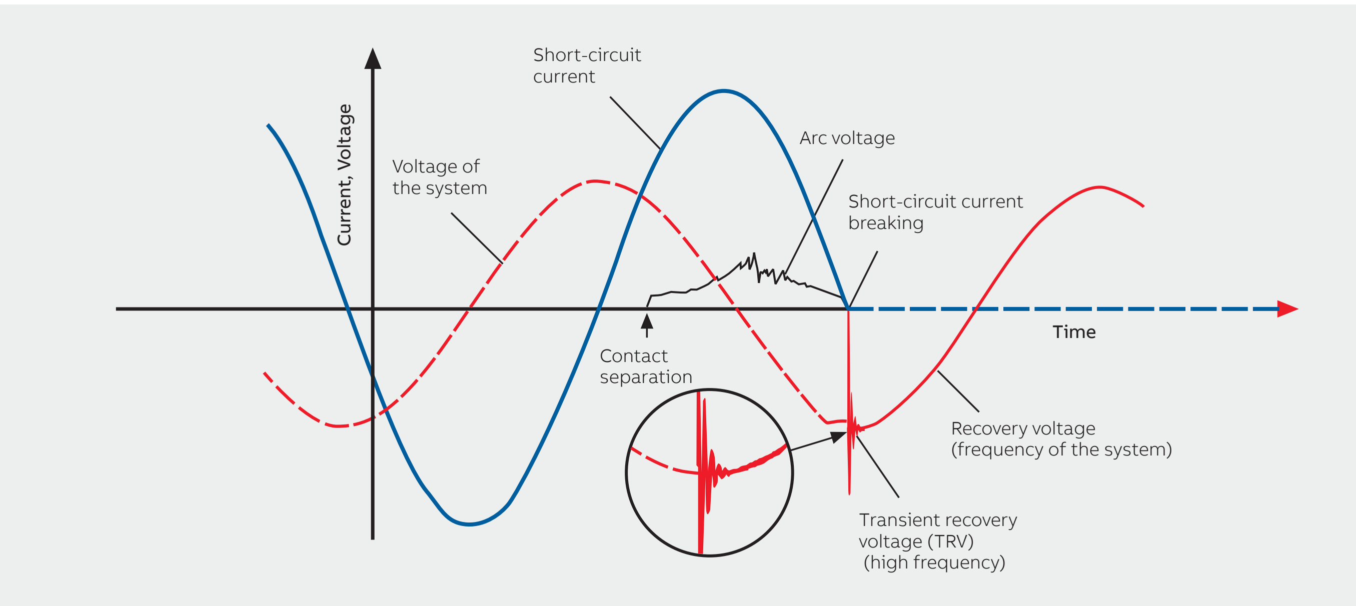


Fig. 2.13

3. The medium voltage circuit breaker

3.1 Breaking techniques

To sum up the issues discussed in the previous chapter, one can say that to interrupt the currents circulating around an electrical installation in the best possible way, the dielectric medium in the arcing chamber of the circuit breaker must be an excellent open circuit insulation. But as soon as the arc develops it must initially become a good conductor, with good thermal conductivity, and then rapidly recover its dielectric characteristics so as to avoid successive restrikes.

3.1.1 SF_6 interruption

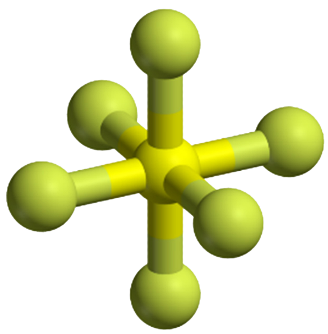
Sulfur hexafluoride or SF_6 is a synthetic gas with excellent insulating capabilities and optimum thermal and chemical stability. Thanks to these characteristics, it is widely used in HV and MV circuit breakers, where it improves their characteristics and general reliability.
Currently, 80% of the world production of SF_6 is used in the electricity industry when smaller dimensions and low fire risk are required (compared to air insulation), as well as low maintenance.
SF_6 was discovered by Henri Moissan in 1900 and since then, much research has been conducted for the purpose of characterizing the gas and identifying its properties. Measurement of its dielectric strength dates back to 1937 and since it was found to be much higher than that of air, SF_6 soon began to be used by the electricity industry. SF_6 gas became a commercial product in 1947 and since then, its field of application has broadened to include other sectors. SF_6 gas possesses a high dielectric strength value, approx. 2-3 times more than that of air at the same pressure. Thanks to its optimum heat exchange aptitude and ability to capture electrons, it has been found to be especially suitable for interrupting arcs and able to restore its insulating properties very quickly. The high dielectric and interruption performance of SF_6 stems from its strong electron affinity (electronegativity), since its molecule has a marked tendency to bind unbound electrons. The large collision diameter (~ 4.77 Å) allows accelerated electrons to be captured in an electric field well before they have sufficient energy to create further current carriers. This causes the discharge mechanism to either slow or cease. Use of SF_6 optimizes the electrical performance and the overall dimensions of switchgear because in practice, the distances between contacts are halved while the mechanical stress to which the switchgear is subjected during the various operating sequences is reduced. The main physical characteristics of SF_6 are listed in table 1.

Property		Value
Sublimation temperature and boiling point (°C)		-63.9 at 1.0133 bar
Latent heat of sublimation (kJ/kg)		153.2
Melting point or triple point (°C)		-50.8 at 2.26 bar
Latent heat of fusion (kJ/kg)		34.37
Vaporization heat (kJ/kg)	at - 20 °C at 0 °C at +20 °C at +40 °C	91.71 78.96 62.54 34.08
Critical temperature (°C)		45.58 at 37.59 bar pressure and 736 kg/m³ density
Density (g/cm³):	gas (20 °C and 1 bar) liquid (0 °C, 12.65 bar) solid (-100 °C)	6.07 1554 2770
Specific heat capacity at constant pressure (J/mole*K)		96.6
Speed of sound (m/s)		136
Refractive index		1.000783
Heat of formation at 25 °C (kJ/mole)		-1221.66
Entropy of reaction 25 °C (J/mole*K)		-349.1
Solubility in water at 20 °C (cm³ SF_6 /kg H_2O)		6.31
Solubility in oil at 27 °C (cm³ SF_6 /cm³ oil)		0,408

Tab. 1

3. The medium voltage circuit breaker

SF_6 possesses excellent heat transfer capabilities even though at high temperatures, its thermal conductivity λth is lower than that of air and other gases. This is due to its lower viscosity and a greater density allowing heat to be conveyed much more efficiently. The transport coefficients for SF_6, air and transformer oil (this latter by natural convection) are illustrated in the graphs of fig. 3.1. The electronegativity of SF_6 and its high λth value at low temperatures (between 1550 K and 3000 K) together with dissociation of molecules allow arc conductance to decay more rapidly, while its dielectric properties will be restored faster.



In its purest form and in normal weather conditions (20 °C, 1 atm) sulfur hexafluoride is extremely stable thanks to its molecular structure in which six fluorine atoms, in the vertices of an octahedron, are linked to the sulfur atom in the center. Its molecular weight is 146.05 g/mole. It is chemically inert: it does not react with water, alkaline hydroxides, ammonia or hydrofluoric acid. It does not corrode metals and up to about 150°C, not even materials like glass, ceramic and polymeric materials in general.
It can be heated up to 500 °C in quartz without decomposing. The presence of certain metals can start it to decompose at about 200 °C with effects that become significant between 400 °C and 600 °C.

Under the effect of high temperature, radiant energy or electric discharges, the atoms forming the sulfur hexafluoride molecule may separate and give rise to free radicals, ions or other electrically neutral molecules, depending on the type of excitation and the quantity of energy involved in the phenomenon.
In the case of electric arcs, complete dissociation in sulfur and fluorine occurs at 3000 °C:
$SF_6 + \Delta E \rightarrow SFx + (6\text{-}x)F$ with $0 < x < 6$

At these temperatures, air or water vapor, which may have penetrated into the apparatus when the gas was handled or from leaks through gaskets or be released by organic insulation materials, are dissociated in the same way. Copper, tungsten, graphite and aluminium vapors due to the heating of electrodes and enclosure walls add to these atoms and ions. The aforementioned **reaction** is reversible. This means that the products of dissociation recombine to form mainly SF_6 once the supply of energy ceases.

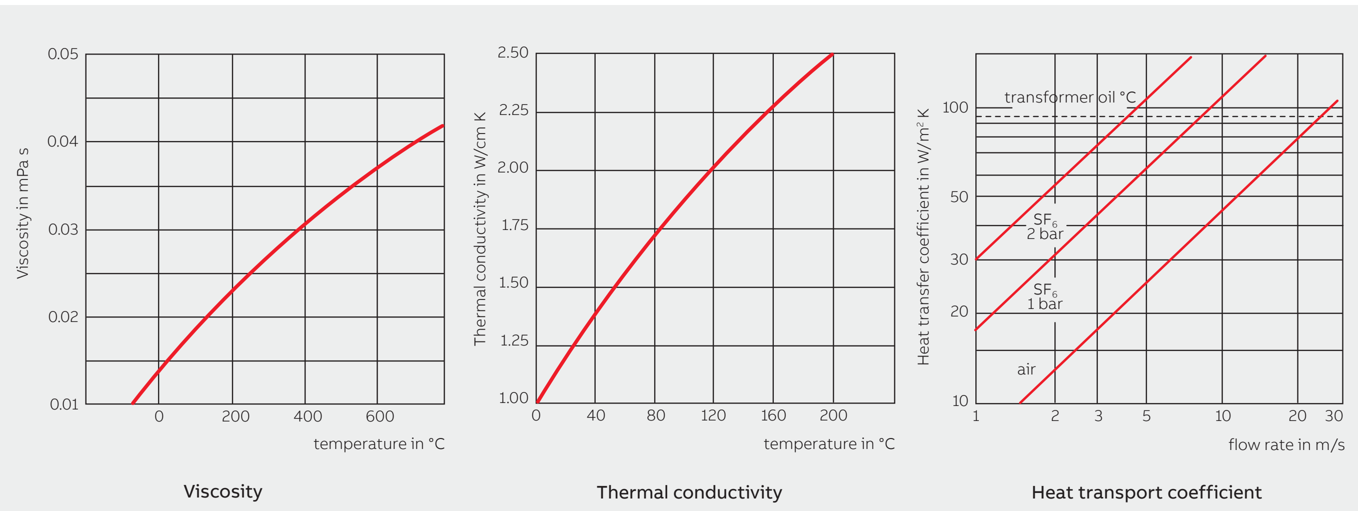


Fig. 3.1: SF_6 viscosity, thermal conductivity and heat transport coefficient

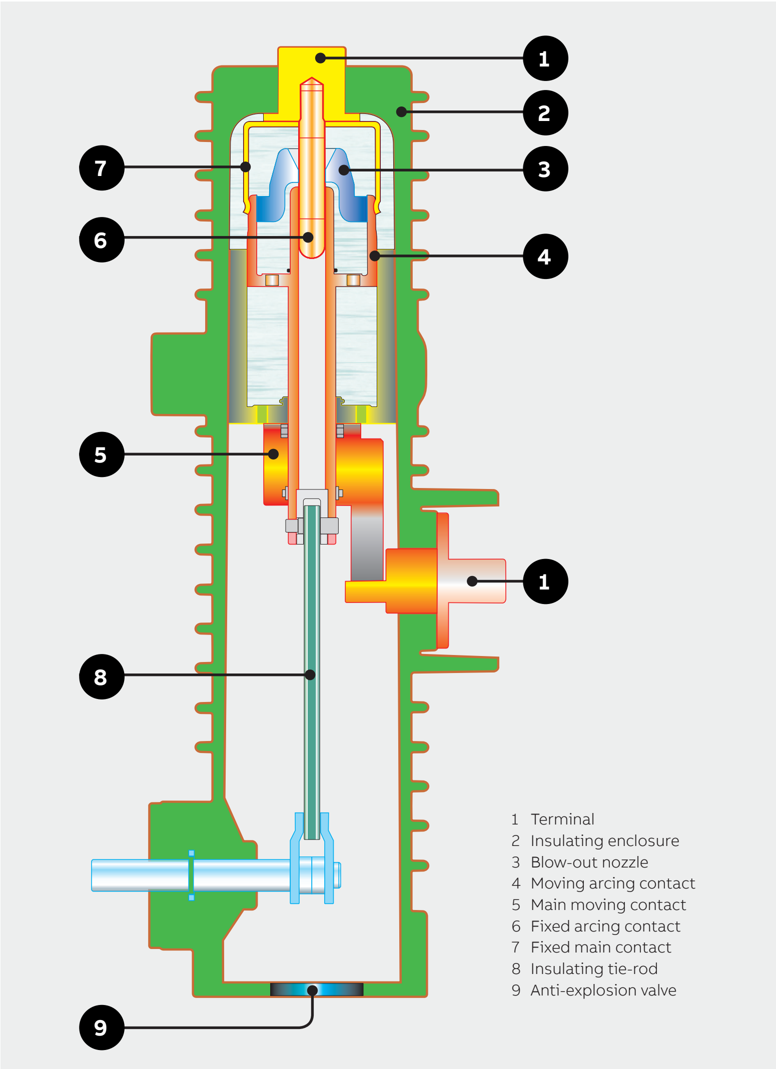


Fig. 3.2

The first generation of circuit breakers used a double pressure system derived from the HV air circuit breakers. The second generation was designed to create a flow of gas, required to quench the arc, thanks to the thrusting action of a piston connected to the opening drive. However, the drive mechanism of this type of solution, called “puffer”, required a great deal of energy even at low current values and the risk was sharp interruption of the current before zero crossing (chopping current). A further development called “self-blast” used the actual arc energy to produce the flow of gas in the arcing chamber. This reduced the mechanical energy required by the drive to a considerable extent but with the risk of ineffective interruptions at low current values.
The latest generation proposed by ABB (figure 3.3) is the so-called “auto-puffer” circuit breaker, which combines both solutions using the puffer technique for currents up to 30% of breaking capacity and the self-blast technique for higher voltage values. This mixed technique only requires a minimum amount of additional energy for the drive mechanism compared to the self-blast version, but achieves optimum arc interruption even at low fault current values. Even interruptions of small inductive currents are optimum and induce only small overvoltages in the installation (< 2.5 p.u.).
The ABB HD4 family of circuit breakers uses the auto-puffer technique described above. The operating principle of the pole is described further on (figures 3.2 and 3.4):

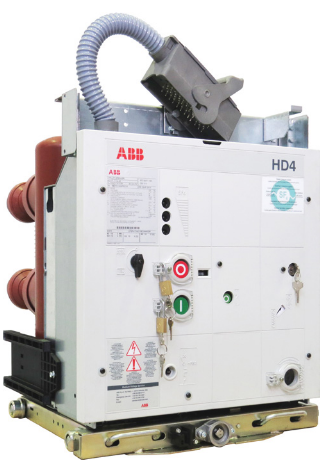
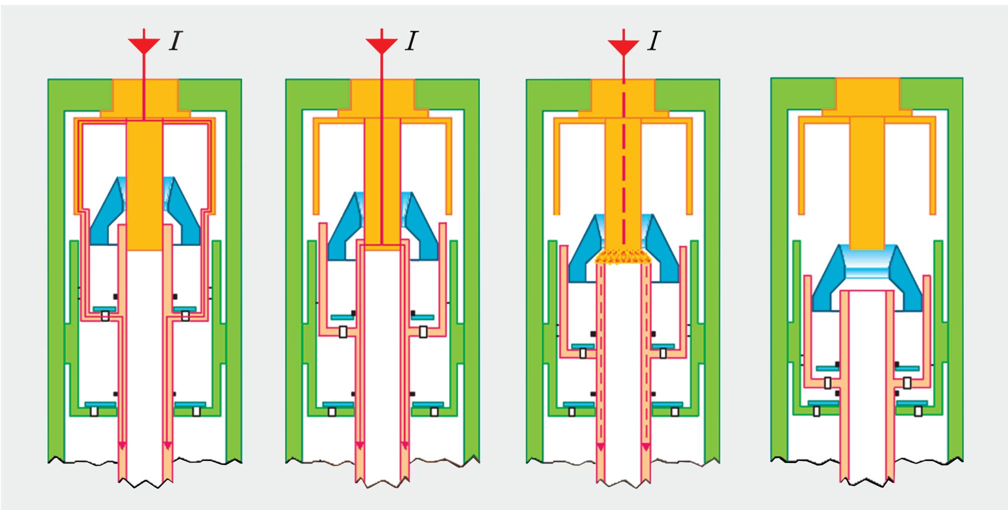


Fig. 3.3



a) Circuit breaker closed b) Separation of main contacts c) Separation of arc-breaking contacts d) Circuit breaker open

Fig. 3.4

3. The medium voltage circuit breaker

Starting from the circuit breaker closed condition (a), if a fault occurs the circuit breaker will begin to open but there will be no electric arc since current flows through the arc contacts (b). During its downward travel, the gas is compressed and flows from the lower chamber to the upper one at a constant pressure.
If the arc contacts separate (c), an electric arc forms and current continues to flow through. Gas can no longer flow through the nozzle of the arc contacts since the hole is closed by the fixed contact and the arc itself.
When the current value is low, the arc quenches and gas flows through the contacts when the current crosses zero. The pressure is low and so there is no arc chopping effect, but the fresh gas is still sufficient to restore the dielectric strength and prevent restrikes after the front of transient recovery voltage.
When there are high short-circuit currents, the wave of pressure generated by the arc shuts the communicating valves between the two chambers and the circuit breaker behaves like a fully self-blast version. The pressure in the upper chamber increases as the gas rapidly heats. The pressure is proportional to the arc current and ensures quenching at the first current zero crossing.
Lastly, after the arc has quenched (d), the self-generated pressure diminishes since gas flows through the contacts. The valves open again and fresh gas flows into the arcing chamber where maximum withstand voltage is reached.

3.1.2 Vacuum interruption

The basic problem faced when vacuum circuit breakers were developed was to create a hermetic insulating enclosure able to maintain the vacuum for very long periods, as well as being mechanically sturdy and able to provide a good resistance to thermal gradients. A solution to this problem was only found at the beginning of the ’60's when blown glass containers were used, but the final solution was only reached later on with the development of alumina ceramic (Al_2O_3), which possesses the required degree of sturdiness and resistance to thermal stress. Finding the most suitable material and shape for the contacts was another problem. The requirements are demanding: the contacts must possess high resistance to arc erosion during both the opening and closing operations. Welding must be avoided while chopping currents must be reduced to the minimum.
Initially, chromium was thought to be the material best able to comply with the requirements, but only after further research was a copper/chromium alloy defined as the best solution to the problem. Nowadays, the standard solution for contact materials is a Cu/Cr alloy containing 20% to 60% chromium, depending on the circuit breaker application.
That very hot points form, with the production of metallic vapors (figure 3.5) when the contacts separate has already been discussed in the description of the electric arc. The formation of ions from these metallic vapours thus ensures that the arc forms. After this, the arc spreads over the entire surface of the anode. This is the typical condition up to the rated current of the circuit breaker, with very limited erosion of the contacts and, thus, a very high number of interruptions.
Interruption of the higher short-circuit currents requires a more sophisticated design. As the current increases, the electric arc tends to concentrate first on the anode after which it develops the typical form of a conductor with high temperatures in the contact zone.

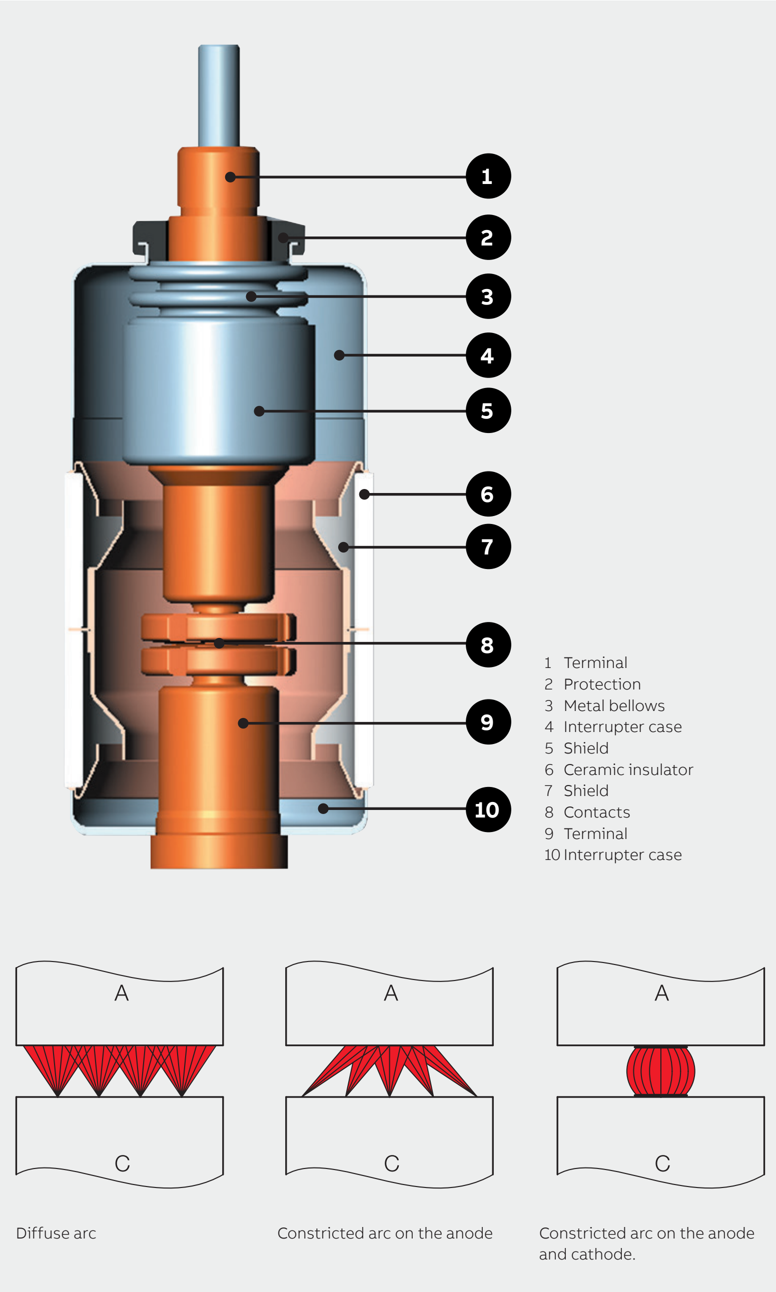


Fig. 3.5

Special contact shapes able to produce radial magnetic fields in the arc region were consequently designed. The magnetic field obliges the arc to move continuously over the entire contact area so as to prevent excessive heating and significant localized wear.
A similar solution for breaking higher current uses an axial magnetic field to spread the arc over the widest possible contact area.
ABB vacuum bottles feature specially shaped spiral contacts able to generate a radial magnetic field. The arc is pushed over the circumference and auto-generates the radial magnetic field which acts tangentially, forcing the arc to rotate around the axis of the contact (figura 3.6). This limits erosion to the minmum and ensures a controlled breaking process even at the higher temperatures. When the current crosses zero, the temperature drops and the vapors quickly condense on the shield, thereby restoring the dielectric strength between the contacts in just a few microseconds.

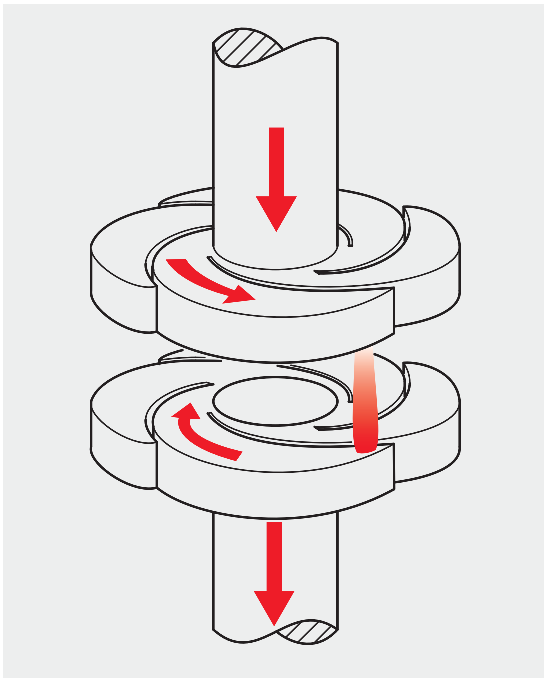


Fig. 3.6

3. The medium voltage circuit breaker

3.2 Drives

3.2.1 The spring drive

The stored energy spring drive has been optimized to provide the circuit breaker poles with the energy they need during the operations, so as to avoid contact bounce or excessive stress which would limit the mechanical life of the circuit breaker. The energy for the operations is provided by specific preloaded springs, which can also be loaded in the manual mode using the charging lever, or automatically by the motor.

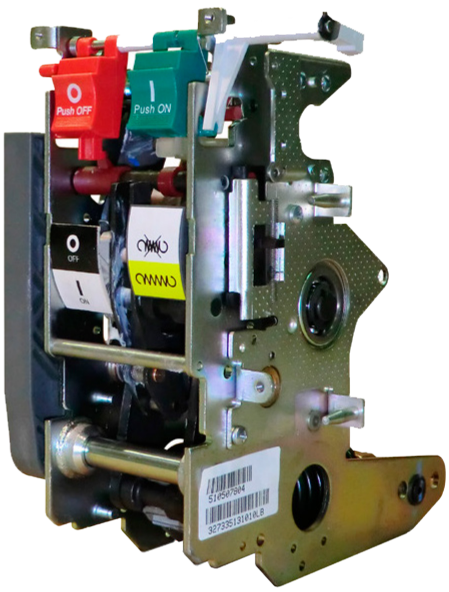


Fig. 3.7: the EL drive used for the vacuum circuit breaker family

The circuit breaker can be opened and closed either mechanically, using opening and closing pushbuttons, or electrically by means of coils. The springs are sized not only to ensure that there is enough energy for the closing operation, but also for charging the opening spring for the next circuit breaker opening operation.

The drive must also ensure that distribution circuit breakers have the operating sequence required for auto-reclosing (O - 0.3 s – CO), normally followed by a further CO for which it is necessary to at least wait for the springs to reload (15 s).

In the case of vacuum circuit breakers, the dielectric properties of the vacuum allow very short distances between contacts to be obtained. The maximum distance in a 12 kV vacuum bottle is just 10 mm. In addition to this, the exposed conductive part of the contacts is extremely small. The result is that in vacuum circuit breakers, the force required for the operation is less than that in circuit breakers based on other breaking techniques. This means that the drives can be more compact, with a normally longer mechanical life.

Figure 3.9 illustrates a very compact drive structure in a vacuum circuit breaker:

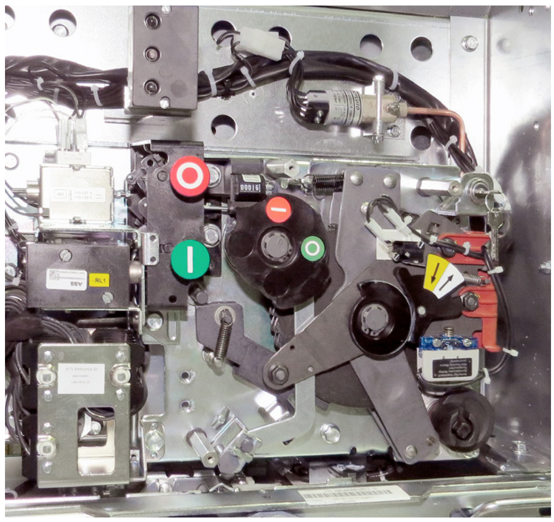
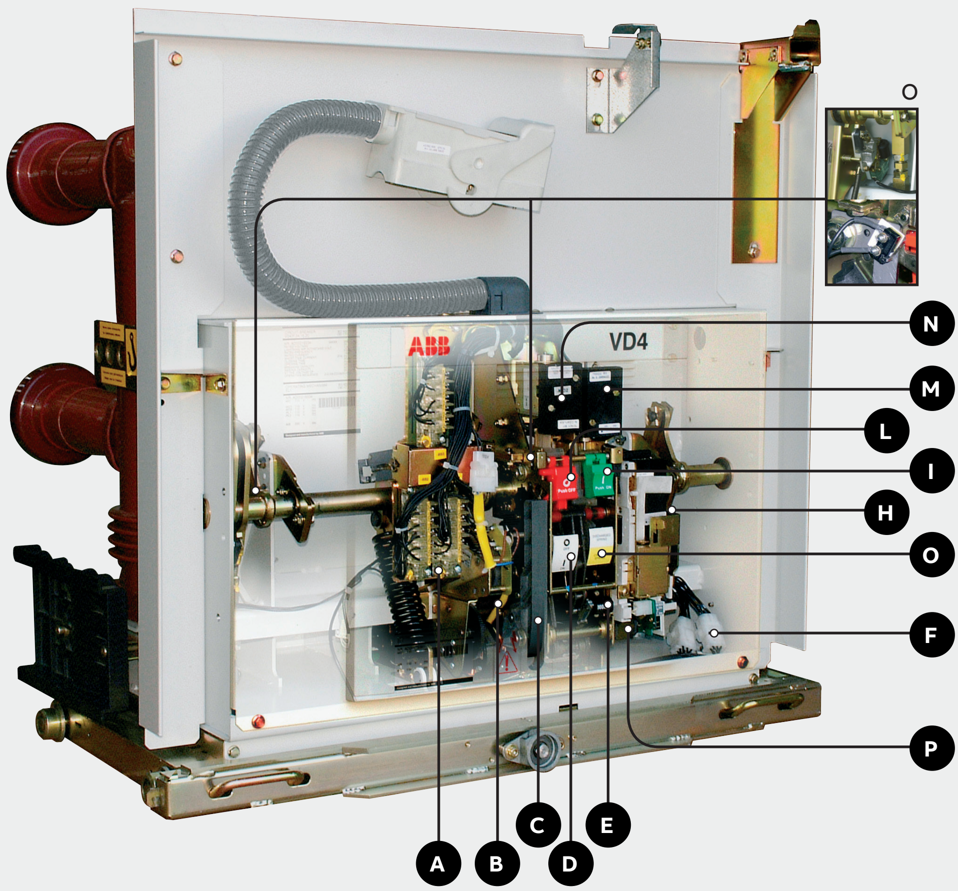


Fig. 3.8: the ESH drive used for the SF_6 circuit breaker family



Circuit breaker drive
A Auxiliary contacts open/closed
B Gearmotor for charging the closing springs
C Built-in lever for charging the closing springs
D Mechanical signaling device for circuit breaker open/closed
E Mechanical operations counter
F Plug-and-socket connectors for electrical accessories in the truck
G Signaling device for closing spring charged/discharged
H Service releases
I Closing pushbutton
L Opening pushbutton
M Operating mechanism locking electromagnet
N Additional shunt opening release
O Transient contact
P Contacts for signaling spring charged/discharged

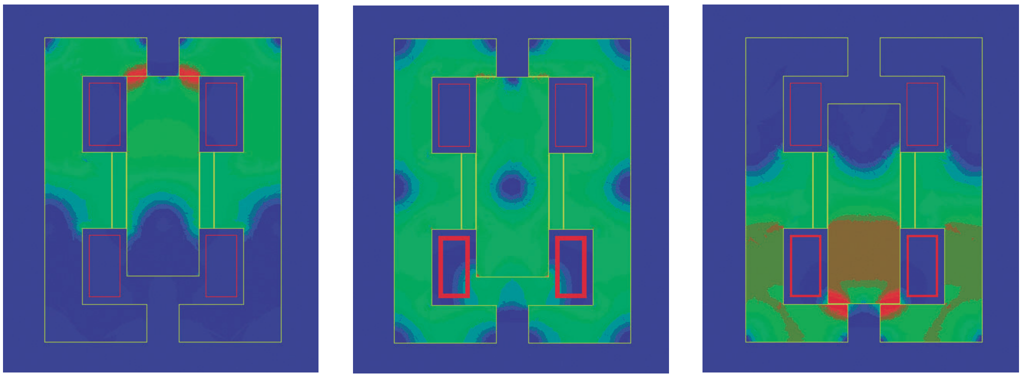
Fig. 3.9

3. The medium voltage circuit breaker

3.2.2 The magnetic drive

The function that the drive of a circuit breaker must perform is basically very simple: move the contacts from the closed position to the open position or vice versa and, once the final position has been reached, ensure that the contacts remain in that position until the next command is received. Fundamentally, it is therefore a simple bistable actuator. The first solution has been, and still is, a precharged spring operating mechanism with mechanical latching. However, thanks also to the opportunities offered by power electronics, new, more flexible and easily controllable solutions like the magnetic actuator have been developed.

Figure 3.12 shows how simple this mechanism is and how few components it contains. These include a true magnetic actuator, capacitors which store the energy required to activate the electromagnets for a complete open-close-open cycle, an electronic module which controls the entire circuit breaker and can receive and transmit command and control signals, and sensors, which determine the exact position of the circuit breaker. A self-diagnosis function completes the system, even though the actuator can perform up to 100,000 operating sequences for circuit breakers with up to 25 kA breaking capacity at 1250 A rated current.



a) Magnetic latching in end of travel position.

b) Magnetic latching and action of the magnetic field of a coil.

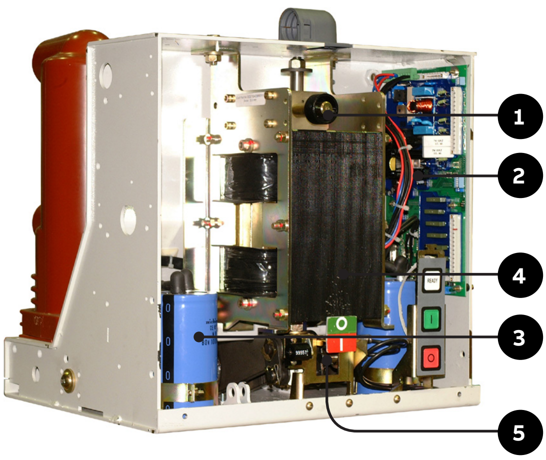
c) Moving keeper in opposite position and end-of-travel magnetic latching.

Fig. 3.10

Fig. 3.11

This consists of a combination of electromagnets, to actuate the command and permanent magnets to stably maintain the position reached (figure 3.10 and 3.11).

Vacuum circuit breakers can be equipped with this mechanism and are kept in the open or closed position by permanent magnets without any external energy. Change of state is commanded by supplying electric current to the electromagnets. The energy provided is controlled by the electronic part, which modulates it to suit the type of circuit breaker. The result is an extremely simple, low-maintenance mechanism with the fewest possible components.



1 Manual emergency opening device
2 Control board
3 Capacitor
4 Magnetic actuator
5 Position sensor

Fig. 3.12

3.2.3 The motor operator

The utlimate frontier in the field of circuit breaker drives is the version with “brushless” servomotors. In this type of drive, each pole is associated with a motor which performs the opening and closing operations. The motors are controlled by an electronic unit.
The architecture of this type of drive is illustrated in figure 3.13.

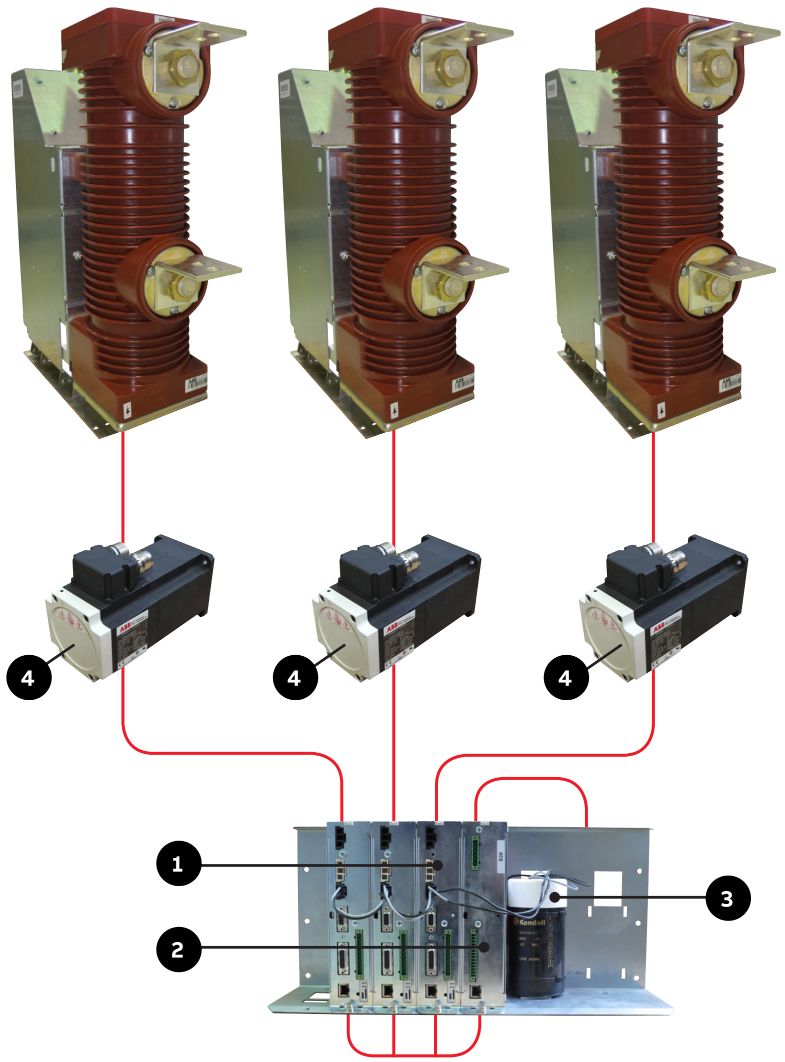


Fig. 3.13

The electronic control unit (1) is built into the device and pre-calibrated in the factory. It consists of three modules, each of which controls its own servomotor (4). The control unit also contains a feeder module (2), which supplies the three previous modules and charges the actuation capacitor (3). The purpose of the capacitor is to ensure the motors receive power even in the absence of the auxiliary supply. This architecture allows the three poles to be controlled independently, depending on the required application. The first module normally acts as “master” and the other two as “slaves” so as to function in a coordinated way. The control unit also provides diagnostic functions for the drive, which include:

- regular monitoring of the state of the cinematic chain, in the closed position, by means of tiny movements to check torque, speed and position every 24 h. This procedure is important for checking the state of the actuation chain before the command is imparted since it ensures a maximum level of reliability for the operation;
- complete control of the movement immediately after the operation has terminated, by checking the position, speed and torque of the servomotors so as to inform the user about the way in which the operation has been performed;
- continuous monitoring of the state of the servomotors by checking the wiring and windings to ensure that the servomotors are always fully functional;
- regular inspection of the state of the capacitor by checking the voltage, so as to ensure that the capacitor is always charged and thus able to supply the servomotors with power when necessary;
- continuous monitoring of the state of the actual control unit by means of self-testing functions.

Further diagnostic functions monitor the pole and the operating modes of the apparatus.

3. The medium voltage circuit breaker

The drive integrated into the apparatus is illustrated in figure 3.14.
Thanks to its high degree of flexibility and the extremely precise control of pole movement, this innovative type of drive can be expected to open the floodgates to numerous interesting applications, impossible to achieve with the previous technologies.

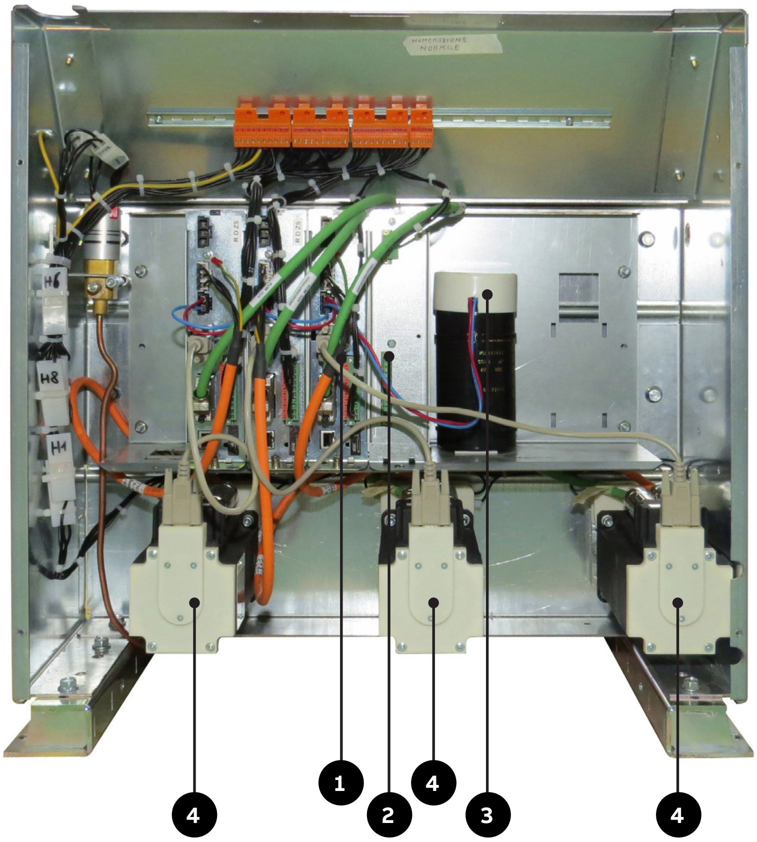
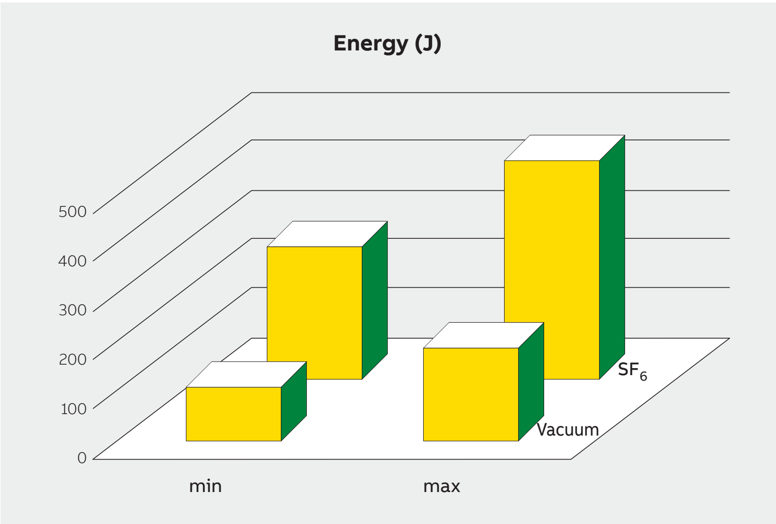


Fig. 3.14



3.3 Switching devices

Generally speaking, the structure of a circuit breaker, whether it is the SF_6 or vacuum type, comprises a breaking part, insulating medium, conductors, insulators and the drive. Besides a different breaking part, the breaking medium may lead to other differences in the construction of the circuit breaker: for example, while SF_6 can provide both the breaking and insulating medium, vacuum is always enclosed in the ceramic "bottle" while the insulation is made of other materials (solid or gas insulation). Another characteristic that may lead to different sorts of construction is dissipation of the heat produced by the flow of current, since SF_6 has an excellent coefficient of heat exchange by convection and this encourages dissipation while, in the case of vacuum, heat transmission takes place solely by conduction through the contacts. This means that high rated currents are easily reached with SF_6 circuit breakers compared to vacuum circuit breakers. Lastly, the energy required to move the contacts in SF_6 circuit breakers is higher than in vacuum circuit breakers and this affects the size of the drive.

Use of breaking techniques and the drives described in the previous chapters allows uniform families of apparatuses to be developed, as described further on. Current limiters based on a special use of fuses do not fall within this context since they are considerably different and are discussed in section 3.3.6.

3.3.1 Vacuum and SF_6 circuit breakers

Vacuum circuit breakers with precharged spring drives and magnetic drives, and SF_6 circuit breakers with precharged spring drives both belong to this extensive family.
Circuit breakers for primary and secondary distribution purposes conform to Standard IEC 62271-100 High-voltage switchgear and controlgear – Part 100: Alternating-current circuit breakers, while those designed for operating and protecting generators conform to Standard IEC/IEEE 62271-37-013, High-voltage switchgear and controlgear – Part 37-013: Alternating-current generator circuit breakers. The range also includes versions that conform to ANSI/IEEE Standards (ANSI/IEEE C37.04-C37.06-C37.09).
The vacuum circuit breaker family includes the ADVAC, AMVAC and VMAX/A series, specifically developed for the North American market to ANSI Standards, and the VMAX, VD4 and VM1 series for markets where compliance with the IEC Standards is required. Lastly, there is one single series of SF_6 circuit breakers called HD4 (table 2).

Characteristics		ADVAC	AMVAC	VMAX/A	VMAX	VD4	VM1	HD4
Breaking capacity	Max 40 kA and less	•	•			•	•	•
	Max 50 kA	•	•			•	•	•
	Max 63 kA	•						
	ANSI tested	•	•	•	•		•	
	IEC tested				•	•	•	•
	UL approved	•	•	•	•		•	
Type of circuit breaker	Withdrawable	•	•	•	•	•	•	•
	Fixed	•	•		•	•	•	•
Interruption medium	Vacuum	•	•	•	•	•	•	
	SF_6 gas							•
	Interrupter embedded in the pole	•	•			•	•	•
Drive	Spring type	•		•	•	•		•
	Magnetic		•				•	

Tab. 2

Fig. 3.15

Fig. 3.16

The ADVAC series comprises a series of vacuum circuit breakers with "bottle" embedded in the pole and drive with preloaded springs for rated voltage up to 15 kV.
The typical application is energy distribution in markets where ANSI regulations are applied, with undoubted advantages as to modularity and reliability. The current ranges from 1200 to 3000 A, with breaking capacities from 25 kA to 63 kA (figure 3.15).

The AMVAC series is also a range of vacuum circuit breakers with embedded "bottle", but features the innovative magnetic drive as a solution when a very high number of mechanical operating sequences are required and for applications where ANSI Standards are applied and heavy duty service is involved. Rated voltage reaches 27 kV, with rated current up to 3000 A and breaking capacities up to 50 kA (figure 3.16).

3. The medium voltage circuit breaker

Fig. 3.17

Vmax circuit breakers are the simplest and most compact breakers in the vacuum circuit breaker family. They are designed for applications in both ANSI and IEC markets when the performance required is not particularly severe. These circuit breakers feature a traditional drive with preloaded springs. The voltage values range from 12 to 17.5 kV for the IEC version and up to 15 kV for the ANSI version. Rated current is up to 1250 A with up to 31.5 kA breaking capacity (figure 3.17).

Fig. 3.18

The VD4 vacuum circuit breaker family VD4 (figure 3.18) is certainly the most successful ABB circuit breaker since there are several hundreds of thousands in service. This series features vacuum "bottles" embedded in the pole and has a drive with preloaded springs. One of the typical applications for this circuit breaker is electricity distribution in IEC markets, even in heavy duty conditions.

Fig. 3.19

There is also a version for secondary distribution purposes with a lateral mechanical drive (figure 3.19).

Fig. 3.20

Rated voltage is up to 40.5 kV. Rated current ranges from 630 to 4000 A with breaking capacities up to 50 kA.
There is also a series for protecting generators conforming to Standard IEC/IEEE 62271-37-013 “High-voltage switchgear and controlgear – Part 37-013: Alternating-current generator circuit breakers. The series is called VD4G (figure 3.20) and has passed all the tests required by the Standard as to short-circuit current breaking with up to 130% degree of asymmetry, breaking of fault currents due to closing in phase difference conditions and rising fronts of the transient recovery voltage (TRV) that are more severe than those envisaged by IEC 62271-100 for normal circuit breakers.

Fig. 3.21

VM1 series circuit breakers feature the innovative magnetic drive. They are similar to the AMVAC series but designed for use in the IEC markets (figure 3.21). Here again, the aim is to provide a solution in situations where a high number of mechanical operating sequences are required and for applications where heavy duty service is involved. Rated voltage reaches 24 kV, with rated current up to 4000 A and breaking capacities up to 40 kA.

Fig. 3.22

One of the possible applications for this breaking technique is rapid switching between two different energy sources if one of the two develops a fault. Previous solutions involved costly components but now, thanks to use of the magnetic actuator, circuit breaker operating time can be reduced to the minimum and, with the aid of purpose-made electronics, switching can be performed in less than 40 ms. Known as SUE 3000, the ABB system can resolve most of the problems due to loads sensitive to the lack of voltage, thereby guaranteeing continuity of service (figure 3.22).

Fig. 3.23

Lastly, there is a series of SF_6 circuit breakers called HD4, featuring a drive with preloaded springs (figure 3.23). This SF_6 circuit breaker provides an excellent performance, especially when it comes to reducing switching overvoltage. In accordance with reference Standard IEC 62271-100, the apparatus is classified as a “sealed pressure system” since operations involving the gas are not required during its service life, in this case for 30 years. This ultra-reliable circuit breaker is available for rated voltage up to 40.5 kV, current values up to 3600 A and breaking capacities up to 50 kA

Fig. 3.24

As in the case of VD4, there is also a version for secondary distribution purposes with a lateral mechanical drive (figure 3.24).

3. The medium voltage circuit breaker

3.3.2 Switch-disconnectors

These apparatuses conform to Standards IEC 62271-102 High-voltage switchgear and controlgear – Part 102: Alternating current disconnectors and earthing switches, IEC 62271-103 High-voltage switchgear and controlgear – Part 103: Switches for rated voltages above 1 kV up to and including 52 kV, and IEC 62271-105 High-voltage switchgear and controlgear – Part 105: Alternating current switch-fuse combinations for rated voltages above 1 kV up to and including 52 kV.

Substantially two breaking techniques are used in switch-disconnectors: air and SF_6. Performance being equal, the gas solution features versions that are more compact. This is why efforts in terms of development have been concentrated on this breaking technique. This latter is therefore the technique that will be analyzed more fully. There are three types of enclosures: versions completely made of insulating material, fully metal enclosures and ones made of both insulating material and metal.

One of these latter is illustrated in figure 3.25 and is the innovative, latest generation solution. This sort of enclosure is formed by two half-shells. The upper one is made of insulating epoxy resin. This version allows the distances towards the walls of the switchgear to be reduced to the minimum and

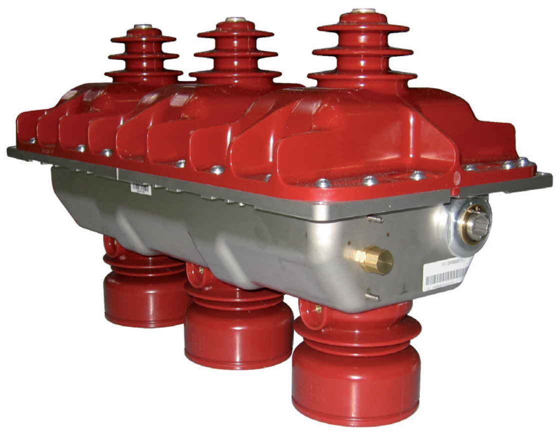
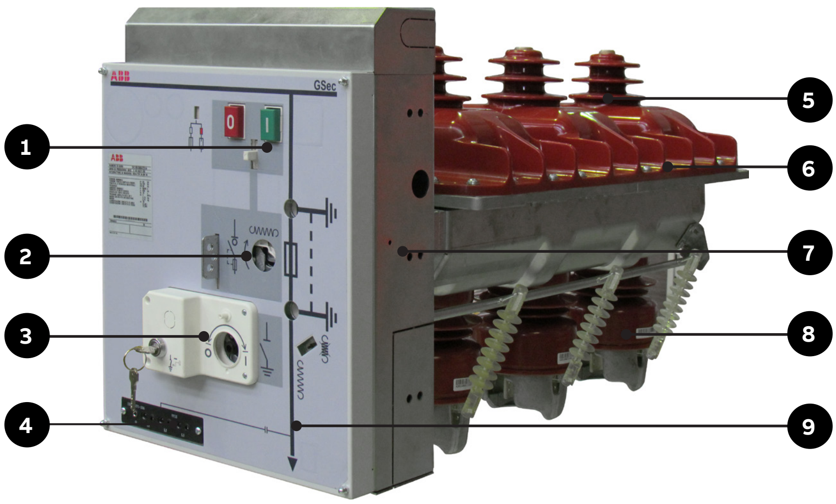


Fig. 3.25



1. Closing and opening pushbuttons
2. Lever seat for line operation
3. Lever seat for earth operation
4. Voltage signaling lamps (if applicable)
5. Upper insulators
6. Enclosure (power part)
7. Drive housing
8. Lower insulators
9. Mimic diagram

Fig. 3.26

thus enables particularly compact enclosures to be obtained. The lower half-shell is made of stainless steel and allows the busbar compartment to be segregated from the cable compartment of the switchgear by means of metal partitions, enabling the two compartments to be earthed and the personnel to work in the utmost safety. Switchgear classified as PM ((Metallic Partitions) between busbar and cable compartments can be designed thanks to this solution. The ABB GSec switch-disconnector illustrated in figure 3.26 conforms to this construction philosophy. In accordance with Standard IEC 62271-1, the apparatus is classified as a “sealed pressure system” since operations involving the gas are not required during its service life, in this case for 30 years. Low maintenance costs are an important feature of this switch-disconnector thanks to the high number of mechanical operating sequences (class M2=5000 operations with single-spring drive and class M1=1000 operations with double spring drive) and electrical operating sequences (class E3 on the line contacts with 5 closing operations with short-circuit current and 100 breaks at rated current). Integration of capacitive sockets and cable connections on the lower insulators improve the compact size of this device to an even further extent. The switchgear can be fitted with a VPIS (Voltage Presence Indicating System), which signals the presence of voltage in the cables connected to it, as prescribed by Standard IEC61958.
Mechanical signaling of the position of the apparatus (figure 3.27) is another of the measures in favour of safety, where signaling is directly connected to the drive shaft of the apparatus itself (as in Annex A of IEC 62271-102).

3.3.3 Multifunction apparatus
This apparatus conforms to the following Standards: IEC 62271-100 High-voltage switchgear and controlgear – Part 100: Alternating-current circuit breakers and to IEC 62271-102 High-voltage switchgear and controlgear – Part 102: Alternating current disconnectors and earthing switches.
Integrated, very compact solutions have recently been developed combining the functions of three different devices in the same apparatus, i.e. the functions of circuit breaker, feeder disconnector and earthing switch. This integrated solution was designed for use in medium voltage switchgear for secondary distribution.

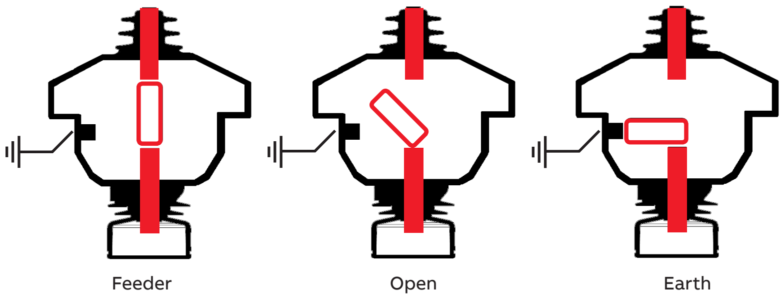


Fig. 3.27

3. The medium voltage circuit breaker

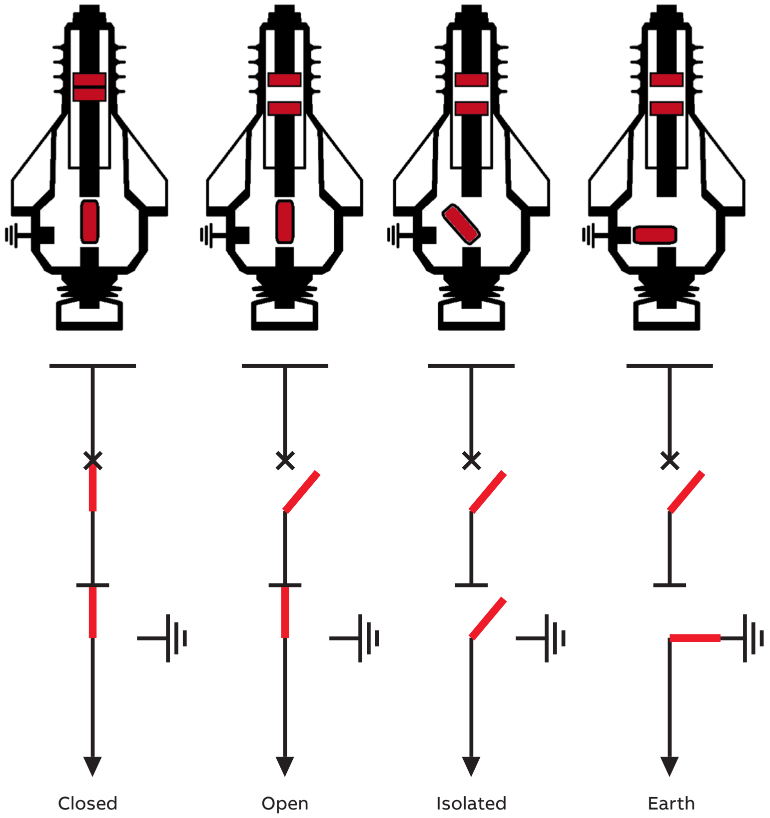
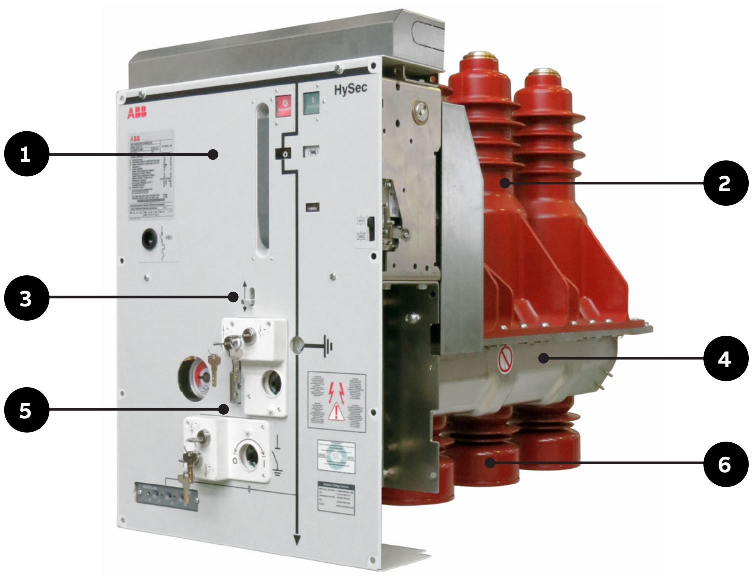


Fig. 3.28



1. Operating mechanism of circuit breaker part
2. Resin enclosure
3. Mechanical interlock between feeder disconnector and earthing switch
4. Lower part in stainless steel
5. Operating mechanism of feeder disconnector and earthing switch
6. Lower insulators with integrated capacitive sockets

Fig. 3.29

As can be seen in figure 3.28, the upper part includes the circuit breaker function and has a vacuum interrupter housed in its upper half-shell . The lower half-shell houses a feeder disconnector (so as to isolate the busbar cables) and an earthing switch (to earth the cables themselves). Use of vacuum interrupters to break short-circuit currents isolates the arcing chamber of the circuit breaker from the remaining environment, filled with SF_6, for disconnector isolating and operating purposes. Vacuum interruption also ensures high electrical performance.
ABB has also developed the HySec multifunction apparatus illustrated in figure 3.29. Similarly to GSec, the stainless steel lower part allows the cable compartment to be segregated from the busbar compartment by means of metallic partitions, thereby guaranteeing maximum safety for the operator during installation or maintenance work while ensuring high continuity of service. And speaking of safety, the interlocks between the various functions are part of the apparatus itself and are therefore factory-tested.
Internal insulation is provided by the SF_6 gas. This, together with the insulating epoxy resin in the upper part, creates an extremely compact device, just 500 mm in depth, which also provides excellent electrical performance with just 300 g of SF_6.
The apparatus is extremely flexible, since it can be used as both an incoming and outgoing unit. The whole device is intrinsically very reliable thanks to the limited number of components that characterize this integrated solution and the fact that it is tested as a single apparatus. In accordance with Standard IEC 62271-1, the apparatus is classified as a “sealed pressure system” since operations involving the gas are not required during its service life, in this case for 30 years. Integration of capacitive sockets and cable connections on the lower insulators improve the compact size of the device to an even further extent.

3.3.4 Synchronous switching devices

These apparatuses are classified by Standard IEC 62271-103 High-voltage switchgear and controlgear – Part 103: Switches for rated voltages above 1 kV up to and including 52 kV, as "special purpose switches" for switching class C2 capacitor banks. Tests for switching capacitive currents have been conducted in accordance with Standard IEC 62271-100, since the test conditions defined by this Standard are more demanding than IEC 62271-103. These tests are comparable to those required by Standard IEEE C37.09a.

Even though modern circuit breakers are designed to minimize the possibility of multiple electric arc restrikes, the statistical probability of occasional restrikes in the case of frequent switchings of capacitive loads exists. Use of traditional methods for limiting the effects of transients generated in this way (such as filters or surge arresters) is unable to completely resolve the problem and in any case, does not deal with its root cause. This risk can be eliminated by adopting controlled switching techniques, such as synchronized closing or opening.

In practice, the closing and opening operations of the switching apparatus are synchronized so that the contacts make or break in the optimal instant, in relation to the phase angle.

In these cases, ABB propores capacitor switch DS1 (figure 3.32). With reference to figure 3.30, before the capacitor bank is energized, the apparatus is in situation a), with the switch open and the bank isolated from the grid. After this, as shown in b), the moving contact connects the diodes and the bank is naturally supplied at voltage zero. Lastly, as shown in c), after a quarter of a cycle, the moving contact closes the switch and allows current to flow without losses.

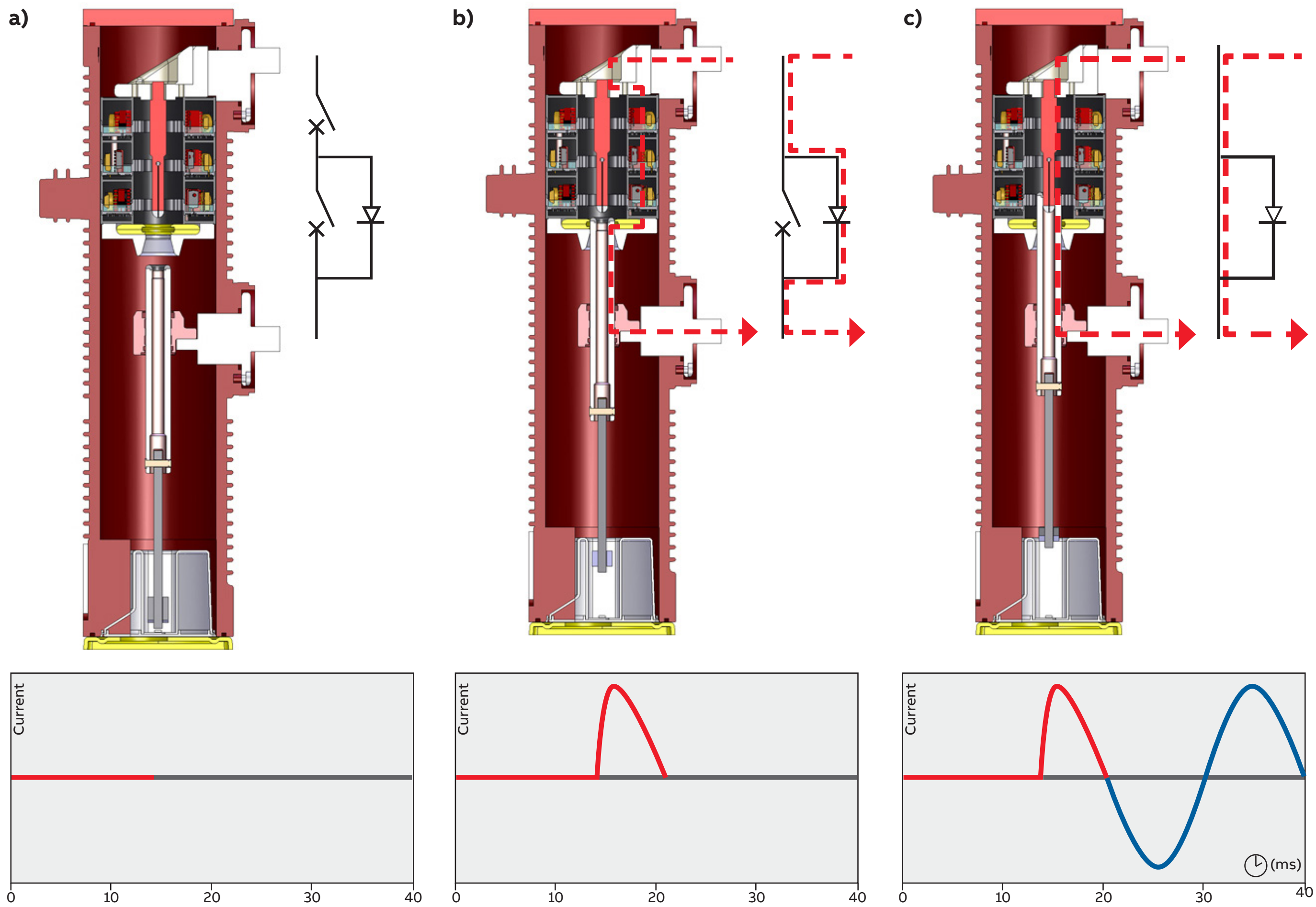


Fig. 3.30: complete closing of DS1

3. The medium voltage circuit breaker

Thus the apparatus is able to supply the capacitor bank at the correct instant, thereby minimizing transients caused by the switching operation. Similarly, the capacitor bank is opened without causing any disturbance in the grid. Figure 3.3 shows the switch initially in the closed position, with the bank connected to the grid (a). After this, in (b), the moving contact connects the diodes, which begin to conduct. Half a cycle afterwards, the diodes shut off the passage of current at zero and are finally disconnected with the main contacts (c) open.

Obviously, all the poles must be singly and independently operated by a similar number of actuators so that each pole can be opened or closed in the most appropriate point of the current or voltage of the relative phase.
The energy dissipated in the arcing chamber is also reduced to the minimum, thereby allowing special solutions to be engineered.
In order to achieve this result, accurate control over the electrical quantities is required so as to synchronize the moment the contact switching operation terminates with current or voltage zero crossing in each phase.

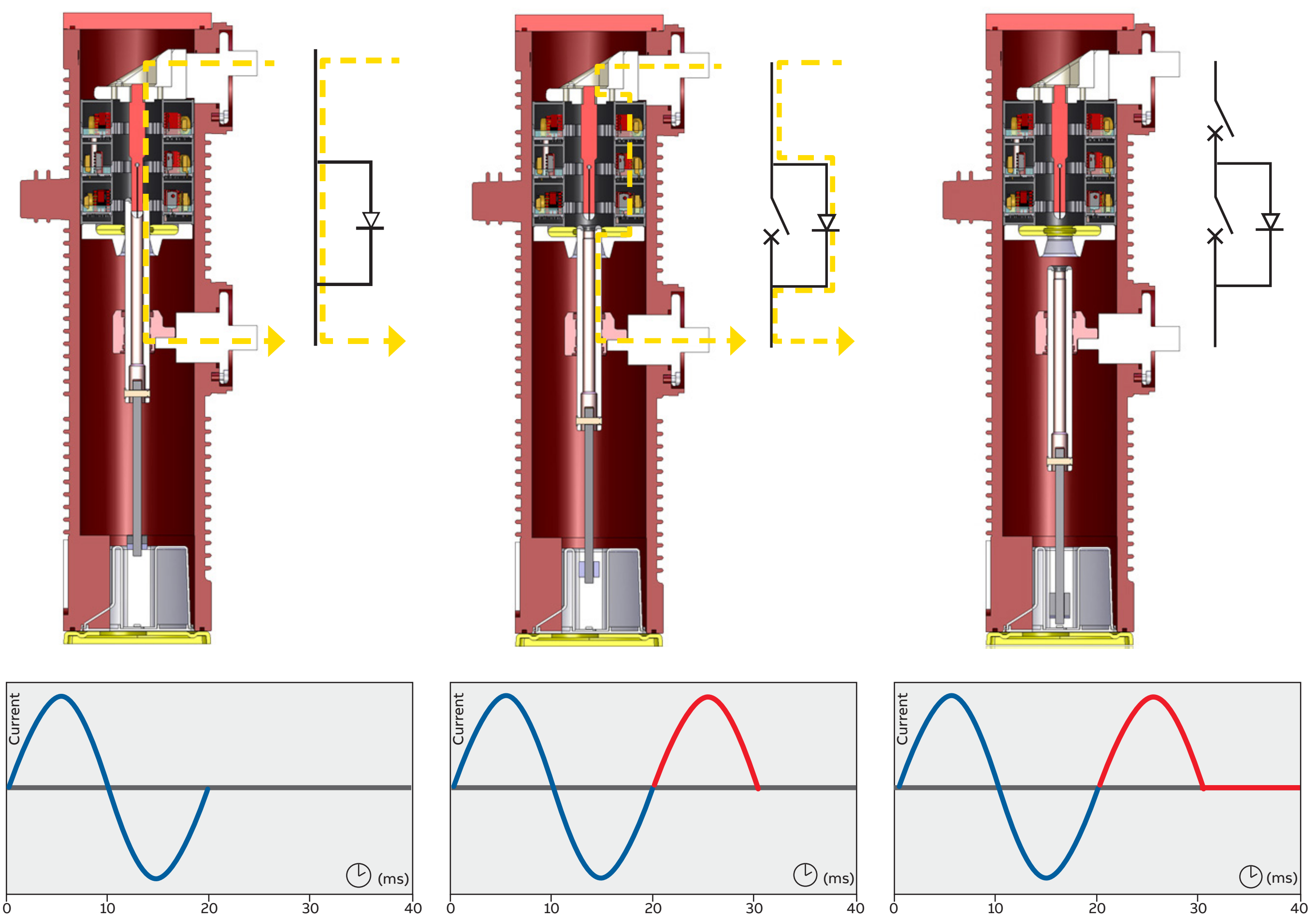


Fig. 3.31

Mechanical switching must be very precise, constant over time and independent of the changing environmental conditions and auxiliary supply voltage.
This is why use of the motor drive described in chapter 3.2.3, with three motors controlled by the controller, is required.
The same electronic system monitors voltage zero crossing with great precision and synchronizes the operation of the device. There are many, very interesting applications for this device. Its natural use is for switching capacitor banks, but any other application that can benefit from synchronized operation can be developed thanks to the flexibility of the electronic controller.

a)

b)

Fig. 3.32

3.3.5 Contactors

These apparatuses conform to Standards IEC 62271-106 High-voltage switchgear and controlgear – Part 106: Alternating current contactors, contactor-based controllers and motorstarters.
Besides being capable of making, carrying and breaking currents under normal circuit conditions, including operating overload conditions, contactors differ from the other switching apparatus categories since they normally have a stable hold position (open position) while the alternative position (closed position) is maintained by an auxiliary power supply or, in certain cases, by a mechanical latch. Not having to “worry” about short-circuit current interruption has allowed contactors able to provide a very high number of mechanical and electrical operating sequences to be engineered. This feature makes the contactor the ideal device for switching loads such as motors, characterized by very frequent starts. The contact material in vacuum contactors must therefore ensure frequent operating sequences and very low chopping current, since the device would typically interrupt normal currents and very probably inductive currents as well. The vacuum interrupters for contactors are consequently different from those of circuit breakers both in their shape and the material with which the contacts are made.

3. The medium voltage circuit breaker

The breaking technique and application in the electrical installation differentiate the contactors from each other. In medium voltage installations, the breaking technique used is that of vacuum, while in low voltage situations the principal dielectric is air. When it comes to the application, Standard IEC 62271-106 envisages two categories: inductive load switching (category AC, next table) and capacitive load switching (class C1 or C2).

Table 3 - Categories of use

Category	Typical application
AC-1	Non-inductive or slightly inductive loads, resistance furnaces
AC-2	Starting and plugging - slip-ring motors
AC-3	Starting and switching off motors during running - squirrel-cage motors
AC-4	Starting, plugging and inching - squirrel-cage motors

Each category features certain current, voltage and power factor values.
The Standard envisages two capacitive load switching classes. Class C1 with a low probability of restrike during capacitive current breaking and class C2, with a very low probability of restrike (in any case, there must be no restrikes during the tests).

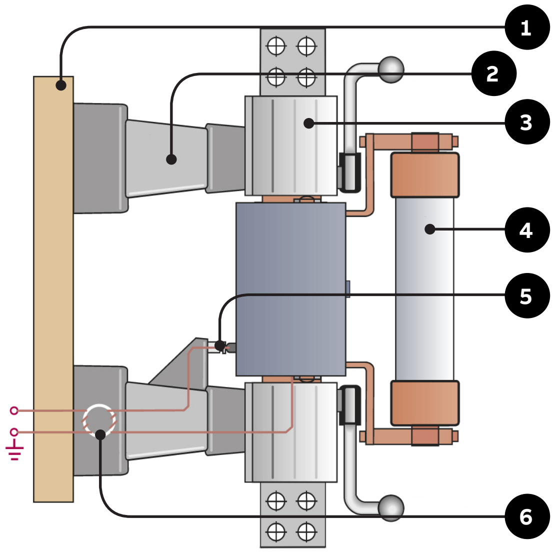
Mechanical operating sequences are expressed in millions of operations according to preferential values 0.01 - 0.03 – 0.1 – 0.3 – 1 – 3 while when it comes to electrical operating sequences, the manufacturer must declare, for each class of use, the maximum number of operations without repairs or replacements.
ABB proposes the V-Contact VSC vacuum contactor, the fixed and withdrawable versions of which are illustrated in figures 3.33 and 3.34. VSC features a permanent magnet drive to hold the open or closed position, since one of the problems with the majority of contactors, which are not bistable devices, is ensuring sufficient energy to maintain the closed position. This allows the contactor to act like a bistable device without consuming energy unnecessarily. The energy for the drive is stored in a capacitor and is not supplied directly by the auxiliary power source. This ensures fade-free contactor switching over time. Thus the permanent magnet drive technique, already broadly researched and used for circuit breakers, is also applied by ABB to contactors. The mechanical simplicity of the solution and the low energy required allow as many as two million mechanical operating sequences to be obtained. The chopping current is very limited, thus the overvoltage upon interruption becomes negligible.

Fig. 3.33

Fig. 3.34

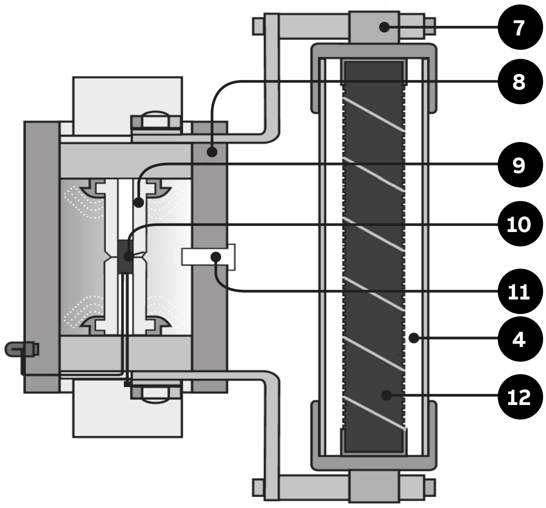
3.3.6 Current limiters

These devices conform to Standard IEC 60282-1 “High-voltage fuses - Part 1: Current-limiting fuses. Current limiters were developed during the second half of the '50's and are able to rapidly break short-circuit currents, thereby reducing their effects on the components of an electrical installation. These devices can detect and interrupt short-circuit current at the very first rise by acting within a few milliseconds. This device basically consists of a part that supports the limiting insert (figure 3.35), the limiting insert itself (figure 3.36), a protection current transformer and an electronic measuring and tripping device. If a fault occurs, the electronic device transmits an impulse, via a transformer in the supporting isolator, to the explosive charge in the insert. Following a small, controlled explosion, the main conductor interrupts and the current flows through the high breaking capacity fuse connected in parallel, blowing of which first limits and then interrupts the current the first time it crosses zero. The current is constantly monitored by the external electronic system, which measures the derivative of the current and is thus able to rapidly decide whether to trip the current limiter or not. In normal operating conditions, the combination of conductor and fuse in parallel allows losses to be kept to the minimum. In short, compared to other limiting devices, this solution keeps service losses down and efficiently limits short-circuit current on the load side. ABB has developed a device of this type called Is-Limiter. This device, which can also be supplied in its own panel on a withdrawable truck (figure 3.37), covers a wide range of voltage values from 750 V and 36 kV and current values from 1250 to 5000 A. I_s-limiter can be used for a wide variety of applications. The most interesting is when it is installed as a bus-tie between two busbar systems fed by two different sources, as illustrated in figure 3.38. If the fault involves one of the two power sources, I_s-Limiter trips at the very first current rise before the current is able to reach high levels.



1 Base
2 Insulator
3 Pole with clamping device
4 Fuse
5 Telescopic contact
6 Insulator with pulse transformer

Fig. 3.35: I_s-limiter support with insert for 12 kV, 2000 A



4 Fuse
7 Fuse indicator
8 Insulating tube
9 Bursting bridge
10 Explosive charge
11 Main conductor indicator
12 Fuse element

Fig. 3.36: I_s-limiter insert

3. The medium voltage circuit breaker

Fig. 3.37

The voltage in the part of the system not affected by the fault only drops for fractions of a millisecond at most. Consequently, all the loads continue to be supplied. As can be seen in the example, the device trips so fast that there is practically no contribution from the second supply source. Thus the switchgear can be sized for a lower short-current value.

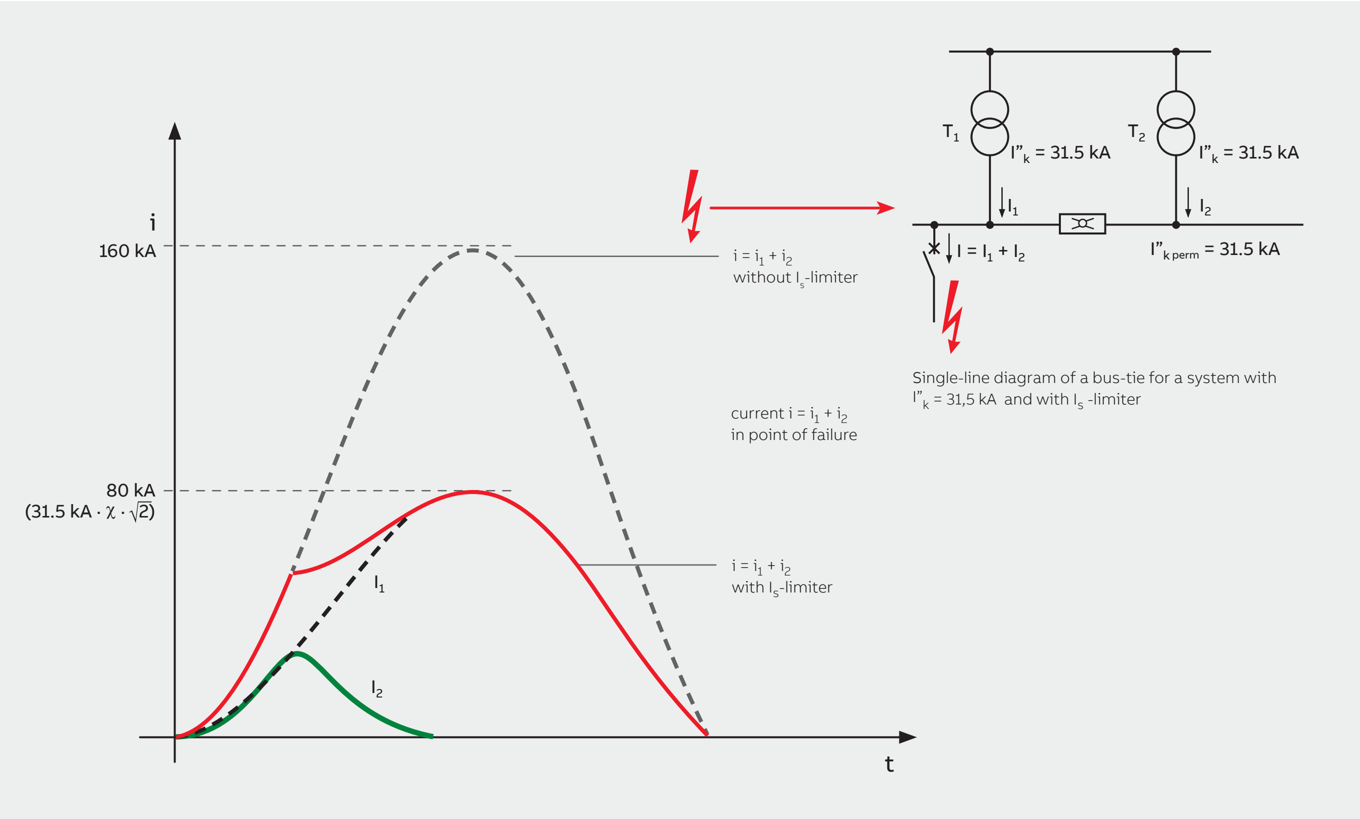


Fig. 3.38

4. Switching of fault currents and transient overcurrents

There are numberless situations in the installations in which circuit breakers may be obliged to operate and interaction with the components in the grid is a very important factor to consider.
Although circuit breakers are capable of breaking all loads up to the maximum short-circuit current, certain plant configurations can be particularly critical and hard on the circuit breaker and on the other components of the electrical system.

4.1 Opening operation

4.1.1 Short-circuit currents

Whichever breaking technique is used, when the behaviour of a circuit breaker that operates in a real circuit is analyzed, the first thing to consider is how the short-circuit current would proceed in the absence of the circuit breaker itself, i.e. as though the circuit breaker had been replaced by a conductor with negligible impedance. This current is known as prospective current. This is because an electric arc is generated during an interruption and, owing to its characteristics, introduces a further element of a transient nature into the circuit. This element modifies the current trend to an even substantial extent.
Thus, the prospective current depends exclusively on the parameters of the electrical circuit, as does the voltage that appears at the terminals of a circuit breaker pole after a current interruption. However, the voltage that appears on the terminals of a pole during an interruption is much more important for the circuit breaker since it is of a transient nature (oscillatory or not) and also depends on the characteristics of the circuit breaker itself. As already explained, this voltage is known as V_r Transient Recovery Voltage (TRV).
The breaking capacity of a circuit breaker is defined as the maximum prospective current the apparatus is able to break at a given voltage and in a given circuit. In other words, with a given TRV, which the Standard defines exactly for the purpose of standardizing the test conditions.

The circuit breaker must be able to break both symmetrical and asymmetrical prospective short-circuit current. An asymmetrical current consists of a symmetrical component superimposed on a direct component which decreases over time.
A simple electrical grid like the one illustrated in fig. 4.1 will now be considered. In normal conditions, normal load current passes through point A.

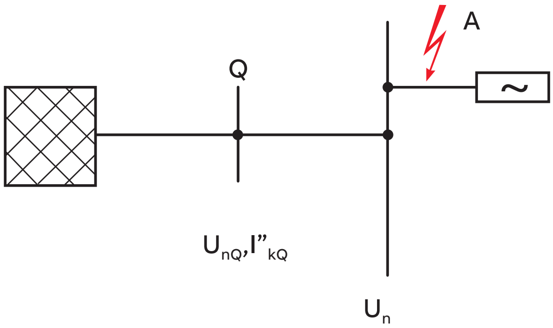


Fig. 4.1

When a short-circuit fault occurs, the current increases by two or three orders of magnitude and can be calculated by representing the grid with an equivalent circuit like the one shown in fig. 4.2, which allows the equivalent impedance to be calculated as seen from the point of failure:

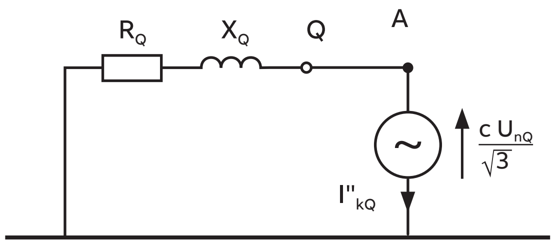


Fig. 4.2

where $Z_Q = c\,U_{nQ} / (\sqrt{3}\,I''_{kQ})$ with U_{nQ} as supply voltage value and I''_{kQ} as the initial short-circuit current of the supply grid. Factor "c" depends on the voltage of the system and takes the influence of the loads and the grid voltage variation into account. Since the circuit is basically inductive, reactance takes precedence over resistance R, which represents losses in the circuit, normally 5% - 10% of the reactance, thus:

$X_Q = 0.995\ Z_Q$

$R_Q = 0.1\ X_Q$

4. Switching of fault currents and transient overcurrents

Let us imagine that we are plotting a graph of the voltage and current trend in point A (fig. 4.3).

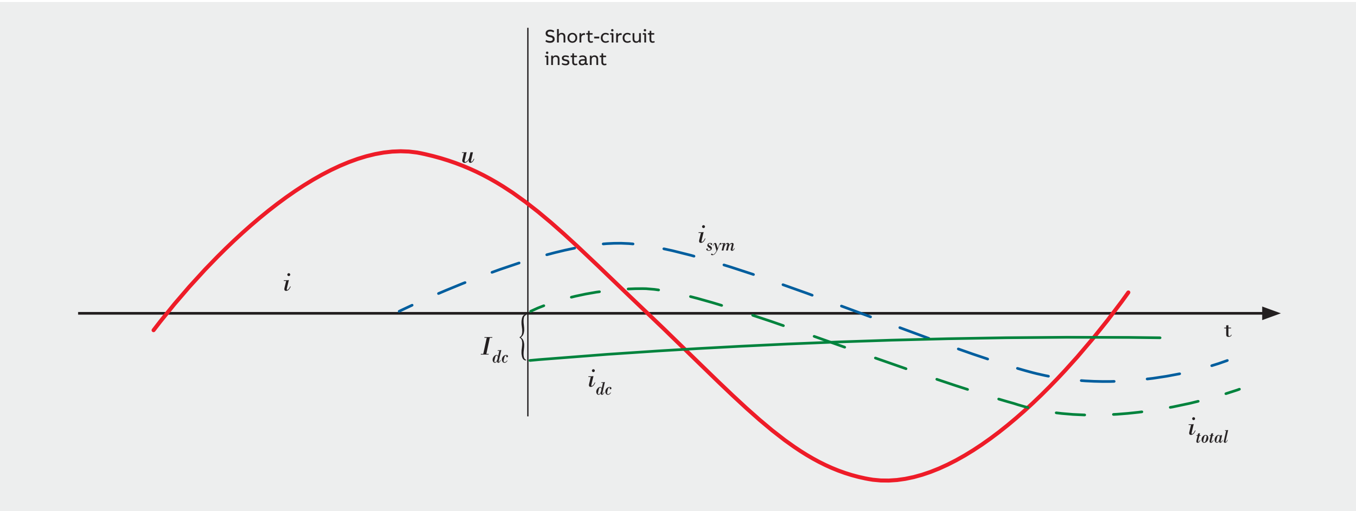


Fig. 4.3

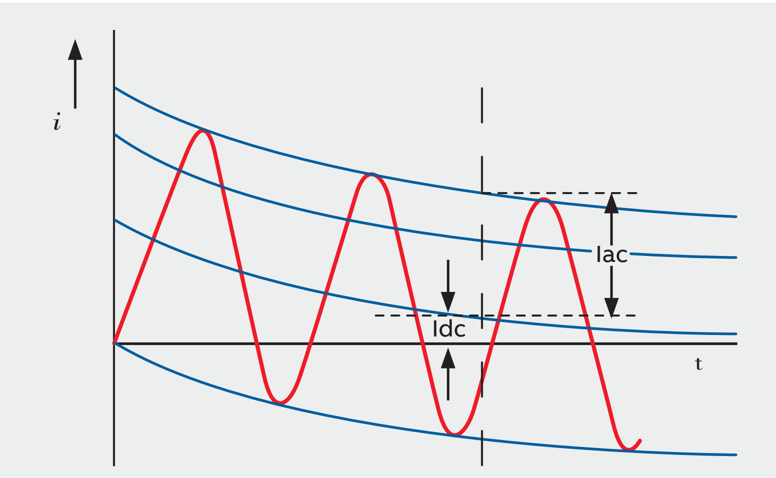


Fig. 4.4

Load current flows initially. This, being of a negligible entity compared to the short-circuit current, is represented by zero value. The instant in which a fault occurs, the current will tend to reach the symmetrical state value i_{sym}. Since the circuit is almost purely inductive, phase displacement will be about 90° and the current, since there can be no discontinuity, will also consist of a direct component, i_{dc} such that:

$$i_{total} = i_{sym} + i_{dc}$$

i.e., the value of the direct component will be the same as the symmetrical component but of the opposite sign, so as to allow discontinuity-free transition between load current and short-circuit.

The direct component will follow a decreasing trend over time

$$i_{dc} = I_{dc}\, e^{-t/\tau}$$

where t is the time from the beginning of the fault and τ the time constant of the circuit, equal to L/R. Standard IEC 62271-100 used a standard time constant τ of 45 ms, which covers cases where the point in which the circuit breaker is installed is sufficiently far from the generators which supply the grid. In such cases, when choosing the circuit breaker, all that needs to be done is to make sure that the breaking capacity is not less than the value of the symmetrical short-circuit current in the installation location.
In other cases, when the circuit breaker is installed near generators, the direct component can be much higher. In these cases, the short-circuit current could actually be without current zeros for a certain number of cycles.
The current asymmetry value at a certain instant is given by the percentage value of the direct component with respect to the peak value of the symmetrical current. With reference to the following oscillogram, the direct component

percentage can be easily calculated as shown below:

$$dc_{\%} = 100 \cdot \frac{I_{dc}}{I_{ac}}$$

I_{ac} is the peak value of the symmetrical component of the short-circuit current when the contacts open:

$$I_{ac} = \sqrt{2} \cdot I_{sym}$$

thus:

$$dc_{\%} = \frac{I_{dc}}{I_{ac}} = \frac{I_{dc}}{\sqrt{2} \cdot I_{sym}}$$

which results in the following:

$$I_{dc} = \sqrt{2} \cdot dc_{\%} \cdot I_{sym}$$

Asymmetrical short-circuit current is given by the following formula:

$$I_{asym} = \sqrt{I_{sym}^2 + I_{dc}^2}$$

As an example, we will consider an I_{sym} = 50 kA with a dc% = 30%. The result is:

$$I_{dc} = \sqrt{2} \cdot dc_{\%} \cdot I_{sym} = \sqrt{2} \cdot 0{,}3 \cdot 50 = 21{,}2 \text{ kA}$$

$$I_{asym} = \sqrt{I_{sym}^2 + I_{dc}^2} = 54{,}3 \text{ kA}$$

The percentage of the direct component a circuit breaker is called upon to break depends on time constant τ and is the value calculated the instant the contacts separate (i.e. at the moment the arc strikes).
As can be seen from the oscillogram, the direct component also contributes towards increasing the peak value of the current. This value is at its maximum when the short-circuit generates at voltage zero crossing. Although the probability of this happening is very low, it must still be taken into account when the components of the installation are sized.

In the worst case, the initial direct component will be:

$$I_{dc} = \sqrt{2}\, I_{sym}$$

The maximum peak value will occur half a cycle after, or at 50 Hz, 10 ms after. Supposing that the standard time constant τ = 45 ms, the result will therefore be:

$$I_p = \sqrt{2}\, I_{sym} \left(1 + e^{-\frac{10}{45}}\right) = 2{,}5\, I_{sym}$$

While at 60 Hz it will be:

$$I_p = \sqrt{2}\, I_{sym} \left(1 + e^{-\frac{8.3}{45}}\right) = 2{,}6\, I_{sym}$$

Standard IEC 62271-100 specifies the two previously mentioned values exactly, for the purpose of determining the making capacity of a circuit breaker. In addition, the Standard requires that factor 2.7 be used at both 50 Hz and 60 Hz for time constants exceeding 45 ms.

4.1.2 Interruption of the short-circuit current of generators

Generally speaking, compared to a fault supplied by the grid, a fault supplied by a generator is characterized by:

1. A symmetrical fault current which is normally lower than that supplied by the grid.
2. An alternating component, the amplitude of which decays as a function of the transient and sub transient time constant of the generator.
3. A direct component which, the moment the contacts of the circuit breaker separate, could be higher than the peak value of the alternating component.
4. The current could fail to cross zero for a certain time, as a result of the previous points.

This last is a very critical condition for circuit breakers, which can only break the current at zero crossing and which must therefore support the fault current and postpone the breaking action until the first zero following the decay of the direct component. However, electric arcs introduce a non-linear resistance which helps to reduce the direct component by decreasing the time constant.

4. Switching of fault currents and transient overcurrents

With reference to fig. 4.5, CB1 is the circuit breaker which could be affected by an interruption with delayed current zeros. The worst case is when the direct component has a high time constant thus, given that this equals $\tau = L/R$, in the point where the ohmic component is lower, i.e. as near as possible to the generator.

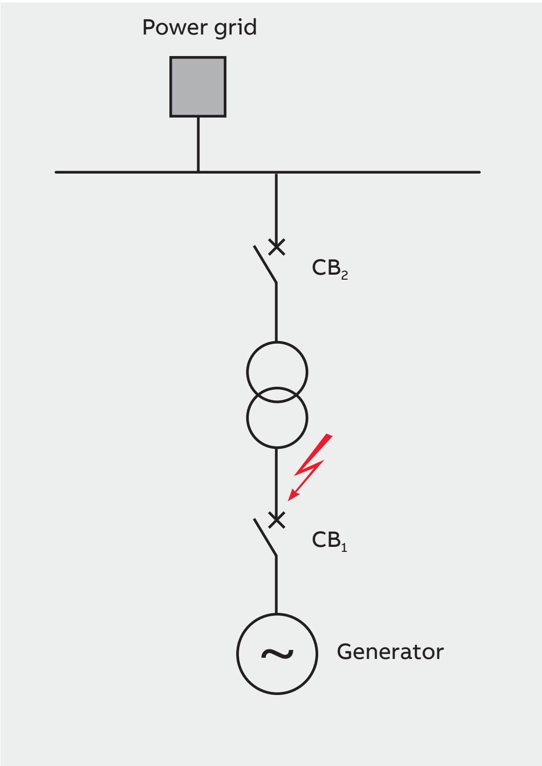


Fig. 4.5

In industrial installations supplied by overhead or cable transmission lines, the reactance of these elements reduces both the direct component and time constant.
Generally speaking, the moment in which the voltage on a phase is at zero is considered as a particular case of the beginning of a fault for faults between the circuit breaker and transformer. This means that the current in the corresponding phase has the maximum asymmetry. As explained previously, degree of asymmetry means the ratio between the direct component and the peak value of the alternating component determined by the current time diagram of the fault. While damping of the alternating component is given by the transient and sub transient time constants of the generator, damping of the direct component is given by armature time constant T_a. Thus the two components have different trends and in some cases, the symmetrical component of the fault current may decay at a faster rate than the direct component. If this were to happen, the value of the direct component could be higher than the peak value of the symmetrical component the moment in which the circuit breaker contacts separate. This would mean that the degree of asymmetry was over 100%, with a consequent lack of current zeros. Note that if the generator had been under-energized prior to the fault, the degree of asymmetry would be even higher. Having examined the behavior of generators with different ratings, one can affirm that in certain cases the degree of asymmetry can be very high and exceed 130%.
Considering what the generator contributes to the short-circuit current, owing to the axial dissymmetry of the generator, this latter must be broken down according to two imaginary axes of reference (so-called Park's model): the direct axis and quadrature axis. Assuming that the voltage is the same on all the internal components, a simplified formula for the generator current can be obtained:

$$I = \sqrt{2} \cdot \left[\left(I''_d - I'_d \right) \cdot e^{-\frac{t}{T''_d}} + \left(I'_d - I_d \right) \cdot e^{-\frac{t}{T'_d}} + I_d \right] \cdot$$
$$\cdot \sin(\omega t - \varphi) + \sqrt{2} \cdot I''_d \cdot e^{-\frac{t}{T_a}} \cdot \sin(\varphi)$$

Where:

$$I''_d = \frac{V}{X''_d} \qquad I'_d = \frac{V}{X'_d} \qquad I_d = \frac{V}{X_d}$$

I''_d, I'_d, I_d are the sub transient, transient and synchronous currents according to the direct axis, T''_d and T'_d are the sub transient and transient short-circuit time constants of the equivalent circuit according to the direct axis, T_a is the statoric time constant equal to $X''_d/(\omega R_a)$ with R_a the d.c. armature resistance.

The previous fig. 4.6 illustrates a net three-phase short-circuit with a fault beginning the moment in which phase voltage is at zero. Note that the current has a zero approximately 520 ms after the beginning of the fault. The contacts in a circuit breaker normally start to separate 40-50 ms after the fault begins. This depends on the time the protection relay takes to detect the fault (approx. 20 ms) plus the time the opening mechanism takes to release and the contacts to begin their initial movement until the electric arc strikes (about 20-30 ms). From this moment on, the electric arc continues inside the pole of the circuit breaker, which must be able to control its energy. Obviously, the longer current zero is delayed, the more the circuit breaker is stressed. In actual fact, the arc introduces a non-linear resistance which interacts with the other impedances in the installation. A voltage drop can be seen in the voltage trend. This, for SF_6 circuit breakers, is around 300-500 V with a peak that can reach 1500 V. Owing to the different breaking technique, the peak arc voltage is typically 100 V for vacuum circuit breakers with rotating arc. Owing to the difficulty in reproducing a similar trend in the laboratory, Standard IEC/IEEE 62271-37-013 requires that the tests be performed at 130% constant asymmetry, shown in the figure by the horizontal dotted line.
In conclusion, short-circuit current breaking near a generator is a complex phenomenon which, for medium and high-power generators, should be analyzed in detail with transient simulations performed using the appropriate calculation tools.

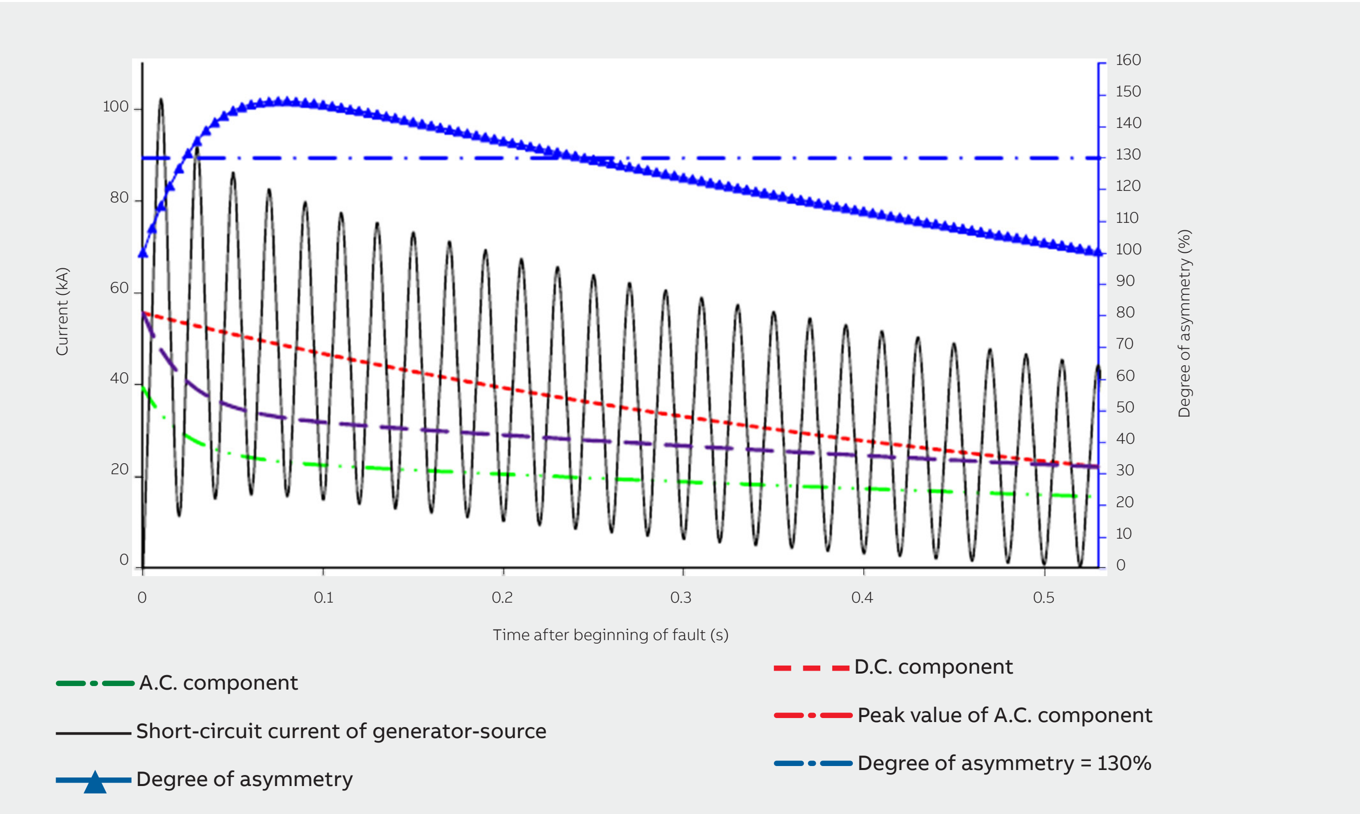


Fig. 4.6

4. Switching of fault currents and transient overcurrents

4.2 Closing operation

4.2.1 Switching-in of capacitor banks

Switching-in capacitor banks (fig. 4.7) is a case that it worthwhile examining since it is often accompanied by transient overcurrents and overvoltages.

The worst case occurs if a capacitor bank is switched-in when other banks are already connected (so-called back-to-back switching). This is because the amplitude and frequency of the inrush current can be very high.

If one observes the circuit in fig. 4.8 (see IEC 62271-100, Annex H and IEC 62271-306 chap. 9.2.2 and chap. 9.4.10), the case where a single bank is switched-in is obtained by considering the circuit breaker of bank 2 to be open.

Fig. 4.7

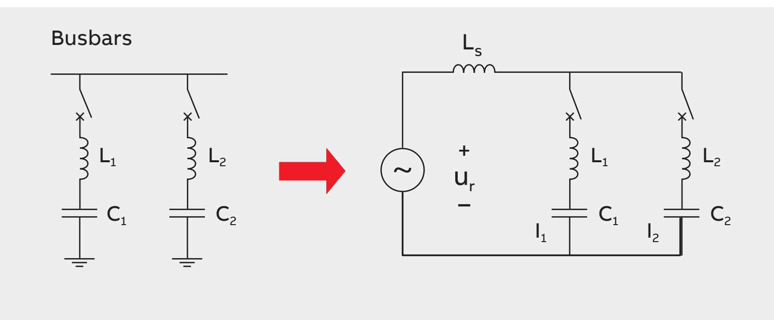


Fig. 4.8

The inductance of source L_s is much larger than parasitic inductances L_1 and L_2, thus the only limit to current amplitude $\hat{\imath}_i$ and the relative frequency f_i is given by L_s.

Thus, for $L_s \gg L_1$ there is:

$$i = U_r \sqrt{\frac{2}{3} \cdot \frac{C_1}{L_s + L_s}} \approx U_r \sqrt{\frac{2}{3} \cdot \frac{C_1}{L_s}}$$

$$f_i = \frac{1}{2\pi \sqrt{C_1 (L_s + L_1)}} \approx \frac{1}{2\pi \sqrt{C_1 L_s}}$$

If bank 2 has already been energized, there is a back-to-back switch-in where the load of the second bank is provided by the first and the inrush current is therefore only limited by L_1 and L_2:

$$i = U_r \sqrt{\frac{2}{3} \cdot \frac{C_1 C_2}{(C_1 + C_2)} \cdot \frac{1}{(L_1 + L_2)}}$$

$$f_i = \frac{1}{2\pi \sqrt{\frac{C_1 C_2}{(C_1 + C_2)} (L_1 + L_2)}}$$

If the capacitors are all the same and thus $L=L_1=L_2$ and $C=C_1=C_2$, the formulas are simpler and become:

$$i = U_r \sqrt{\frac{C}{6L}} \quad \text{and} \quad f_i = \frac{1}{2\pi \sqrt{LC}}$$

In the case of n capacitors already connected, the situation can be described as:

$$L'' = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} + \cdots \frac{1}{L_n}} \quad \text{e} \quad C'' = C_1 + C_2 + \cdots C_n$$

In particular, the result if the capacitors are all the same is L”= L/n and C”=nC, thus, by substituting, in the previous formulas, L_1 for L” and C_1 for C”, the result becomes:

$$i = U_r \frac{n}{n+1} \sqrt{\frac{2C}{3L}} \quad \text{and} \quad f_i = \frac{1}{2\pi \sqrt{LC}}$$

By writing L_s as a function of grid frequency f_s, voltage U_r and short-circuit current I_{sc}, the result is:

$$L_s = \frac{U_r}{2\pi f_s \cdot I_{sc}}$$

Lastly, by substituting capacitance C_1 for the relative capacitive current I_1 and using the following formula:

$$I_1 = 2\pi f_s \cdot C_1 \cdot U_r$$

The formulas for switching-in a single capacitor bank become:

$$\hat{i}_i = \sqrt{2}\ \sqrt{I_{sc} I_1} \qquad \text{e} \qquad f_i = f_s \sqrt{\frac{I_{sc}}{I_1}}$$

And the formulas for switching-in a capacitor bank in back-to-back mode:

$$\hat{i}_i = \sqrt{\frac{10^3\, U_r\, I_1\, I_2}{\pi f_s \sqrt{3} \times 10^{-6}\, L_{eq}\, (I_1 + I_2)}} =$$

$$= 13\,556 \sqrt{\frac{U_r\, I_1\, I_2}{f_s\, L_{eq}\, (I_1 + I_2)}} \approx 13\,500 \sqrt{\frac{U_r\, I_1\, I_2}{f_s\, L_{eq}\, (I_1 + I_2)}}$$

$$f_i = \frac{1}{2\pi} \times 10^{-3} \sqrt{\frac{2\pi\, f_s\, 10^3\, U_r\, (I_1 + I_2)}{\sqrt{3} \times 10^{-6}\, L_{eq}\, I_1\, I_2}} \approx 9{,}5 \sqrt{\frac{f_s\, U_r\, (I_1 + I_2)}{L_{eq}\, I_1\, I_2}}$$

with $L_{eq} = L_1 + L_2$ expressed in µH, U_r in kV , f_s in Hz and the currents in A.

Briefly outlining the simplified formulas in tab. 3:

Condition	Measurement	Formula
Energizing of a capacitor bank	i_i (A)	$1{,}41\sqrt{I_{sc} \times I_1}$
	f_i (Hz)	$f_s\sqrt{\frac{I_{sc}}{I_1}}$
Energizing of a capacitor bank plus another shunted from the same busbars	i_i (A)	$13\,500\sqrt{\frac{U_r I_1 I_2}{f_s L_{eq}(I_1 + I_2)}}$
	f_i (kHz)	$9{,}5\sqrt{\frac{f_s U_r (I_1 + I_2)}{L_{eq}(I_1 \times I_2)}}$
Energizing of a capacitor bank plus another identical one shunted from the same busbars	i_i (A)	$9545\sqrt{\frac{U_r I_1}{f_s L_{eq}}}$
	f_i (kHz)	$13{,}5\sqrt{\frac{f_s U_r}{L_{eq} I_1}}$

Tab. 3

Fig. 4.9 below gives an example of an oscillogram showing the overvoltages and overcurrents that generate when a capacitor bank switches in

4. Switching of fault currents and transient overcurrents

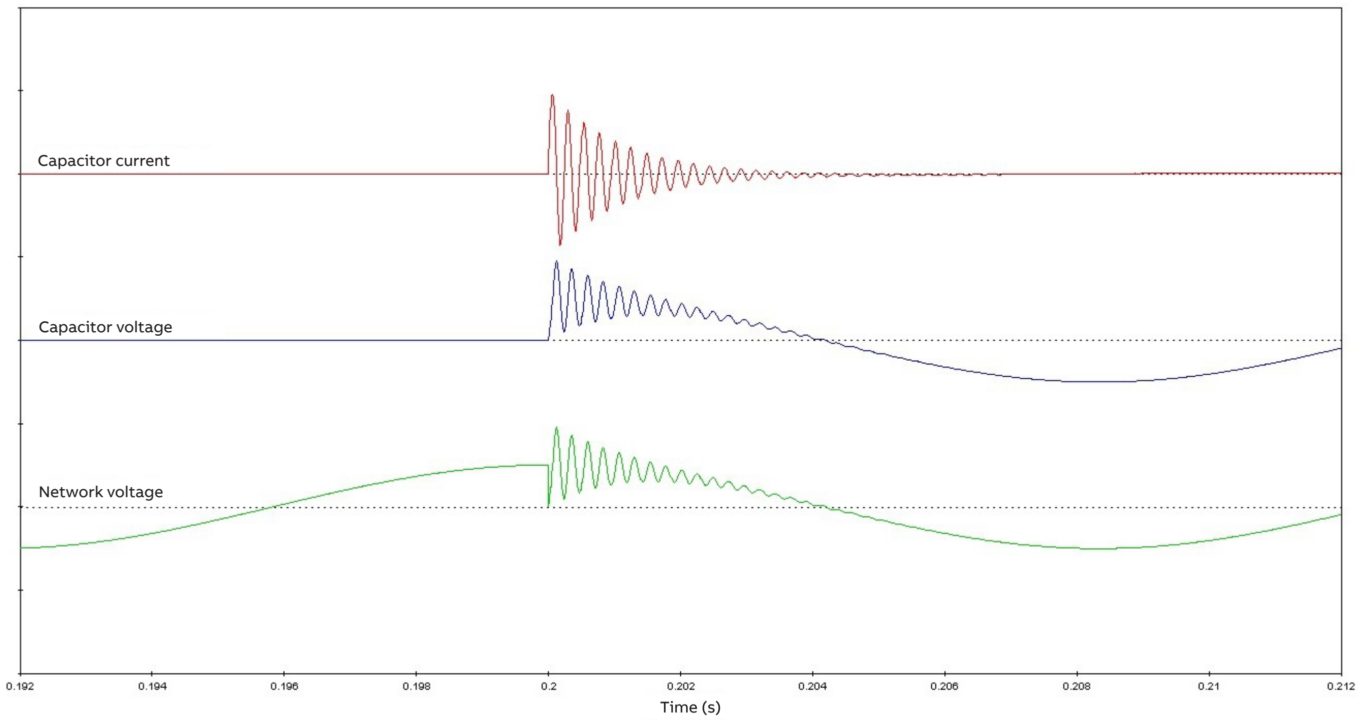


Fig. 4.9

The typical values of the overcurrent for switching capacitors in back-to-back mode run to many kA, with frequencies that range from 2 to 5 kHz. Consider that capacitor banks normally support currents up to 100 times their rated current at most.
In any case, when more than two capacitor banks are installed on the same busbar, it is advisable to calculate the inrush current parameters more precisely using appropriate computer tools (EMTP).

Fig. 4.10

4.2.2 Switching-in of no-load transformers: inrush current

When a transformer is de-energized, a residual magnetic flux remains in its core which depends on the material with which it is made. Residual flux can be as much as 80% of the magnetic flux of normal on-load operation. A transient overcurrent is generated when the transformer is energized again. The value of this transient overcurrent depends on the instant in which the voltage is applied and on the value and direction of the residual magnetic flux. In certain cases, the transient flux can reach and exceed the saturation limit of the ferromagnetic substance of the core before the applied voltage changes sign.
Thus the amplitude of the magnetized transient current can reach even very high values, up to a maximum which can be more than the rated current and actually approach the short-circuit current of the transformer.

Three cases are illustrated in figs. 4.11, 4.12 and 4.13:

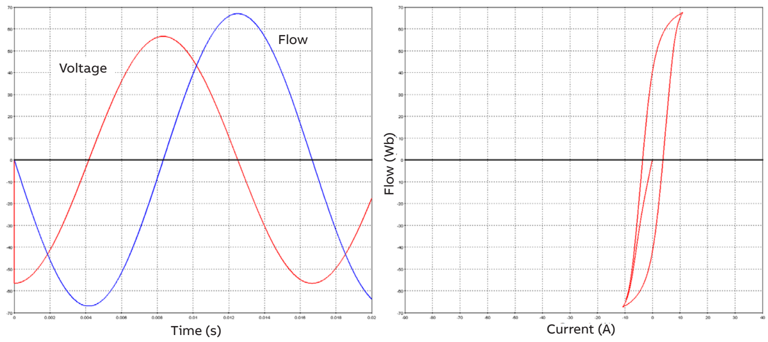


Fig. 4.11: best case, no transient

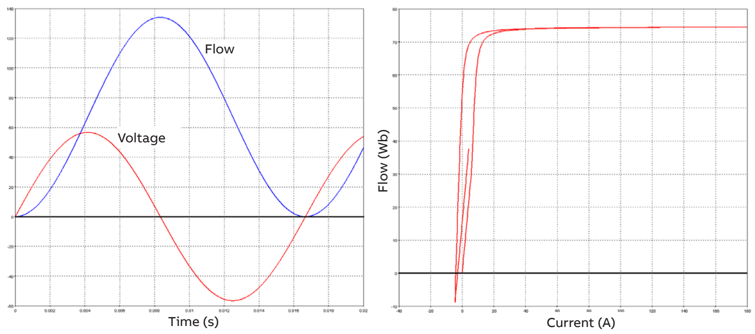


Fig. 4.12: maximum overlap

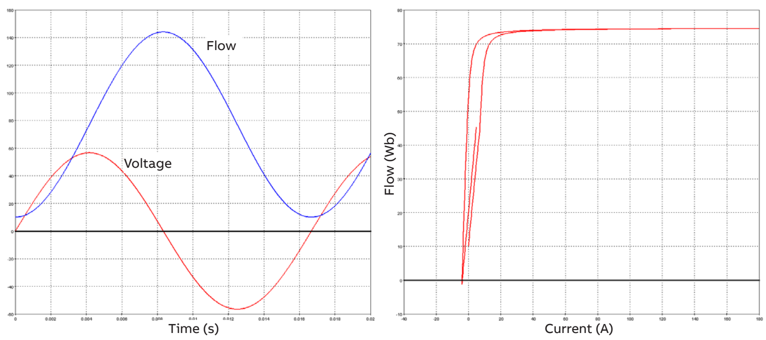


Fig. 4.13: worst case, maximum overlap with negative value

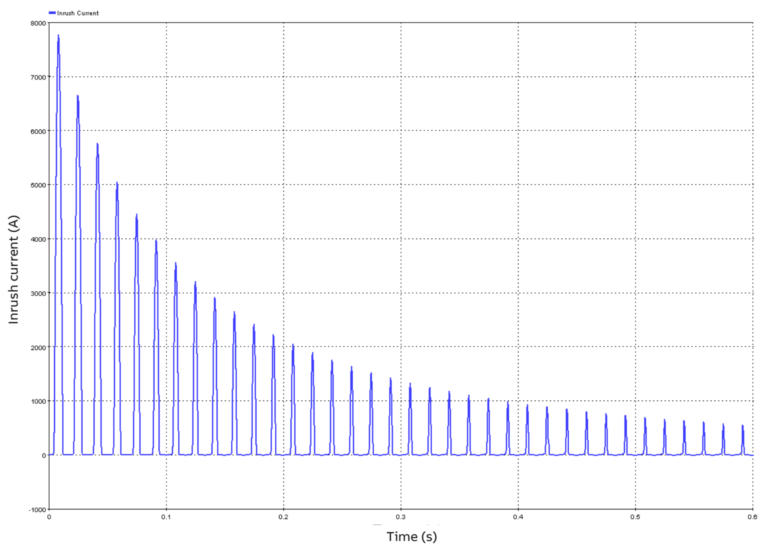


Fig. 4.14

It is evident that the phenomenon is absolutely random and that it occurs occasionally in relation to the frequency with which the transformer is energized in the no-load mode. Inrush currents always have one single polarity and therefore contain a direct component, which normally decays in less than a few seconds. Time constant τ_{rush} thus depends on the type of transformer and is higher for transformers with low-loss high power cores. An example of inrush current is illustrated in fig. 4.14.

The peak value decays exponentially with the formula:

$$\hat{i}_{rush}(t) = \hat{I}_{rush}\, e^{-\frac{t}{\tau_{rush}}}$$

Where: $\hat{i}_{rush}(t)$ is the peak value as a function of time, $\hat{I}_{rush}$ is the maximum peak, i.e. the first, τ_{rush} is the time constant. The inrush current value is usually given in multiples of the rated current of the transformer:

$$n_{rush} = \frac{\hat{I}_{rush}}{I_n}$$

4. Switching of fault currents and transient overcurrents

4.2.3 Switching-in of motors
Medium voltage motors possess a wide variety of electrical and technological characteristics. The main families are characterized by the type of armature or rotor:

- squirrel cage asynchronous motors with single or double cage
- wound rotor asynchronous motors with ring collector
- synchronous motors

Each type of motor has different current and torque characteristics, depending on the rpm rate. From the electrical viewpoint, there are 380 V to 13.8 kV motors with 140 to 23,000 kW power ratings and 50 and 60 Hz frequencies.
The asynchronous motor (fig. 4.16) is the most economical, simple, sturdy and reliable type of electric motor. Consequently, it is the most widespread device for applications in which electricity is used as 'motive power'.

The difference between single and double cage lies in the different torque/speed values involved. The starting torque and starting current of the single-cage motor are slightly lower, while torque and starting current are slightly higher in the double-cage motor.

The advantage of wound-rotor asynchronous motors with ring collectors is that the rotor winding can be connected outside, thus allowing their resistance to be modified. This means that the torque/speed characteristic can be changed so as to optimize maximum torque in relation to load and reduce the problem of high initial starting currents. However, these machines are more complex than the previous ones.
Lastly, synchronous motors feature a fixed rotation speed called synchronous speed. The rotor is the wound type and is powered by direct current. By adjusting the energizing current, the motor can change its power factor and can also supply reactive power when over-energized. This characteristic allows asynchronous motors to be used for rephasing inductive loads in place of capacitor banks. However, in view of the constant speed, they can only be used with very regular loads.

Fig. 4.15: examples of MV motors

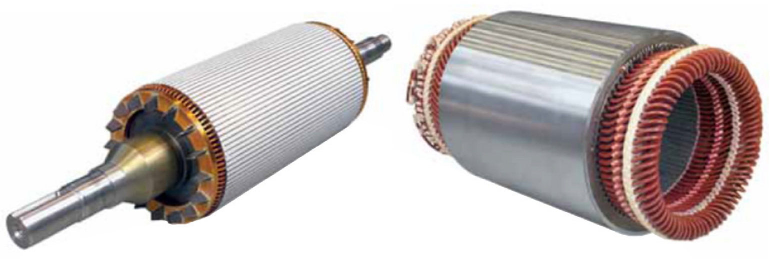


Fig. 4.16: rotor and stator of an asynchronous motor

The principal starting methods for squirrel-cage and synchronous motors will now be discussed.

Direct on-line starting: the motor simply starts when circuit breaker S closes (fig. 4.17). Since the drive is very simple, this type of starting technique is extremely economical and sturdy.

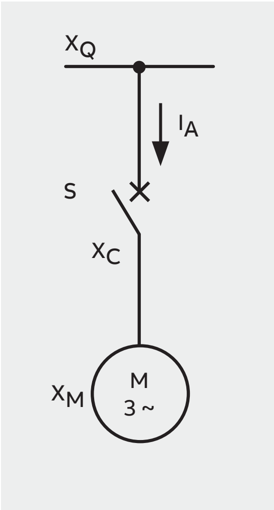


Fig. 4.17

However, the inrush currents are rather high and are from 3.5 to 7 times the rated current, depending on the power and rated speed. The starting current equals:

$$\frac{I_{A1}}{I_N} = \frac{I_A}{I_N} \cdot \frac{X_M}{X_M + X_C + X_Q}$$

where I_A/I_N is the starting current given by the manufacturer as multiple of the rated current, X_M is the reactance of the motor, X_C the reactance of the cable and X_Q the reactance of the grid. Note that during the transient, the resistive components are negligible compared to the value of the reactances. Thus the starting current can, with a good approximation, be calculated from the sole reactances.
The real starting torque T_{s1} will be less than the nominal starting torque T_s owing to the voltage drop caused by the reactances on the supply side, thus:

$$\frac{T_{s1}}{T_n} = \frac{T_s}{T_n} \cdot \left(\frac{X_M}{X_M + X_C + X_Q}\right)^2$$

Typically, the power factor will not exceed 0.25 even in high powered motors. This leads to a consumption of power and, thus, of current. The current is reactive during the starting phase and causes a voltage drop across the inductances on the supply side, with consequent impact on motor torque (remember that torque is proportional to the square of voltage). Switching-in a capacitor bank during the starting phase could be a possible way of addressing this problem during direct starting. The capacitor back could then be disconnected when the current begins to diminish so as to increase the cos fi of the “load” and consequently reduce the voltage drops.

The next starting methods are called **reduced voltage starting**. In such cases, the intention is basically to limit the inrush current by reducing the supply voltage when the starting currents are high. However, this also reduces the starting torque, which is proportional to the square of the voltage applied to the motor, as shown in the example in fig. 4.18. Thus, this method can only be used when there is very little load torque, or when the motor possesses such a high starting torque that voltage reduction will not compromise starting.

Reactance stator starting: this method is also very simple (fig. 4.19). The starting current reduces as the additional reactance X_A increases. The motor starts when S1 closes with reactance X_A in series. After this, once the motor has started, reactance X_A short-circuits, thereby closing switch S_2 and preventing dissipation and additional voltage drop. On the other hand, since the initial torque is also reduced, the reactance value must

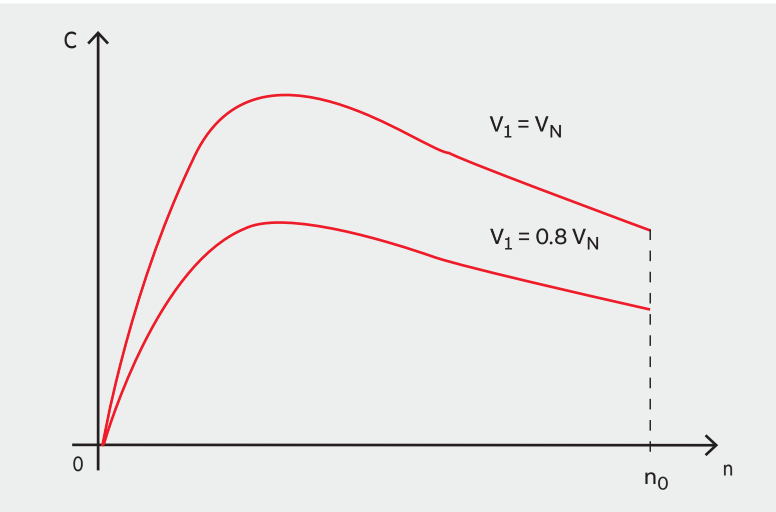


Fig. 4.18

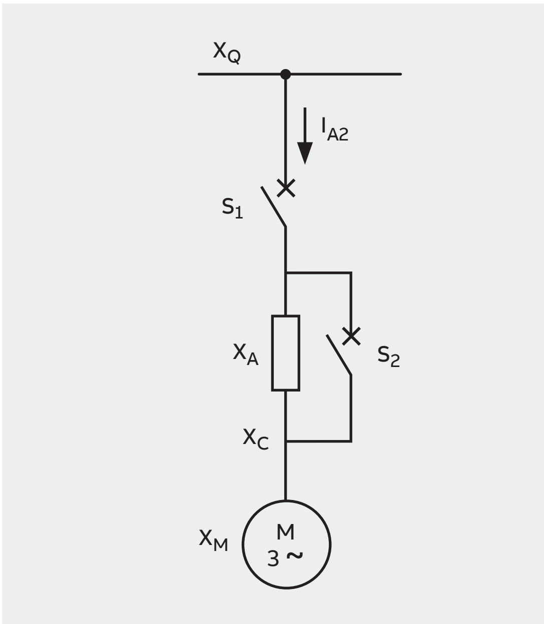


Fig. 4.19

4. Switching of fault currents and transient overcurrents

be a comprimise between the decrease in current and the load torque.
The starting current equals:

$$\frac{I_{A2}}{I_N} = \frac{I_A}{I_N} \cdot \frac{X_M}{X_M + X_C + X_A + X_Q}$$

And the real starting torque:

$$\frac{T_{s2}}{T_n} = \frac{T_s}{T_n} \cdot \left(\frac{X_M}{X_M + X_C + X_A + X_Q} \right)^2$$

Autotransformer starting:
As illustrated in fig. 4.20, the motor starts when switch S_1 closes and with S_2 closed and S_3 open. This enables the current to pass through the autotrasformer, which can reduce the supply voltage and, proportionally, the starting torque. An autotransformer thus achieves an excellent balance between current and starting torque as the connected power outlet varies (a_1 … a_3).
Neutral point switch S_2 is opened just before rated speed is reached so that the motor can be supplied by means of the part connected to the winding of the autotransformer and successively excluded by closing switch S_3, thus supplying the motor at full grid voltage.
The disadvantages of this type of starting method are its cost and the complexity of the additional apparatus. The starting current is calculated in the following way (fig. 4.21):

$$\frac{I_{A3}}{I_N} = \frac{I_\mu}{I_N} + \frac{I_A}{I_N} \cdot \alpha^2 \cdot \frac{X_M}{X_M + X_C + X_Q}$$

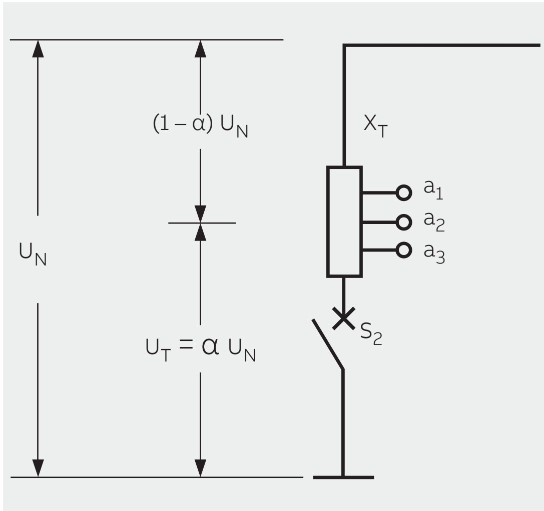


Fig. 4.21

where I_{A3} is the real starting current, I_μ is the no-load current of the transformer, α is the ratio between reduced voltage and rated voltage U_T/U_N.
The real starting torque will obviously be:

$$\frac{T_{s3}}{T_n} = \frac{T_s}{T_n} \cdot \alpha^2 \cdot \left(\frac{X_M}{X_M + X_C + X_Q} \right)^2$$

Other types of starting systems, such as star-delta starting and starting by means of resistors are commonly used in low voltage installations but not in medium voltage systems.
Rotor starting systems, i.e. wound-rotor asynchronous motors with slip ring collectors are an interesting choice for medium-voltage installations. Theoretically, these systems are able to address all the problems that may arise when motors start since they reduce the inrush current, adapt torque to load and allow progressive starts.

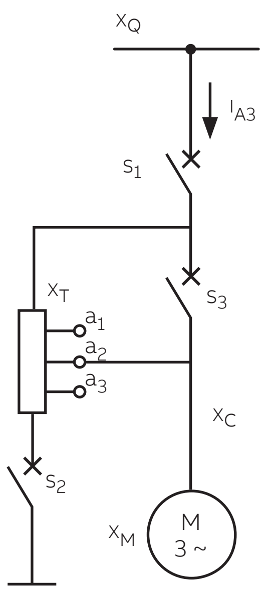


Fig. 4.20

Rheostatic starting in n steps:
this functions by switching-in additional resistors in series with the rotor windings, by means of a system of brushes and rings. On the one hand, connection of an additional rotor resistor while the motor is starting and with constant supply voltage leads to an increase in rotor impedance with a consequent decrease in the current consumed by the starter motor. On the other hand, the increased resistance causes the phase shift of the rotor currents to decrease, consequently increasing the value of the starting torque.
The additional resistors are normally calculated so as to reduce current consumption on starting by about 1/3 and to provide starting torque which is about 60 to 90% of the rated torque. The problem with this method is the limited number of consecutive starts caused by power dissipation owing to the Joule effect on the rotor rheostat.
In the circuit illustrated in fig. 4.22, the motor is started by closing switch S_1 with all the contactors C_n open and, thus, with all the resistors connected.

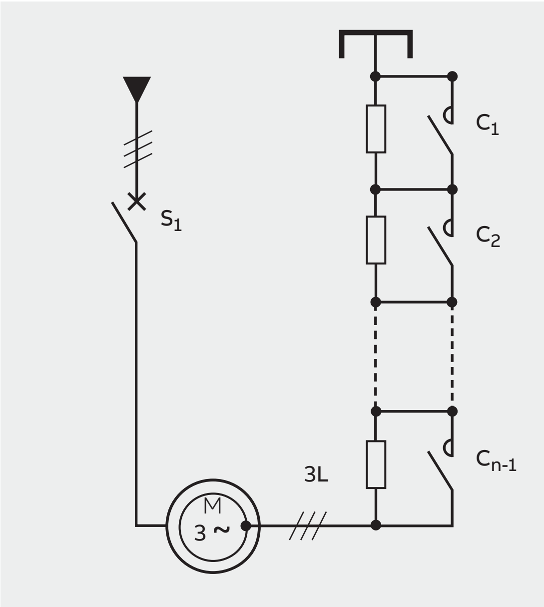


Fig. 4.22

After this, the resistors are progressively disconnected, short-circuiting them by closing the corresponding contactor starting with C_1 onwards, until complete exclusion. However, this type of starting is not linear, as can be seen in the graph of fig. 4.23 of the current for n=4. One must thus

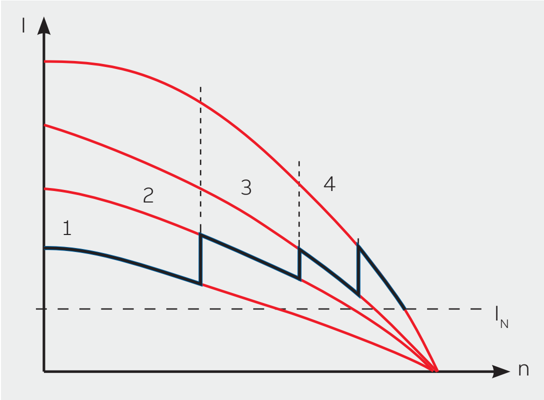


Fig. 4.23

resort to other types of starting if the intention is to adapt motor torque to load starting torque.
A modern method for starting is to use electronic soft starters. These devices reduce the starting current, achieve the torque rate most able to suit the load and allow starting time to be determined. Thanks to this, the motor can be supplied very gradually so as to achieve linear starting and prevent the electrical or mechanical parts from being stressed.

Starting with a soft starter
This starting technique is obtained by reducing the voltage, which is achieved by electronic components able to choke the supply voltage by reducing its rms (fig. 4.24). This system allows a supply voltage rise to be programmed and to thus control the starting voltage, but the disadvantage is that starting torque is also reduced. A considerable harmonic content is also generated.

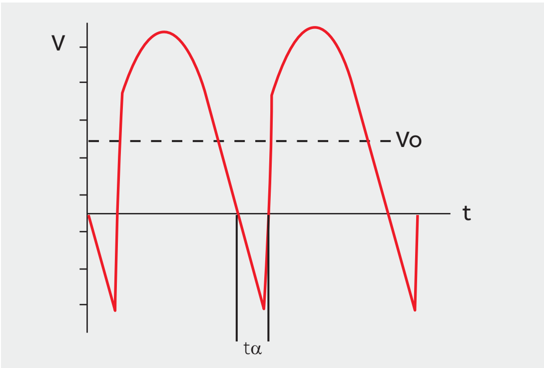


Fig. 4.24

4. Switching of fault currents and transient overcurrents

Rectifier/inverter starting
These systems are able to supply the motor with voltage of variable amplitude and frequency. Since the torque of asynchronous motors is proportional to the square of the supply voltage (at constant speed, fig. 4.25) and inversely proportional to the supply frequency (at constant voltage, fig. 4.26), one can affirm that these systems allow motors to be controlled with the utmost flexibility.

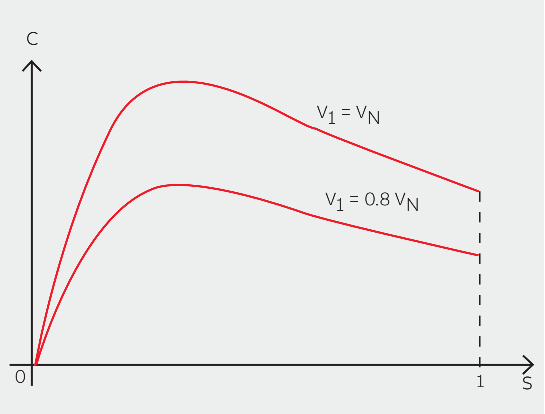


Fig. 4.25

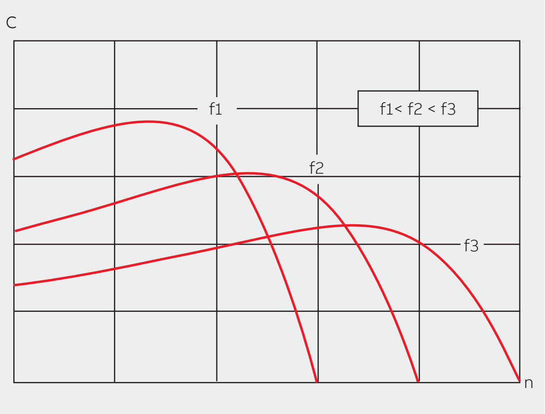


Fig. 4.26

Broadly speaking, these starters consist of a rectifier module and an inverter module (fig. 4.27).

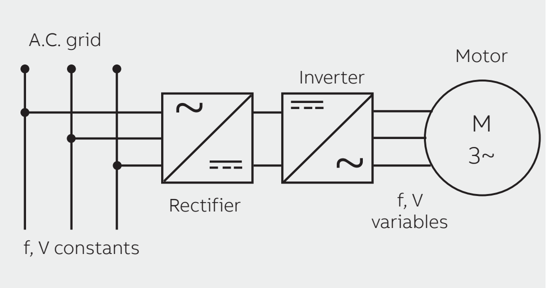


Fig. 4.27

Two different methods are adopted to re-convert direct current into alternating current.
The first is based on direct voltage regulation (technically known as voltage source conversion). Regulation allows square wave voltage to be obtained on the output, which can still be regulated as to amplitude and frequency (fig. 4.28).

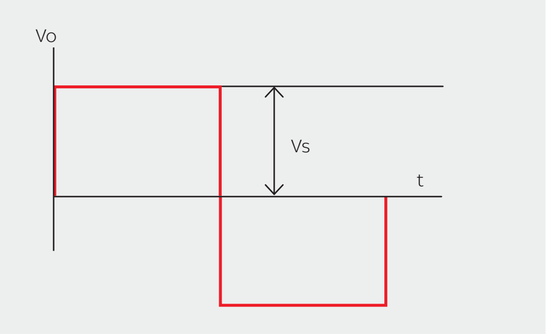


Fig. 4.28

The most widely used modulation technique is PWM, the principle of which is based on synthesizing a sine wave by means of pulse width modulation (fig. 4.29).

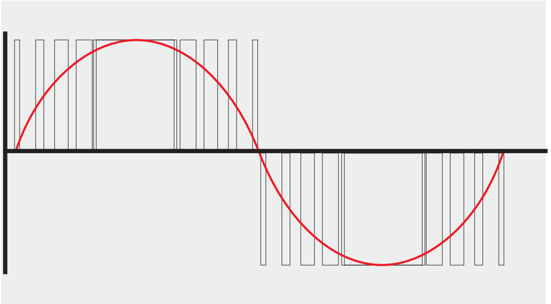


Fig. 4.29

Lastly, there is a third type where the rectifier functions like a direct current generator and the inverter as a current source inverter (CSI).

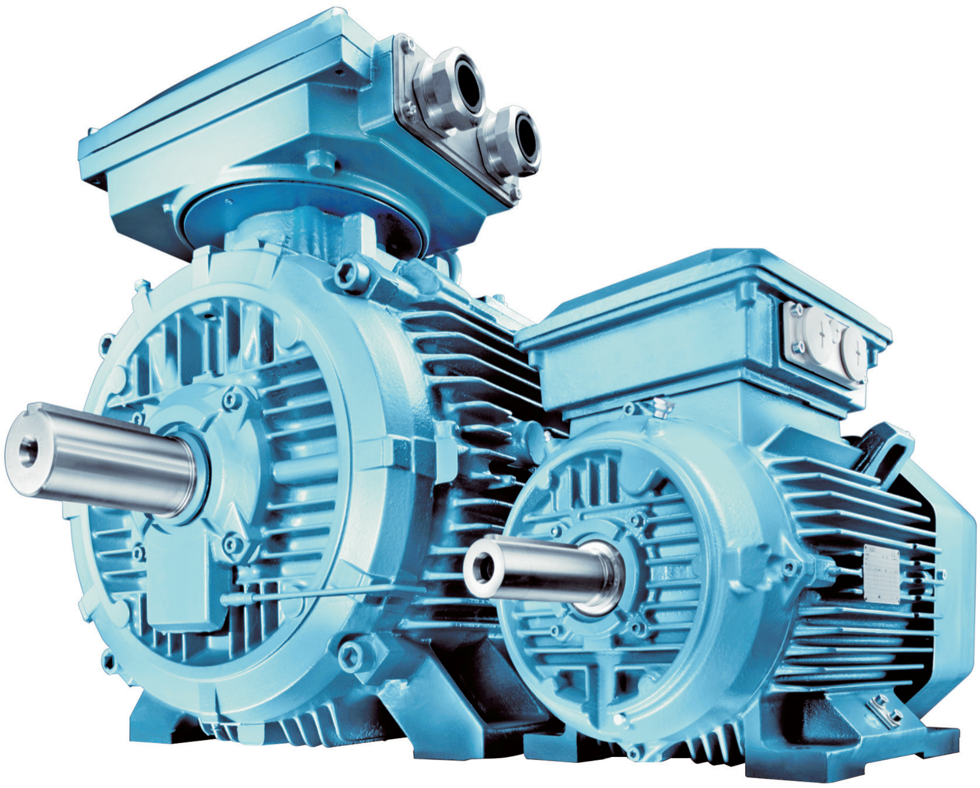
Although the solution is extremely flexible, there are also negative aspects. Firstly, the way in which this starter works generates voltage harmonics which are not present in the supply. These harmonics are present as both current harmonics in the motor and voltage harmonics in the supply. In addition, some of the methods lead to a phase shift of the fundamental component of the output voltage and, consequently, of the load current by influencing the power factor.

Other types of electronic starters
Other technologies for starting and controlling the speed of motors include cycloconverters and subsynchronous cascade drives. These variators are used in special sectors and applications and are not discussed in these papers.

Tab. 4 outlines the indications concerning motor starting currents given in the previous sections:

Type of starting system	Direct	By reactance	Auto-transformer	Rheostatic by steps	Soft starters	Rectifier/inverter
Formula	$I_{A1}/I_N = I_A/I_N \cdot X_M/(X_M+X_C+X_Q)$	$I_{A2}/I_N = I_A/I_N \cdot X_M/(X_M+X_C+X_A+X_Q)$	$I_{A3}/I_N = I_\mu/I_N + I_A/I_N \cdot \alpha^2 \cdot X_M/(X_M+X_C+X_Q)$			
Typical starting currents	From 3.5 to 7 I_N	From 3.5 to 7 $I_N \cdot$ (Va/Vn)	From 3.5 to 7 $I_N \cdot \alpha^2$	Typically from 3.5 to 7 $I_N \cdot$ (1/3)	From 3.5 to 7 $I_N \cdot$ (Va/Vn)	From 1 to 1.5 I_N

Tab. 4



4. Switching of fault currents and transient overcurrents

Starting time assessment
The starting time of a motor is basically linked to its motor torque T_M, to its start mode and to the type of load connected, which possesses a certain load starting torque T_L.
The required starting torque T_{acc} can be expressed as $T_{acc} = T_M - T_L$ and must be well calibrated to prevent it from being too low, since this would make starting either long and laborious with the risk of overheating the motor, or too high to prevent excessively high mechanical stress on joints or machinery. Starting time is thus a fundamental parameter if the motor starting system is to be properly sized, but it is not easy to calculate beforehand. The method for calculating starting time in the case of direct starting is described below.
Acceleration torque, the difference between motor torque and load starting torque, can be expressed in relation to the moment of inertia of the motor "J_M", of the load "J_L" and of angular acceleration, thereby obtaining the following expression:

$$(T_M - T_L) = (J_M + J_L) \cdot \frac{d\omega}{dt}$$

and since $\omega = \frac{2\pi n}{60}$, it follows that $d\omega = \frac{2\pi\, dn}{60}$
and by integrating for the variation in speed on starting from 0 to n_0, one obtains the following expression:

$$t_a = \int_0^{n_0} \frac{2\pi (J_M + J_L)}{60} \cdot \frac{dn}{(T_M - T_L)}$$

which gives the starting time of the motor.

Since motor torque T_M is not given as such in the catalogs of motor manufacturers, the formula that expresses T_M in relation to T_S or starting torque and T_{max} or maximum motor torque, must be introduced by way of a simplification:

$$T_M = 0.45 \cdot (T_S + T_{max})$$

The second simplifying assumption is that of categorizing the type of load by defining the torque trend of the load itself for each category and then multiplying T_L by a coefficient K_L which corrects its value. Tab. 5 gives the K_L value for certain categories of loads:

	Load category			
Load factor	Hoists	Fans	Piston pumps	Flywheels
Torque trend	Constant increase	Increase according to square law	Linear increase	No torque
K_L	1	0.33	0.5	0

Tab. 5

thus:

$$T_{acc} = (T_M - T_L) = 0{,}45\,(T_S + T_{max}) - K_L \cdot T_L$$

Lastly, by substituting the previous term and integrating, the result is:

$$t_a = \frac{2\pi\, n_0\, (J_M + J_L)}{60\, T_{acc}}$$

Switching and protection devices can always be chosen correctly given the starting time.

5. Switching overvoltages

5.1 Opening operation

5.1.1 Transient Recovery Voltage (TRV)

We will now consider the following equivalent circuit of fig. 5.1, similar to the one discussed previously (fig. 4.2) but with the addition of stray capacitances of the grid towards the supply:

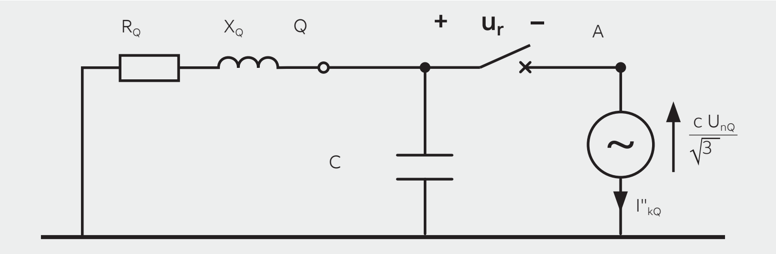


Fig. 5.1

TRV depends on the configuration and characteristics of the grid, and on the type of circuit breaker installed. When the circuit breaker opens, the two networks, supply side and load side, are disconnected and each releases its stored energy, thus developing a voltage which appears at the respective terminals of the circuit breaker and whose sum is called transient recovery voltage, or TRV. Since the circuit breaker can only break the current as it crosses zero, the almost purely inductive voltage in the circuit is, at that moment, at its maximum. Until then, the voltage between the terminals of the pole will have been very low, equal to the arc voltage (from approx. 100 V for vacuum circuit breakers to almost 1000 V for the SF_6 types), but it successively increases to the value of the supply voltage with a trend that depends on the L and C values of the grid. In addition to the value of the fault current, the values of the TRV, as to peak value and rate of rise, are the parameters which determine the severity of the break for the circuit breaker.
Since it depends on the combination of these parameters, TRV can have different values and forms: it can be oscillatory, with single frequency or multifrequency, or have an exponential trend. Thus, the exact calculation of TRV is extremely complex. It requires purpose-made simulation software called Electro Magnetic Transients Program (EMTP) and considerably experienced technicians.
Generally speaking, only the three-phase short-circuit need be considered since the highest values occur with this type of fault. In any case, the most critical TRV concerns the first pole that opens.

Fig. 5.2 shows that, in the case of the equivalent circuit of a three-phase network with earthed neutral point, in view of the symmetry of the system, this latter becomes two-phase and the earthed reference point shifts to halfway between U_c and U_b when the first pole of the circuit breaker opens. Compared to the other terminal, the voltage U_{ra} on the open pole thus equals 1.5 U_a, i.e. 1.5 times the star voltage of the grid (fig. 5.3).

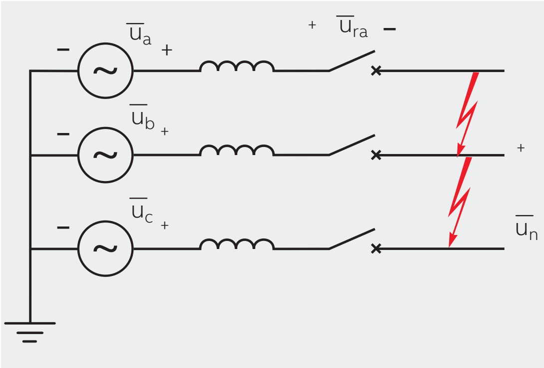


Fig. 5.2

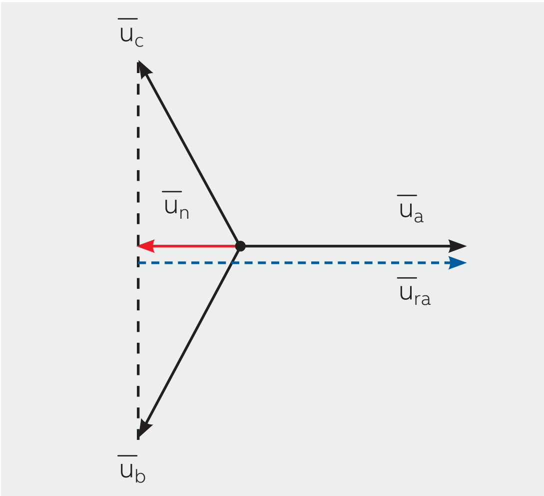


Fig. 5.3

The ratio between power frequency recovery voltage in the first pole that opens and the star voltage of the system is called k_{pp} First-pole-to-clear-factor, thus:
$K_{pp} = U_{ra}/U_a$.
It is evident that the K_{pp} factor depends on the characteristics of the grid. We have seen how K_{pp} equals 1.5 for a three-phase system with earthed neutral. This is the highest value it can reach and is symmetrically valid also in the case of grids with isolated neutral which is the typical configuration of medium voltage grids, and three phase earth fault.

5. Switching overvoltages

Based on the fault statistics, earth faults are the most common type according to Standard IEC 62271-100. Thus 1.5 is always adopted as k_{pp} factor for medium voltage below 100 kV.
To represent the TRV for the purpose of defining tests for the breaking capacity of an apparatus, the Standard uses a reference plot (fig. 5.4) for medium voltage below 100 kV characterized by two parameters, U_c and t_3, and by a further segment defined by delay time t_d.

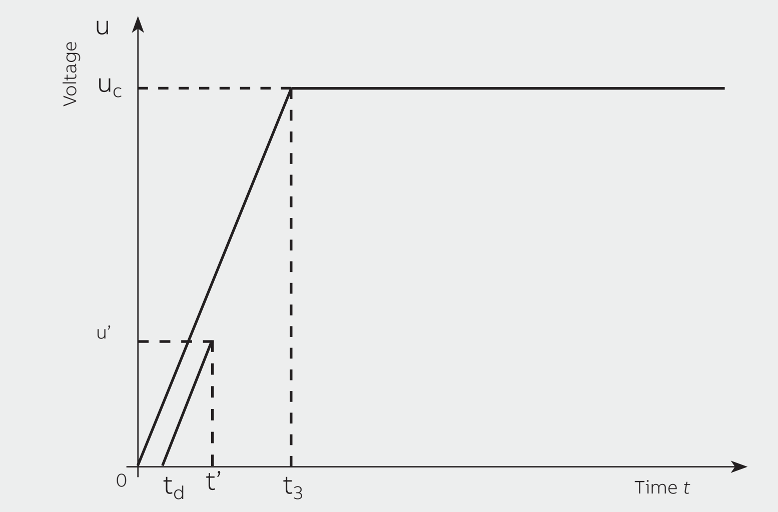


Fig. 5.4

The peak value of TRV is defined as:
$U_c = k_{pp} \cdot k_{af} (2/3) \cdot U_r$ where k_{af} depends on the type of test and on the type of application (cable lines or overhead lines, see fig. 5.5). Similarly, t_3 and t_d also depend on the type of test and on the type of application. The other two parameters, u' and t', are derived from u_c and t_d, t_3, respectively.

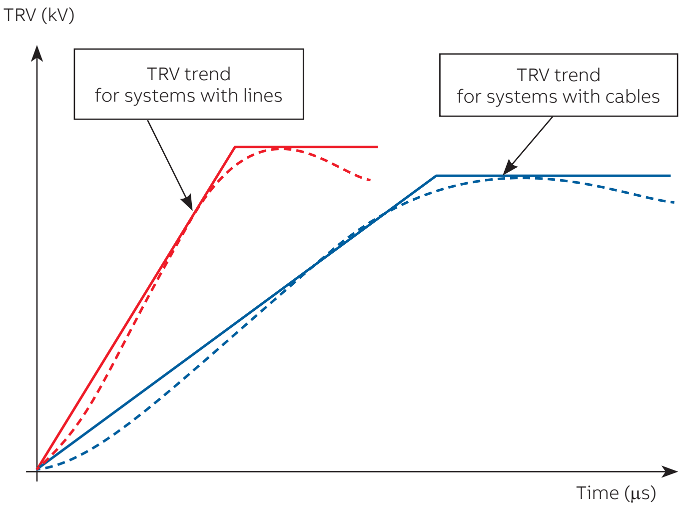


Fig. 5.5

5.1.2 Out-of-phase

In medium voltage installations, out-of-phase can typically occur in the situation illustrated in fig. 5.6:

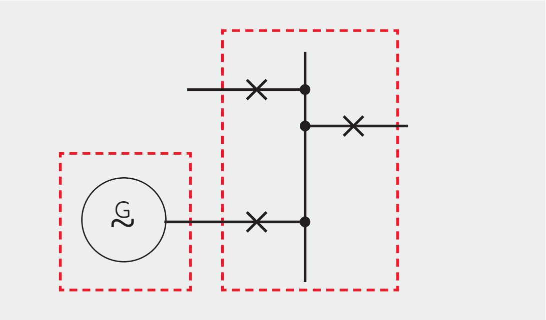


Fig. 5.6

If the generator is accidentally connected to the grid with the wrong phase angle, this could result in a out-of-phase fault which must be eliminated by the circuit breaker. Consider the equivalent circuit (fig. 5.7), where source U_1 is a generator and source U_2 is the grid in which parallel must be obtained.

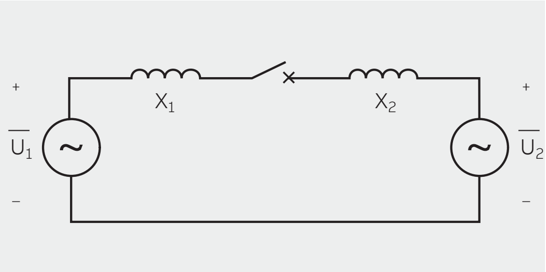


Fig. 5.7

Voltages should normally be approximately equal in both amplitude and phase. However, if switching-in is incorrect, the two vectors can differ by as much as 180°. If this happens, the maximum power frequency recovery voltage can reach 2U in the case of an earthed neutral and a maximum 3U in the case of an isolated neutral. However, both the IEC and IEEE Standards indicate that it is sufficient to use a 2.5 factor for systems with isolated neutral. One should also consider that when it occurs at the terminals of a generator, the phenomenon is always more critical for the circuit breaker since the impedance of overhead lines and cables normally causes overvoltage damping. A short-circuit at the same time as an attempt at out-of-phase parallel can therefore be extremely hard on the circuit breaker owing to the value reached by the TRV. Fortunately, the fault current is lower than the three-phase short-circuit current in the grid as the impedances of the two sources add together ($X_1 + X_2$ in the figure). The Standard specifies that for this type of fault the circuit breaker must be tested at 25% of its breaking capacity, considering higher current values to be highly improbable.

5.1.3 How capacitance affects TRV

Interruption of strongly inductive loads, such as an inductor, a stalled motor or during the starting phase, can give rise to TRV with a high RRRV value (dv/dt). This is why it may be useful to apply surge capacitors, which lower this value and prevent unnecessary stress due to transient phenomena. They safeguard the load from steep rate of rises in voltage, which could damage the windings of the machine or reactor by stressing its coils.
Let us consider, for example, a 1.2 MVA asynchronous motor at 11.5 kV; the relative estimated starting current is 5 In. Supposing that the circuit breaker must open after the rotor locks during the work process. The current interrupted will be more or less the same as the short-circuit current (5 · In ≈ 301 A), while the cosφ while the motor is stalled, could be an estimated 0.13 (fig. 5.8).

In this context, current breaking at such a low cosφ value creates TRV values comparable to those due to the interruption of a reactor, while there is no such problem for interruptions of motors at full rate. This means that it is important to check that the TRV values of the circuit breaker are compatible with those obtained by the simulation. If this is not the case, possible solutions could be to increase the voltage rating of the circuit breaker or to add a surge capacitor (fig. 5.9) to attenuate the RRRV value while diminishing the stress on the coils of the machine.

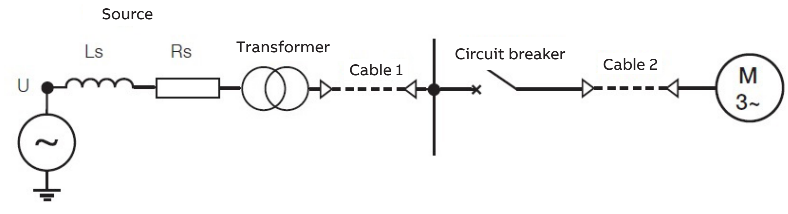


Fig. 5.8

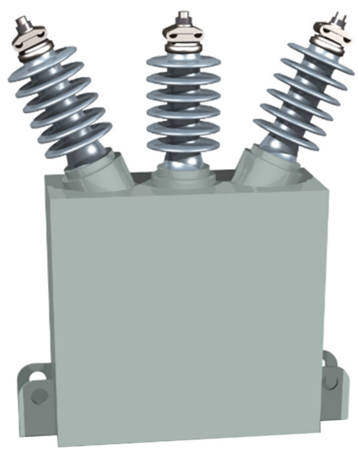


Fig. 5.9

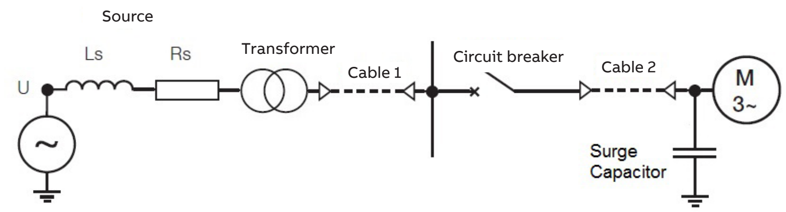


Fig. 5.10

Although it lowers the RRRV, application of a surge capacitor to the terminals of the machine (fig. 5.10) could raise the voltage peak. If the circuit breaker had been chosen without a due tolerance, the risk would be to approach the TRV limits for that specific voltage and current duty value.

5. Switching overvoltages

In figure 5.11, the TRV at the ends of the first pole without the application of a surge capacitor is shown in green. After 50nF capacitance has been applied to the terminals of the machine (red line), the RRRV attenuates, but the peak increases as a consequence. These variations become accentuated if 100nF capacitance is applied (blue line).

For the reasons described previously, cable length and the stray capacitances of the machines can be of fundamental importance when TRV is calculated and, consequently, when choosing the right electrical apparatuses and ensuring that the actual electric machine is safeguarded.

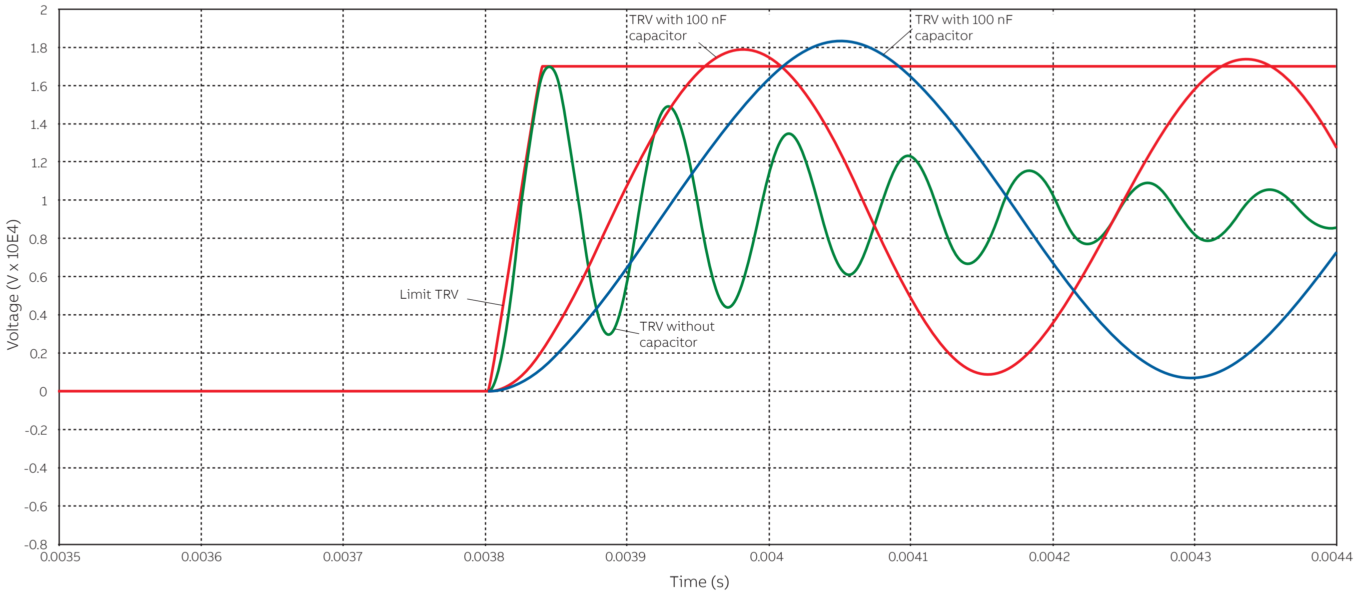
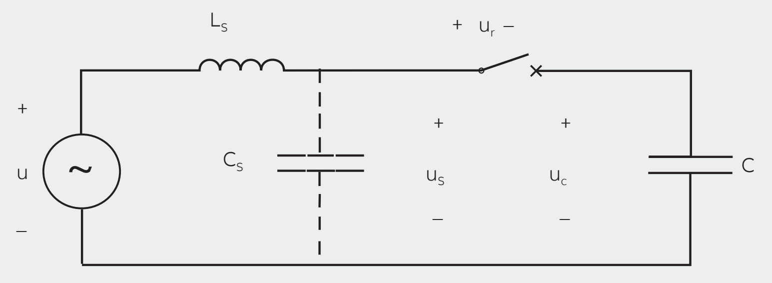


Fig. 5.11



C	Capacitive load (capacitor bank)	u_S	Voltage on supply side
u_r	Voltage at ends of circuit breaker	L_S	Inductance on supply side
u_c	Voltage at ends of capacitor bank	C_S	Capacitance on supply side

Fig. 5.12

5.1.4 Interruption of capacitive loads

Capacitive load interruption is encountered in the following cases:

- No-load overhead line opening
- No-load cable opening
- Capacitor bank opening
- Filter opening

The capacitive currents are normally modest. However, the risk is that restrikes could occur and bring undesired overvoltages into the installation. With reference to fig. 5.12 and supposing that the load is purely capacitive, the current is out-of-phase by 90° with respect to the voltage, thus this latter is at its maximum value when the current is interrupted.

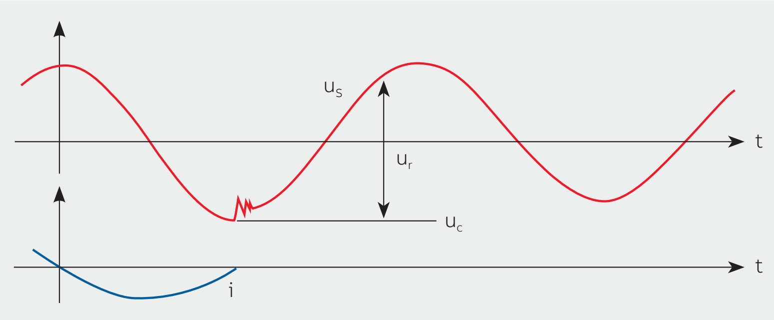


Fig. 5.13: Voltage and current waveform at the time of capacitive current breaking

The supply voltage u_s remains practically unchanged after the interruption (fig. 5.13) while on the load side, the capacitive load, isolated from the power grid, tends to maintain voltage u_c at a constant level even though, in actual fact, voltage decreases as capacitance discharges. In the case of capacitor banks, there are discharge resistors to accelerate this process. Half a cycle after the interruption, the TRV thus reaches a level equal to twice the peak value of the supply voltage.

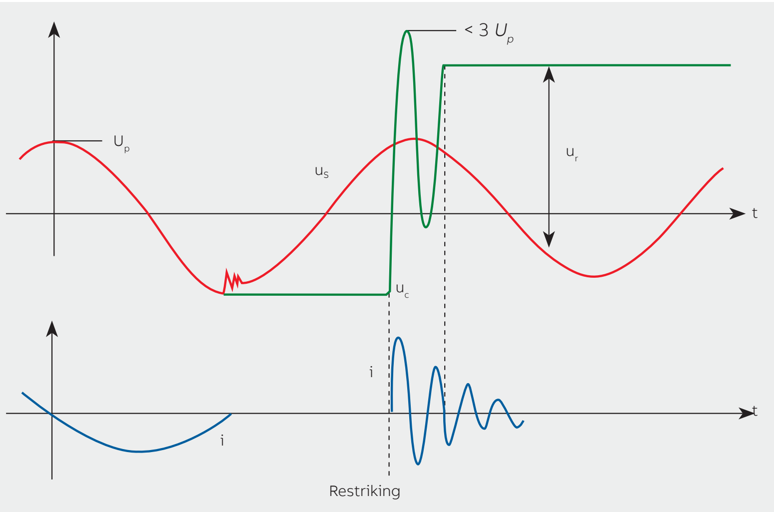


Fig. 5.14: Voltage and current waveform in the case of restrikes

Here again, owing to the short contact travel the circuit breaker might not be able to maintain the TRV and restrikes could occur (fig. 5.14).

5. Switching overvoltages

In this case, the voltage on the load can reach a theoretical value (i.e. without considering damping) of 3 p.u. at a frequency that depends on the inductance of the source L_s and on load capacitance C (if C >> C_s). The circuit breaker can interrupt the current in one of the current zeros, the result being that the capacitor could reach a higher voltage than the previous value. The process can repeat itself until the current is definitively interrupted.
In a three-phase system, the form of the TRV will be more complex than that of a single-phase circuit. Generally speaking, the TRV will be higher than in the single-phase case and its form more complicated during the opening of the first pole. Fig. 5.15 gives the value of TRV for opening the first pole when a capacitor bank with isolated neutral is opened.

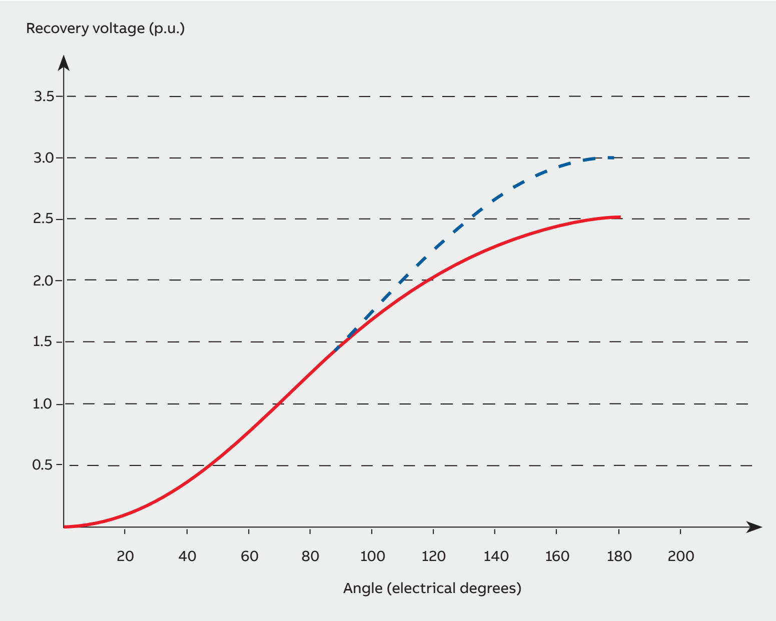


Fig. 5.15

The initial trend of the TRV would lead to a peak of three times the grid supply voltage (dotted blue line). However, when the last two poles interrupt a quarter of the cycle after the first (90°), a discontinuity appears in the trend and the final peak drops to 2.5 times the peak supply voltage.
Standard IEC 62271-100 establishes two classes, depending on the behavior towards restriking:
- class C1 with a low probability of restriking during the interruption of capacitive currents;
- class C2 with a very low probability of restriking during the interruption of capacitive currents;

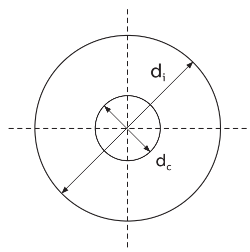
The Standard also describes the tests to which the circuit breaker must be subjected, depending on the type of capacitive load envisaged (especially for powering-up overhead lines L and cables C), and for capacitor banks B. Thus there will be a total of six test cycles: LC1, LC2, CC1, CC2, BC1 and BC2. The tests can be combined so as to cover the three types of load, by declaring a single value.
The type tests for class C2 are conducted after pre-conditioning, which includes short-circuit current interruptions followed by a certain number of capacitive current interruptions.
Pre-conditioning is not required for class C1 tests, and there are fewer capacitive current interruptions than class C2.
In the case of no-load cables, the charging current depends on the following characteristics:
a) system voltage
b) cable geometry
c) dielectric constant of the insulation
d) cable length
The transverse (or operating) capacitive reactance value can be obtained from the cable manufacturer or be calculated if the cable geometry is known.
This capacitive reactance can be calculated in the following way for single- or three-phase shielded conductors:

$$C_C = \frac{\varepsilon_r}{18 \cdot \ln \frac{d_i}{d_c}} \quad \mu F/km$$

and thus:

$$X_C = \frac{1}{2\mu f_s C_c} \ M\Omega/km \text{ per phase}$$

Where:
f_s is the grid frequency, in Hz;
ε_r is the dielectric constant of the cable insulation in F/m;
d_i is the internal diameter of the shield in mm;
d_c is the diameter of the conductor in mm.



For HEPR-insulated 12/20 kV MV cables the capacitance C_c can vary from 0.19 µF/km for 25 mm^2 cables to 0.62 µF/km for 630 mm^2 cables. The transverse capacitive reactance value can be used to calculate the charging current of the cable so as to compare it with the values given by Standard IEC 62271-100. The circuit breaker manufacturer must be consulted if the value obtained is higher than the one specified in the Standard.
The recovery voltage for cables with shielded conductors (fig. 5.16 a) is similar to that of capacitor banks with earthed neutral. The recovery voltage for belted cables (fig. 5.16 b) is similar to that of non-compensated overhead lines.

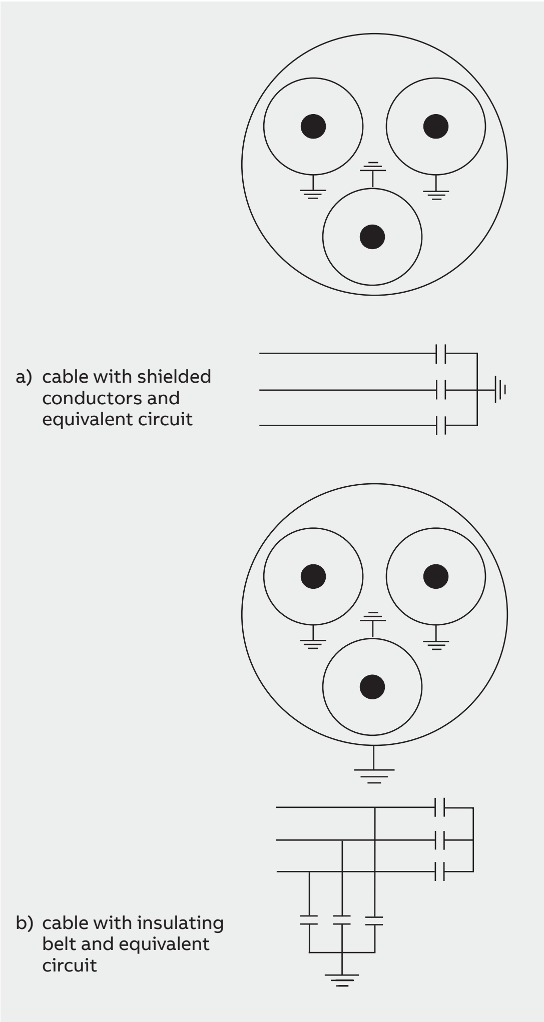


Fig. 5.16

5.1.5 Short line interruption

Short-line faults (SLF) are short-circuits which occur in overhead lines at a short distance from the substation from which they are supplied. This type of fault is not only determined by the impedance of the source but by the impedance of the line between the circuit breaker and the fault itself. In this case, TRV is characterized by wave propagation along the power transmission line.

Fig. 5.17: example of an MV overhead line

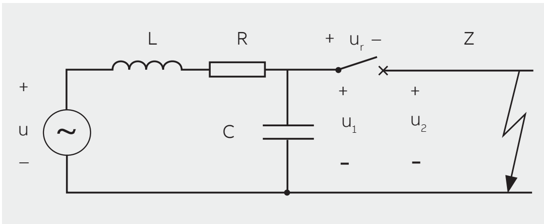


Fig. 5.18

With reference to the simplified circuit of fig. 5.18, a wave impedance Z of the line between the circuit breaker and fault can be seen on the load side of the circuit breaker. After fault u_1, it will tend to oscillate at supply voltage while u_2 will tend towards zero with a damped oscillation associated with the voltage wave transmitted in the section of the line affected by the fault (fig. 5.19).

5. Switching overvoltages

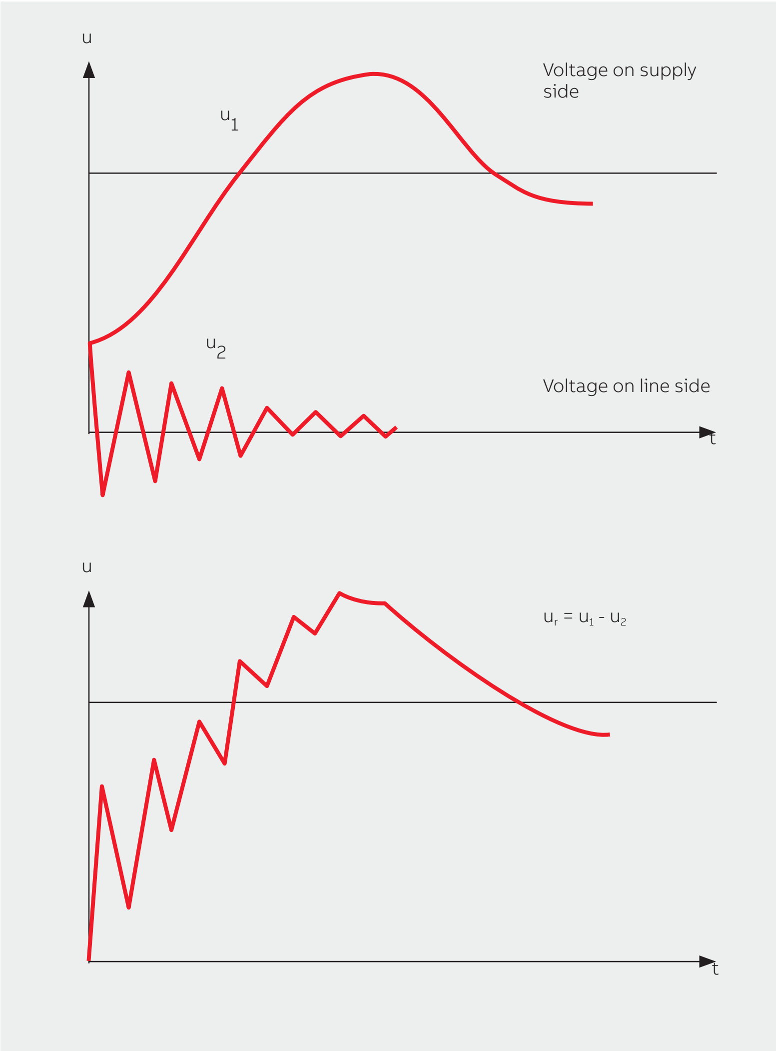


Fig. 5.19

The slope of the line side voltage, which presents a saw-tooth shape, is proportional to the trend of the current just before zero crossing and of equivalent wave impedance Z:

$$\left(\frac{du_2}{dt}\right)_{t=0} = Z\left(\frac{di}{dt}\right)_{t=0}$$

Where di/dt = $2\pi f\, I_p$ with f grid frequency and I_p peak current of the fault.
This type of fault can be extremely critical. However, it is not a normal service condition for indoor MV circuit breakers. Consequently, Standard IEC 62271-100 only prescribes specific tests for circuit breakers designed to be directly connected to overhead lines with 15 kV to 100 kV voltage values and breaking capacities exceeding 12.5 kA (Class S2). MV indoor circuit breakers are classified S1 since they are installed in switchgear with cable connections.

5.1.6 Opening of filter banks

The widespread presence of non-linear loads such as static converters, welding systems, induction furnaces, etc., has increased the problem of harmonics management in electrical installations to a considerable extent.
Generally speaking, the form of the supply voltage when these loads are present is distorted, i.e. it is as though the grid frequency sine wave voltage were to superimpose one or more undesired sine wave voltages at different frequencies. Fourier analysis allows any periodic and non-sinusoidal waveform to be decomposed into sinusoidal components of different frequencies and into a possible direct component. The lowest frequency of the series is called fundamental frequency, while the others can be integer multiples of the fundamental frequency and are called harmonic frequencies.

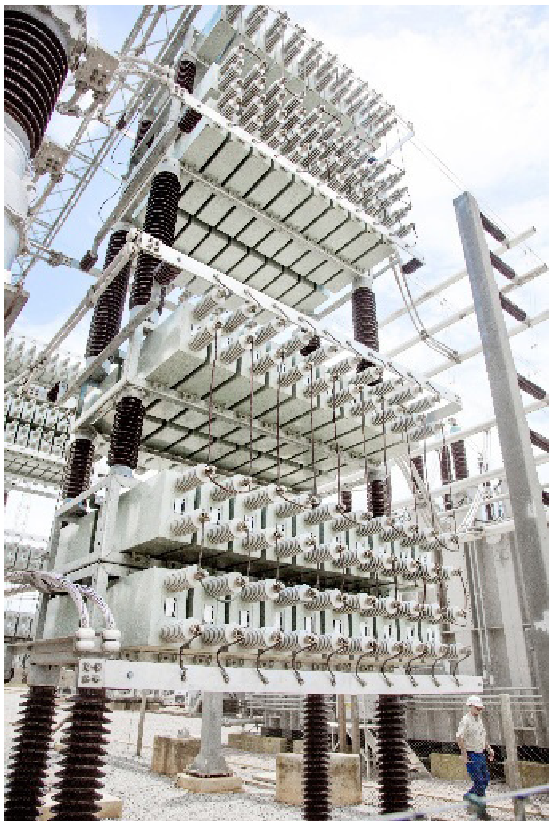


Fig. 5.20: examples of filter banks

The result of the Fourier transform analysis is a spectrum in the domain of the frequency where the lines represent the fundamental and the harmonics of the corresponding Fourier series. The Fourier analysis of the deformed waveform in fig. 5.22 showing a presence of 23% of the 3rd harmonic (150 Hz) and 11% of the 5th harmonic (250 Hz), is illustrated in the example of fig. 5.21.

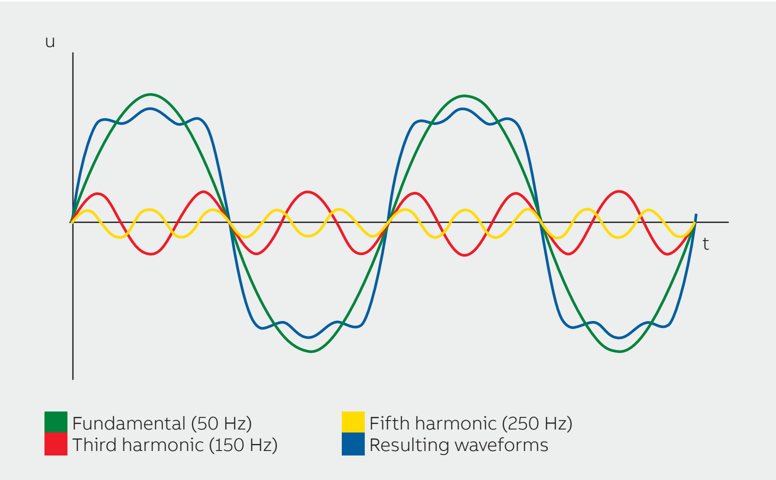


Fig. 5.21

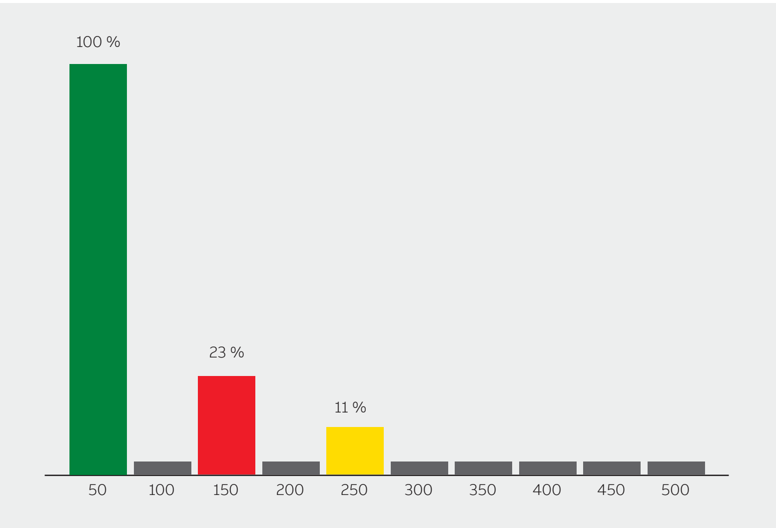


Fig. 5.22

In practice, there are simplified Fourier transform methods. One of these is the Discrete Fourier Transform (DFT), where the signal is analyzed in a limited window of time T_w using a limited number M of signal samples. Thus the result depends on T_w and M. The method presumes that beyond window T_w the signal repeats in an identical way, so the more the examined voltage is periodic, the more accurate the method will be.
Certain parameters are used to define the level of voltage and current distortion in an electrical installation:
Total Distorsion Content (TDC) is defined as the quantity that remains after the fundamental component has been subtracted from an alternating quantity:

$$TDC = \sqrt{Q^2 - Q_1^2}$$

Where Q_1 is the root mean square value of the fundamental component and Q is the total root mean square value.
Total Distorsion Ratio (TDR) is defined as the ratio between the TDC and the root mean square value of the fundamental component Q_1:

$$TDR = \frac{TDC}{Q_1} = \frac{\sqrt{Q^2 - Q_1^2}}{Q_1}$$

Lastly, Total Harmonic Distorsion (THD) is defined as the root mean square value of the sum of the harmonic components up to a certain order H divided by the root mean square value of the fundamental component:

$$THD = \sqrt{\sum_{h=2}^{h=H} \left(\frac{Q_h}{Q_1}\right)^2}$$

The reference Standard in this field is IEC 61000-2-4 “Electromagnetic compatibility (EMC) – Part 2-4: Environment – Compatibility levels in industrial plants for low-frequency conducted disturbances”, which is applicable to disturbances in the 0 to 9 kHz frequency range in industrial and distribution (not public) installations, for voltage up to 35 kV and 50 and 60 Hz rated frequency.
As to the harmonic content, this Standard considers up to the 50th harmonic, thus H=50 applies in the THD formula.
The Standard envisages three classes of electromagnetic disturbance in industrial installations:
Class 1 applies to installations with very low disturbances, less than those in the public grids, suitable for supplying very sensitive loads such as the measuring instruments in laboratories, certain automation devices and computers.
Class 2 is typical of industrial environments and private distribution networks with disturbance levels comparable to those normally to be found in public grids, suitable for supplying the majority of electrical devices.
Class 3 applies to industrial installations with higher levels of disturbance, where converters, welding systems, large motors with frequent starts and rapidly variable loads are present.

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The total harmonic distortion for the three classes is as follows:

	Class 1	Class 2	Class 3
Total harmonic distortion	5%	8%	10%

Tab. 6

When the harmonic content is excessive, the solution is to install filters for selective reduction of the harmonics. These filters can be connected and disconnected in industrial installations in a time-based mode (e.g. at certain times of day) or whenever the harmonic content so requires, depending on the type of production process.
The number of filter operations may be very high and seriously pose the problem of switching overvoltage, as well as consequences affecting the circuit breaker and, generally speaking, all the components of the electrical system.
In this case, the TRV of the circuit breaker is not the classic sine wave shape but includes various harmonic components. The waveform could be the type shown in fig. 5.23:

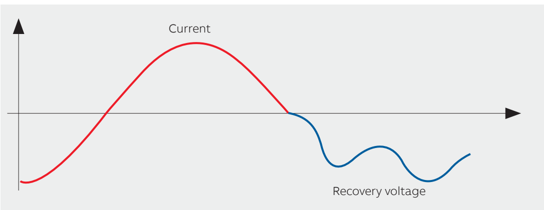


Fig. 5.23

This must be considered when analyzing the behavior of the circuit breaker when these currents are interrupted, since re-ignitions could occur.
By way of example, we will now consider an industrial installation like the one illustrated in fig. 5.24 (foundry with arc furnace):

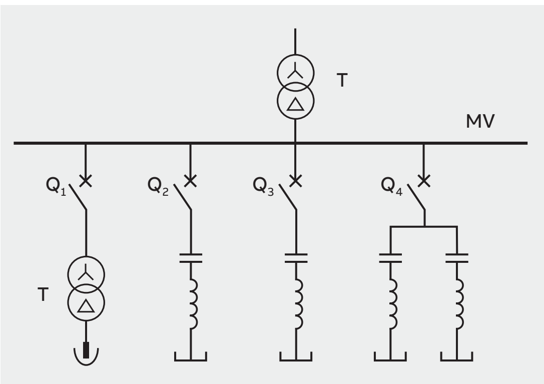


Fig. 5.24

There are four banks of filters for selective damping of the 2nd, 3rd, 4th and 5th harmonics.
The overvoltages associated with filter supply are not dangerous for either the components of the electrical system or the filters themselves. On the other hand, the particular shape of the TRV when the circuit breakers open could lead to re-ignitions, thus to considerable overvoltage.
The simplified diagram of a bank of filters can be represented in the following way:

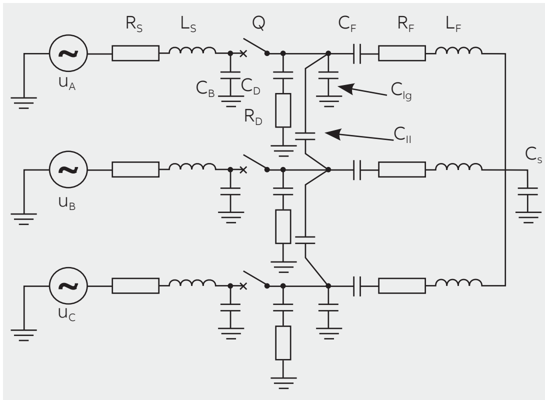


Fig. 5.25

where R_S and L_S are parameters of the power supply grid, R_F, C_F and L_F are filter parameters, R_D and C_D are the parameters of a device for limiting overvoltage (if applicable) (e.g. surge arrester), C_{II} and C_{Ig} are the capacitances of the connection cables, C_B the busbar equivalent capacitance and C_S the stray capacitance of the system. Using a circuit of this type in EMTP (Electro Magnetic Transient Program) simulation software, the behavior of the TRV can be examined case by case and critical situations can be predicted so that the necessary countermeasures can be adopted. There is no standard answer to the problem since the possibility of re-ignitions occurring depends on the order of the harmonics and the amplitude of the relative currents. The TRV trend when a third harmonic filter opens followed by two re-ignitions is illustrated in fig. 5.26.

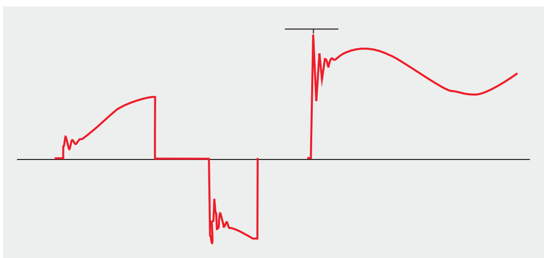
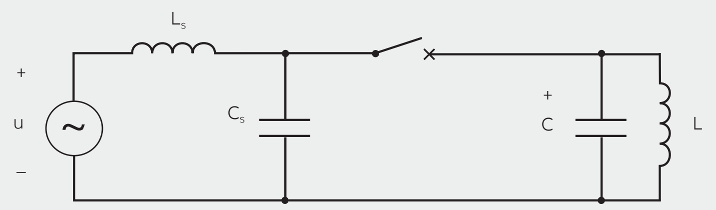


Fig. 5.26

5.1.7 Interruption of inductive loads: chopping current and re-ignitions

If one considers the interruption of inductive loads such as reactances, motors or no-load transformers, one notes that the currents involved are much lower than the short-circuit currents normally interrupted by circuit breakers and that they range from a few amperes to a few hundreds of amperes. It may therefore seem strange to go to the trouble of addressing the issue. However, interrupting such loads can be very hard on the circuit breaker and the installation.

With reference to the simplified circuit in fig. 5.27, let us suppose that a load consisting of reactance L must be opened.



L_s	Grid reactance	C	Capacitance on load side
C_s	Grid capacitance	L	Reactor inductance

Fig. 5.27

In the case of an ideal opening operation, current continues to flow by means of the electric arc in the arc chute after the contacts have separated, as indicated by CP in fig. 5.28.

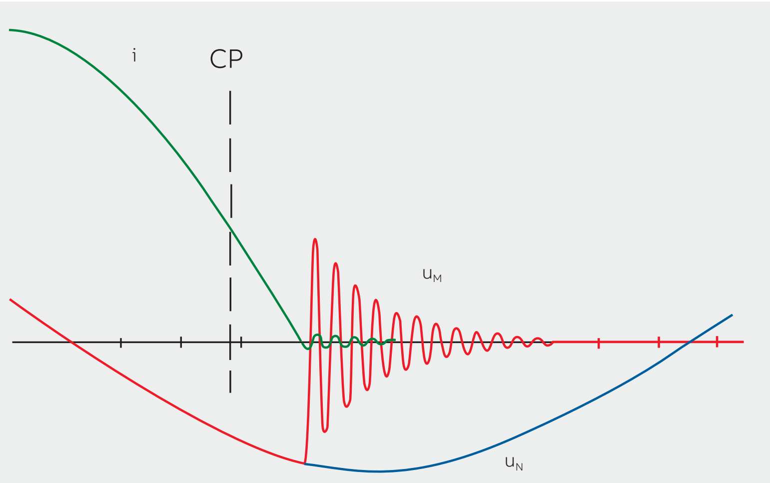


Fig. 5.28

The difference in voltage between the contacts of the circuit breaker is practically nil until the current crosses zero. After this, the voltage on the supply side follows the grid voltage while on the load side, the contact senses the charging voltage of capacitance C. The capacitance then begins to discharge into inductance L, by oscillating at frequency equal to:

$$f = \frac{1}{2\pi \cdot \sqrt{L \cdot C}}$$

The frequency thus depends on the value of the inductance and capacitance. This value can range from one to 10 kHz. There are no overvoltages in this ideal case.

In actual fact, the situation can be very different. When the circuit breaker opens, the arcing time for interrupting these modest currents is very brief. Consequently, the gap between the contacts is small. Meanwhile, as the recovery voltage is at its maximum, the withstand voltage between the contacts may not be sufficient to prevent the arc from restriking.
A further problem is due to the fact that the electric arc is unstable owing to the low current value and tends to be interrupted prematurely, before the current crosses zero (chopping current). Thus overvoltages (which are the effects of arc restrikings, chopping currents or a combination of both) are generated when small inductive loads are interrupted.

The value of the chopping current and inductance of generators and transformers and of loads like motors or reactances and the capacitance of the connection cables determine the value of the energy stored in the installation, thus also of the consequent overvoltage generated upon opening.

With reference to the simplified circuit illustrated in fig. 5.27, let us imagine that a load consisting of inductance L is being opened. If the chopping current is I_{ch}, then the magnetic energy stored in the inductance the moment interruption occurs will be:

$$W_m = \frac{1}{2}\, L I_{ch}^2$$

Again at the time of opening, the voltage on the load will equal the peak value of the star voltage of the source, thus:

$$U_P = \frac{U\sqrt{2}}{\sqrt{3}}$$

5. Switching overvoltages

And the energy stored in the capacitances will therefore be:

$$W_0 = \frac{1}{2}\, C\, U_p^2$$

Immediately after the interruption and before the phenomenon dampens owing to the losses in the circuit, there will be total energy W_c equal to W_m+W_0, which we will define as being equivalent to a voltage U_m applied to the total capacitance of the circuit, thus:

$$W_c = \frac{1}{2}\, C\, U_m^2$$

The equation of the energy balance can be written as:

$$\frac{1}{2}\, C\, U_m^2 = \frac{1}{2}\, C\, U_p^2 + \frac{1}{2}\, L\, I_{ch}^2$$

In conclusion, the overvoltage due to the chopping current is:

$$U_m = \sqrt{U_p^2 + \frac{L\, I_{ch}^2}{C}}$$

Which can also be expressed as an overvoltage factor equal to:

$$k_a = \frac{U_m}{U_p} = \sqrt{1 + \frac{L\, I_{ch}^2}{C\, U_p^2}}$$

while the oscillation frequency can range from 1 to a few kHz. As can be seen in fig. 5.29, after an interruption, the circuit breaker is subjected to the difference between the supply voltage and the voltage that generates on the inductive load. TRV is at its maximum at the second peak and re-ignition could occur since the gap between the contacts is still small.

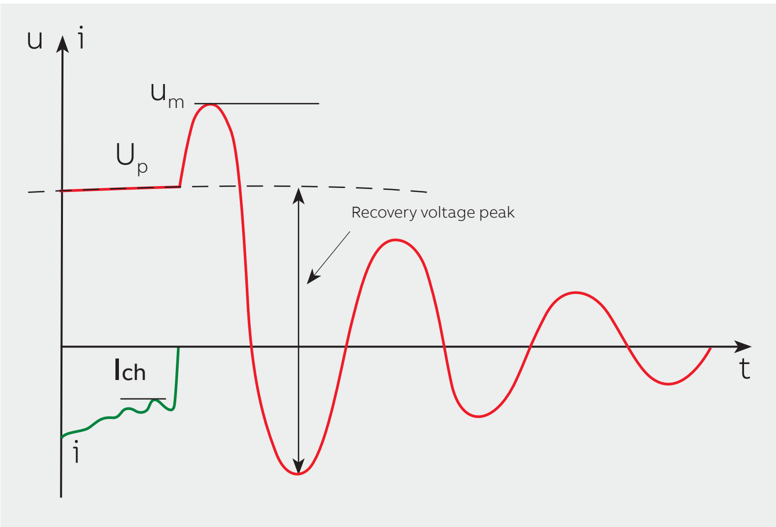


Fig. 5.29

5.1.8 Virtual chopping current

In actual fact, virtual chopping current is not a real chopping phenomenon but the normal interruption of a transient current. In a three-phase network, re-ignition as the dielectric in the pole of the first phase to be interrupted is being restored can cause instantaneous interruption of the current flowing in the other two phases. The pre-requisite is strong capacitive coupling between the phases and modest circulating currents.

The phenomenon can be described in the following way: with reference to fig. 5.30, when the current in the first phases is nil, the currents in the other two phases continue to flow thanks to the electric arcs that will have developed in the poles of the circuit breaker. If, a certain time t_b after current zero, re-ignition occurs in the first phase, a high frequency current with amplitude i_a generates due to the capacitance of the source C_{source} having discharged into the capacitance on the load side C_{load}

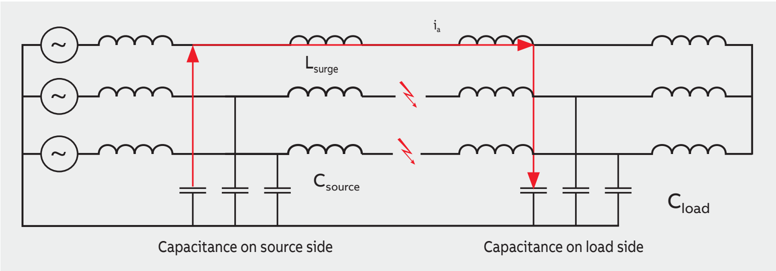


Fig. 5.30

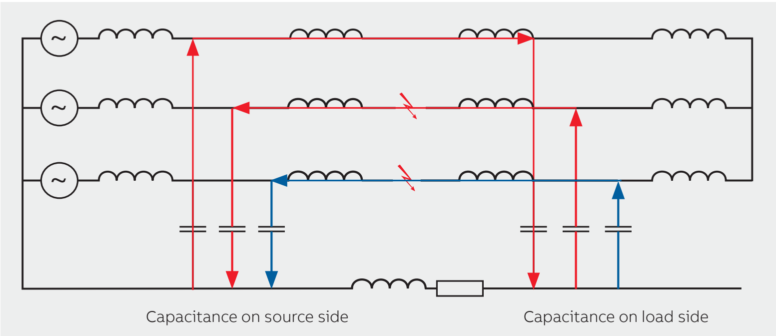


Fig. 5.31

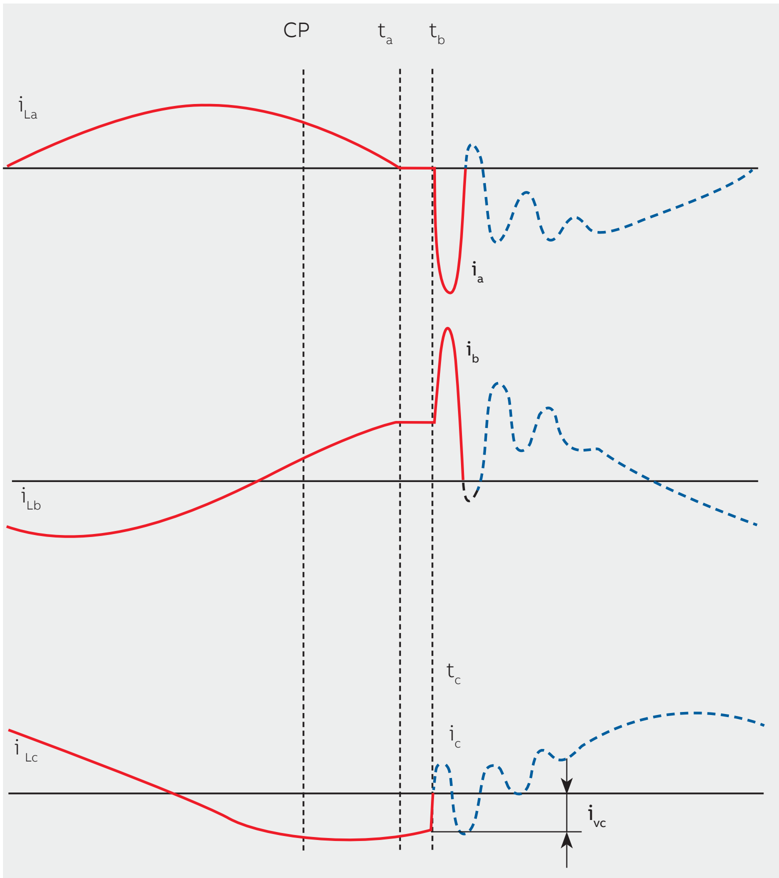


Fig. 5.32

The frequency and peak of current i_a are a function of the impedance of the electrical connection line L_{surge}. The values can be calculated with the same formulas used in the case of back-to-back capacitor switching. Since the source capacitance is normally larger than the load capacitance, the formulas can be simplified with fair approximation:

$$f_{re\text{-}ignition} = \frac{1}{2\pi} \cdot \sqrt{\frac{C_{load} + C_{source}}{C_{load} \cdot C_{source} \cdot L_{source}}} \approx \frac{1}{2\pi} \cdot \sqrt{\frac{1}{C_{load} \cdot L_{source}}}$$

$$\hat{I}_a = \Delta\hat{U}_{recovery} \cdot \sqrt{\frac{C_{load} \cdot C_{source}}{(C_{load} + C_{source}) \cdot L_{source}}} \approx \Delta\hat{U}_{recovery} \cdot \sqrt{\frac{C_{load}}{L_{source}}}$$

where ΔU is the difference between the voltage on the load side capacitance and the source voltage, i.e. the recovery voltage on the contacts of the circuit breaker.
If the impedance of the earth network is high or the system has an isolated neutral, the discharging current returns through the two phases, b and c, owing to their coupling via the earth capacitances (fig. 5.31). The high frequency currents superimpose the phase currents and have half the amplitude and the opposite polarity compared to the i_a which circulates in phase a. Depending on their value, these currents can considerably reduce or annul the phase currents and therefore cause an unexpected current zero.

The trend of the currents described above is illustrated in fig. 5.32, where CP is the instant the contacts separate, t_a is the instant of zero crossing of the first phase and, t_b is the instant that re-ignition occurs.

The currents resulting from this phenomenon can easily reach 100 A.

5. Switching overvoltages

5.1.9 Multiple re-ignitions

Re-ignitions occur when the contacts of the circuit breaker separate just prior to current zero crossing. One can assume that this time is typically less than 0.5 ms and the probability of a condition like this occurring is far from negligible since there is a current zero every 3.3 ms in a three-phase system at 50 Hz.
With reference to the circuit and fig. 5.33, the difference between the voltage on the source side u'_N and the voltage on the load side u_M is applied to the contacts of the circuit breaker after the interruption.
Since, initially, the gap between the contacts is still very small, re-ignition occurs if the dielectric withstand capacity is not sufficient to oppose the recovery voltage. The consequence of re-ignition will be circulation of a current which oscillates at high frequency, function of load capacitance C_K, capacitance C_N and the inductance of the connection line L'_N (see virtual chopping current formulas).

Current oscillation can cause a series of high frequency current zeroes, where the current can be interrupted again depending on the dielectric capacitance of the interruption medium, as illustrated in fig. 5.34.

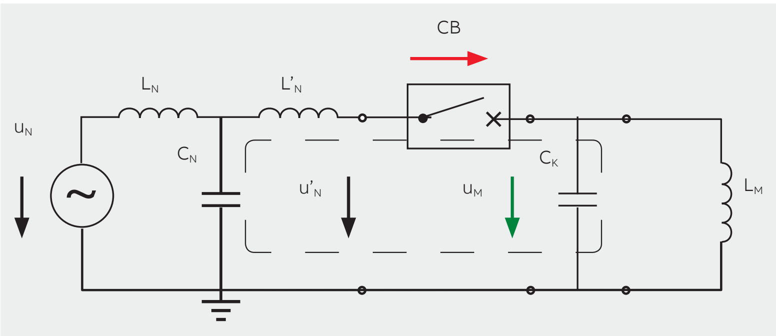


Fig. 5.33

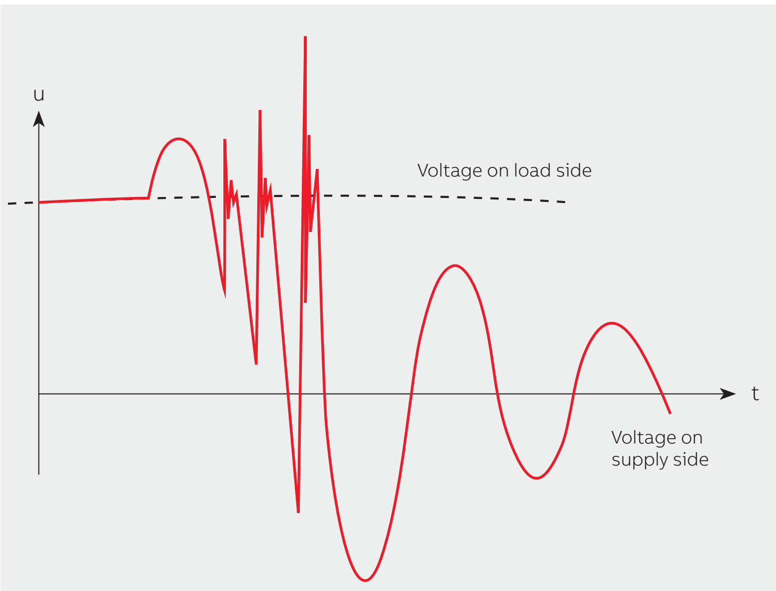


Fig. 5.34

Since, during re-ignition, further magnetic energy will have been stored in the load inductance, another re-ignition could occur, this time at a higher voltage than the previous one. Interruptions and re-ignitions continue (multiple re-ignitions) until the contacts are far enough away from each other to allow the dielectric withstand capacity to exceed the transient recovery voltage (generally after a few ms).

Depending on the dielectric withstand capacity of the gap between the fully open contacts (impulse withstand voltage) the peak value of the overvoltage can rise from 1 to 5 p.u. (where p.u., or value in per unit, expresses the ratio between the absolute value and predetermined reference value, in this case the phase voltage of the source). The rising front is very steep, from 1 µs to many µs, thus the overvoltage is not evenly distributed over all the coils of the winding of the reactance L_M but especially on the input coils.

Fig. 5.35: example of a power transformer

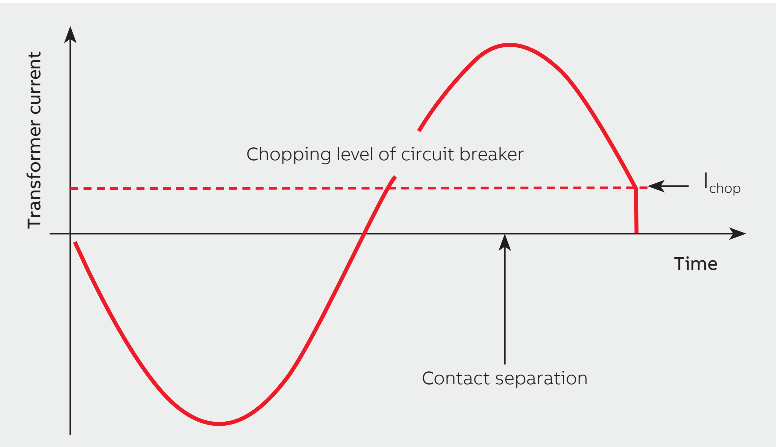


Fig. 5.36

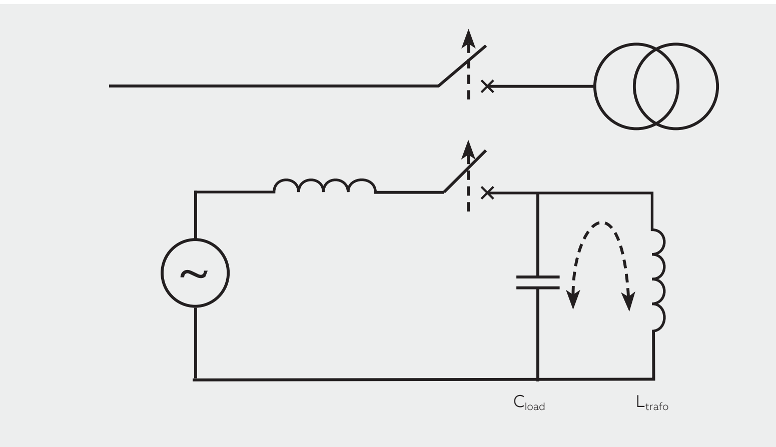


Fig. 5.37

5.1.10 Overvoltages relating to the switching of transformers

When a no-load transformer opens, e.g. after all the loads have been disconnected for scheduled maintenance or if the circuit breaker on the low voltage side has opened, the probability of re-ignitions occurring depends on its power and on the length of the cable between the circuit breaker and the transformer itself.
On the other hand, since the no-load current of a transformer is about 1% of the rated current, the risk of critical overvoltage due to the chopping current of the circuit breaker only becomes real in the case of large transformers.
When a high-power transformer is de-energized, the current flows through the contacts of the circuit breaker by means of the electric arc until the current drops below the value of the chopping current, after which the arc is extinguished. As explained in the chapter on chopping current, at this point the energy stored in the inductance of the transformer creates a peak in the recovery voltage which depends on the value of the chopping current I_{chop}, on the no-load inductance of the transformer L_{trafo} and on the capacitance C_{load} on the load side in relation to the circuit breaker (figs. 5.36 and 5.37).
This means that:

As explained in the previous chapters, the energy balance leads us to define the additional overvoltage as being worth:

$$\hat{U} = I_{chop} \sqrt{\frac{L_{Traf}}{C_{load}}}$$

Which adds to the grid voltage with a frequency of:

$$f = \frac{1}{2\pi \sqrt{L_{Trafo} \cdot C_{load}}}$$

Thus the overvoltage for a given transformer can reach high values depending on the chopping current and when the circuit breaker is very near the transformer, or the capacitance of the connection cable C_{load} is small. On the other hand, the frequency for large transformers is low (e.g. 1 kHz), thus the potential number of re-ignitions is limited (one or two) and the possibility of multiple re-ignitions is modest.

5. Switching overvoltages

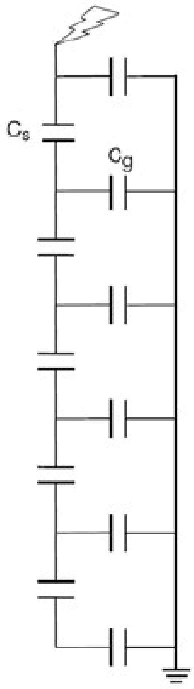


Figura 5.38: simplified circuit of the winding of a transformer in the first instants of the transient

A transformer or, more generally, a reactor can be imagined as though it were a series of RLC circuits where the resistance is that between the terminals of the winding and the inductance is formed by that of the individual coil plus the mutual inductance between the coils themselves. As illustrated in figure 5.38, the capacitances are those between the individual coils (Cs) and those between the coil and the casing of the transformer (Cg).
When a voltage step is applied to one end of the winding, the voltage first distributes over the various capacitive elements of the winding itself with values that depend on the value of the capacitance to earth Cg and that between the coils Cs. Using α to identify the coefficient that links Cs and Cg, one will note that the higher the value of α, the greater will be the stress on the initial coils as they face steep voltage ramps like the ones produced by restriking.

Considering that, $\alpha = \sqrt{\frac{C_{G\ TOT}}{C_{S\ TOT}}}$ one obtains the graph of figure 5.39 for a transformer with earthed neutral:

In actual fact, since this is an RLC circuit, the voltage propagates along the winding with a typical oscillation over time. Oscillating at different frequencies, the voltage along the windings has a different amplitude at every instant. The voltage values along the winding for different times t and α=10 are given in figure 5.40.

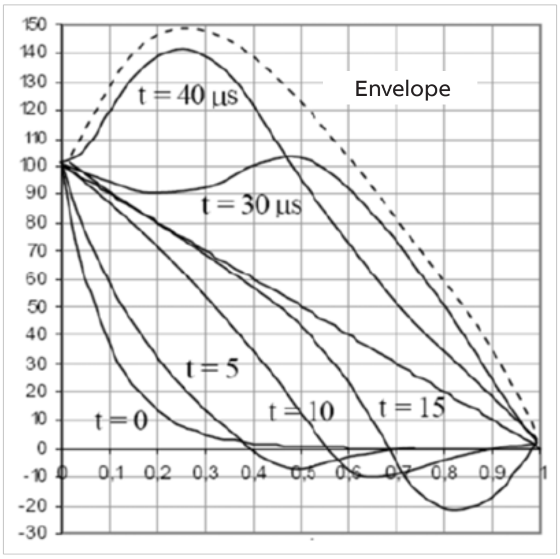


Figure 5.40: voltage oscillations in a winding with earthed ends (α =10).

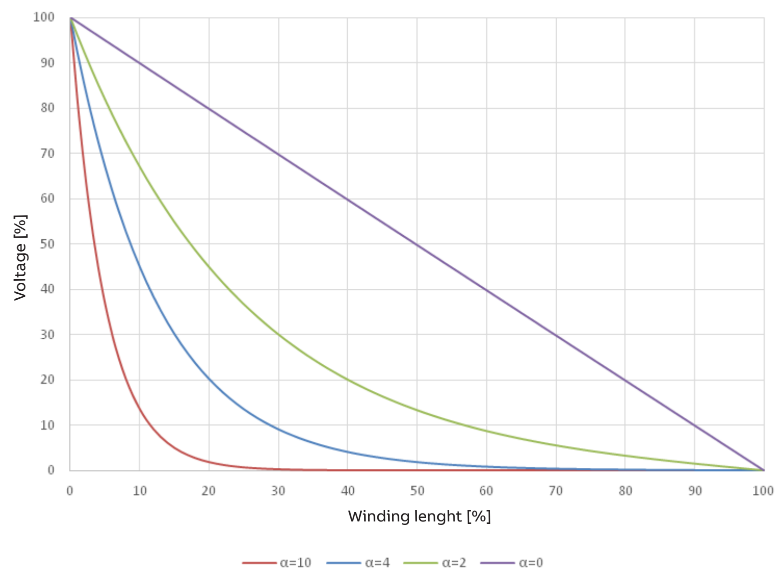


Figura 5.39: distribution % of overvoltage along the length of the winding for different values of α

The voltage oscillates around the final distribution (of the inductive type), thus for t, which tends towards infinity. The nearer initial distribution is to final distribution, the more these oscillations will be reduced. Here again, it is better for α to be as small as possible.
A typical value of α for a winding like the one in figure 5.41 is between 5 and 30. Remember that the lower α is, the more uniform distribution will be.

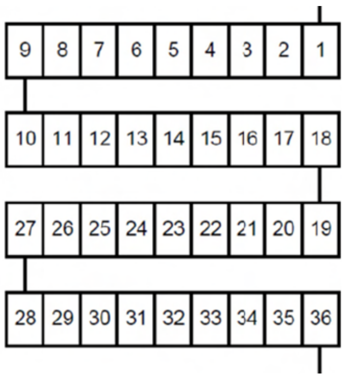


Figure 5.41: "Continuous disc" winding

Overvoltages linked to possible resonance points inside the transformer are another problem since, if stimulated as a result of repetitive phenomena such as restrikes or pre-strikes, can lead to considerable internal overvoltage.
This is why knowing the response in frequency of the transformer is of fundamental importance. The graphs of the impedance (amplitude and phase angle) of a 600 MVA single-phase transformer with three windings as a function of the frequency are illustrated in figure 5.42.

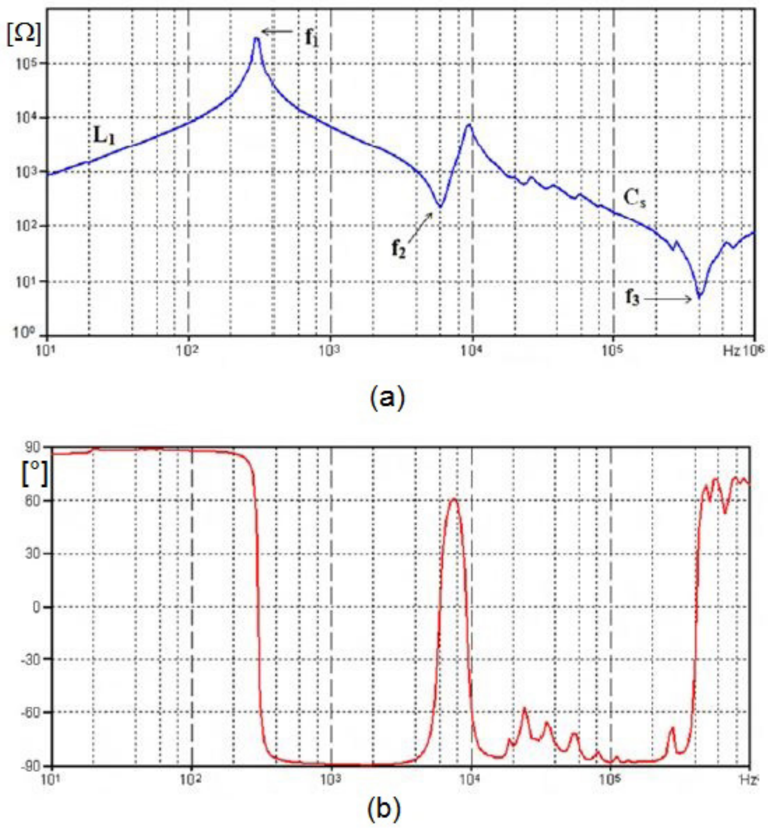


Figura 5.42: graphs of the impedance of a transformer as a function of frequency by amplitude a) and phase angle b).

If one considers the problem of re-ignition from the viewpoint of the different breaking techniques one can affirm that although the vacuum circuit breaker has chopping currents that are typically higher than those of the SF_6 circuit breaker, there are a modest number of arc restrikes thanks to the dielectric capacitances of the vacuum.
However, in smaller transformers with lower no-load currents than the chopping current of the circuit breaker, the overvoltage consequently depends on the value of the current in the instant the arc is suppressed rather than on the characteristics of the circuit breaker, so its values are therefore lower.
Experience shows that opening by means of a vacuum circuit breaker does not generate critical overvoltages in oil-insulated transformers with power ratings of less than 2MVA. Dry-type transformers are a different matter since they are more sensitive to overvoltage. In this latter case, it is advisable to protect the circuit with suitable devices as occurs for large transformers.

No-load transformer supply by closing the MV circuit breaker is yet another case.
Transformers are normally supplied after maintenance work or after the MV circuit breaker has opened for the purpose of eliminating a fault. After the circuit breaker has closed, the energy stored in the cables attempts to discharge itself via the magnetizing inductance of the transformer which, as long as the transformer core is not saturated, is a very high inductance and therefore results in very slow discharging. Vice versa, as soon as the core becomes saturated, the impedance quickly diminishes, thereby allowing the cable capitance to rapidly discharge. This phenomenon repeats itself cyclically as energy is exchanged between no-load inductance and line capacitance. In practice, the voltage oscillates with a square wave and dissipates a certain amount of energy at each cycle until the oscillation has been completely damped (figs. 5.43 and 5.44).

5. Switching overvoltages

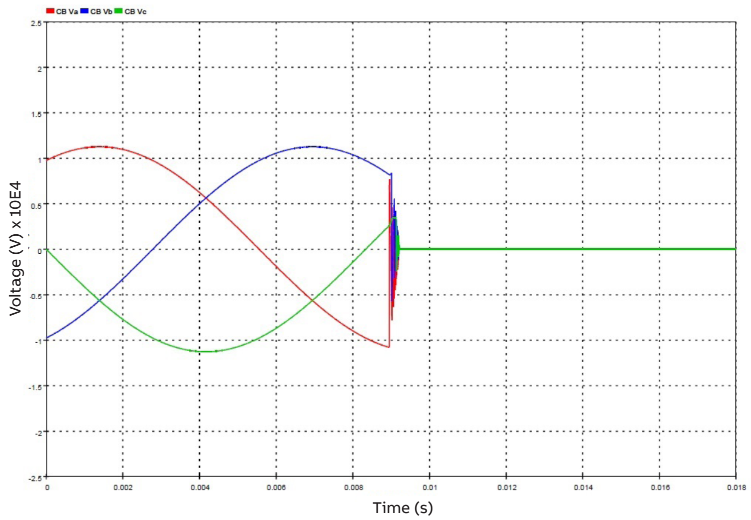


Figura 5.43: voltage between the circuit breaker contacts

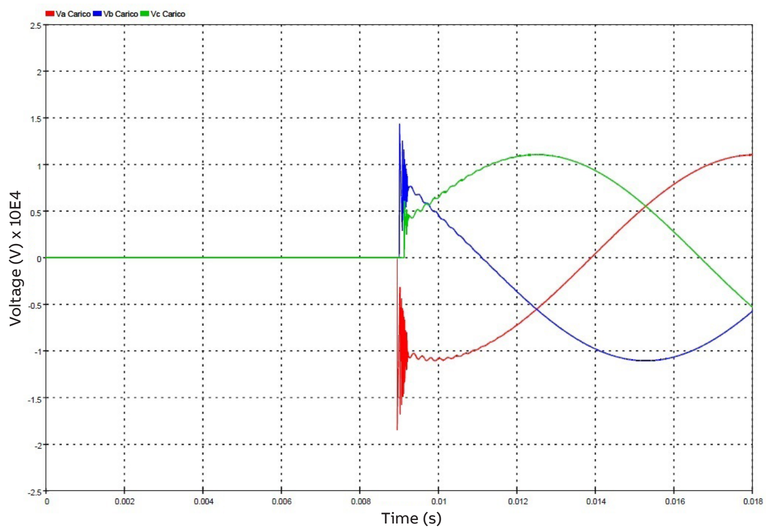


Figura 5.44: voltage on the load

If opening occurs during this transient, the overvoltages add to the already existing oscillation with values that can even be very high (many times the rated voltage) when the resonance frequency of the cable and transformer coincide. If this results in discharges inside the windings of the transformer, this latter could actually break down. In actual fact, it is very easy to resolve the problem by changing the length of the cable or installing capacitors on the transformer secondary.

5.2 Closing operation

5.2.1 Overvoltages in the supply of lines

To examine this case, one can start from the simplest situation, i.e. supply from a transformer of a single-cable. With reference to fig. 5.45, where the transformer is represented by its inductance L, one can affirm that when the circuit breaker closes the resulting transient voltage oscillates between Inductance L and cable capacitance C at a very low frequency and with an overvoltage whose peak can reach twice that of the grid voltage (fig. 5.46).

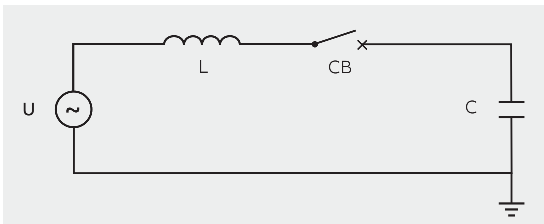


Fig. 5.45

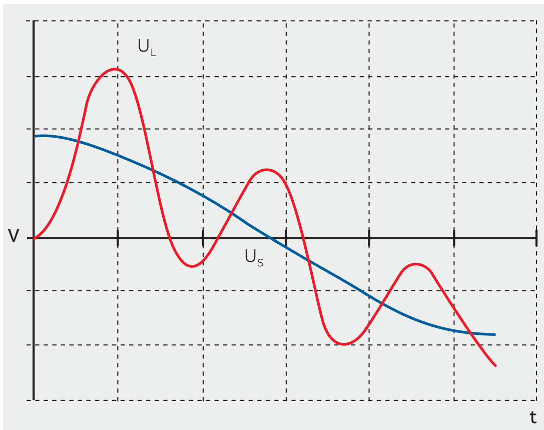
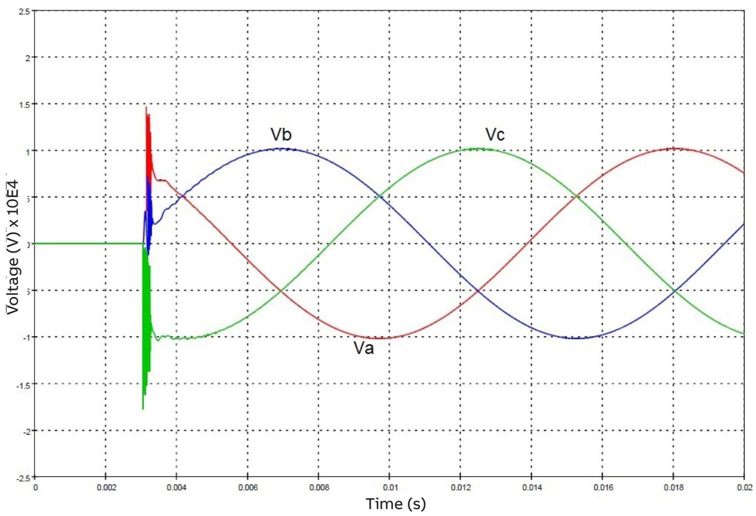
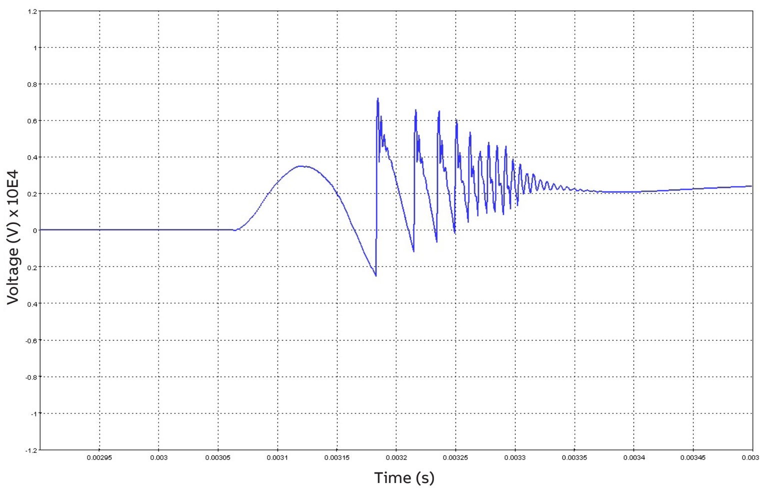


Fig. 5.46

In actual fact, this is the simplest case since in real installations, groups of cables and overhead lines that are more or less long are often present together. Generally speaking, when one or more no-load lines are supplied, the overvoltage increases as the length of the lines increases, as the inductance and frequency of the source increase and as line impedance decreases. However, the phenomenon is significant in HV installations owing to the very long overhead lines, but is negligible in MV systems.



a) Behavior of line-to-earth voltage when a motor starts.



b) enlargement of the voltage of phase Vb.

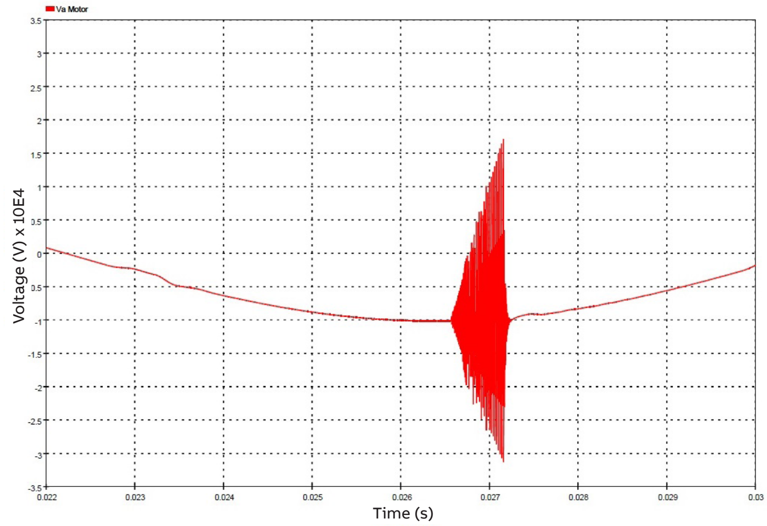
Fig. 5.48

5.2.2 Overvoltages in the supply of motors

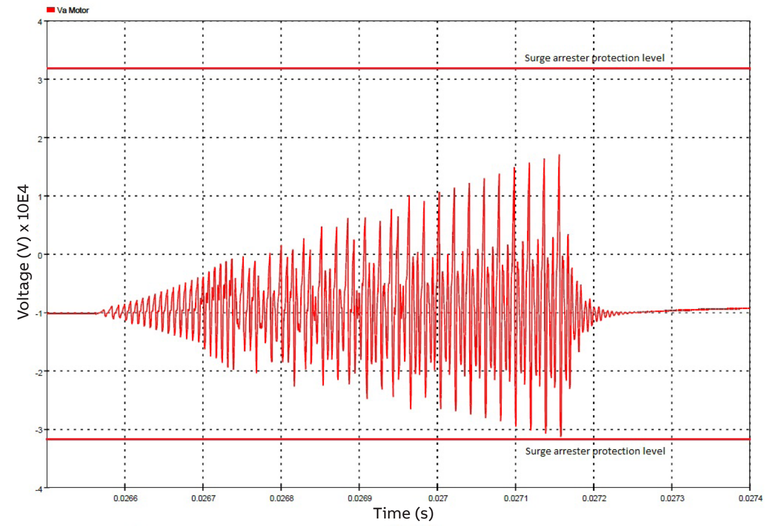
Fig. 5.47: example of an MV motor

Generally speaking, motors are switched more frequently than transformers and there are also more of them in the same network. This means that overvoltages able to put a strain on the motor insulation are very probable and that facing the problem is therefore worthwhile.
Besides the normal motor starting and stopping operations, one must also consider motor opening during the starting stage or with the rotor locked. However, overvoltages are not normally generated when motors are stopped. The starting stage of a large synchronous motor is illustrated in fig. 5.48, which also shows the line-to-earth voltage trend towards the motor terminals. The presence of multiple pre-strikes causing overvoltages in all three phases at the motor terminals is also shown.
Circuit breaker opening before the motor has reached top speed is also a critical operation. The starting current of a motor can rapidly reach high values after the circuit breaker has closed and since the motor is like a strongly inductive load when it starts, current zero occurs at the same time as the voltage peak. If opening occurs in this situation, the voltage at the terminals of the motor begins to oscillate at a frequency given by the inductance of the motor and by the capacitance on the load side until complete damping has occurred. The recovery voltage on the circuit breaker rapidly increases until it reaches values able to cause re-ignitions in relation to the instant in which the contacts separate, in other words, in relation to their distance.

5. Switching overvoltages



a) Line-to-earth voltage of a motor during an interruption caused by multiple restrikes.



b) enlargement of the voltage.

Fig. 5.49

Fig. 5.49 illustrates the interruption of a 12MW synchronous motor during the starting stage. The trend is that of line-to-earth voltage towards one of the motor terminals. A certain number of re-ignitions with increasing amplitude on each can be seen.
Asynchronous motors, especially the squirrel-cage type, can also be affected by multiple re-ignitions since their capacitance to earth is lower. During the starting stage, their behavior is similar to that of synchronous motors since rotor magnetization during that stage is practically nil.
There is less possibility of overvoltage due to re-ignitions in high-power motors since, owing to the higher current, arcing time is longer during interruptions thus the contact gap becomes large enough to avoid re-ignitions. However, different starting methods are often used for these motors, so the possibility of overvoltage must still be analyzed case by case.
As mentioned previously, a motor which stops during normal service does not generally cause overvoltage since the motor continues to turn over for a certain time when the circuit breaker opens, thereby maintaining the voltage on the load side of the circuit breaker. This voltage opposes the voltage on the supply side, so the recovery voltage to the circuit breaker is modest and slowly increases after current zero.

5.3 Overvoltage limitation

The transient phenomena discussed in the previous chapters were assessed on a statistical basis as to both number and entity. This means that it is difficult to establish beforehand when an overvoltage will occur or its absolute value. By and large, one can affirm that the peak values of the overvoltages should be limited to maximum 2 - 2.5 p.u. in installations where the service voltage is less than 72kV. As an even more precautionary measure, it would be advisable to limit the overvoltage to 70% of the impulse withstand voltage of the apparatus and especially of the power transformer of the installation.
Overvoltages can damage the windings of rotating machines, of transformers and reactances. During high frequency phenomena, the rising front of the voltage is very steep. This inevitably leads to uneven distribution in the windings and especially stresses the first, which have to withstand extremely high overvoltage.
These considerations lead one to affirm that limiting the peak value of the overvoltage is often not sufficient if the slope of the rising front is not limited at the same time.
The most widely used methods for limiting overvoltage refer to use of the following equipment:
- Surge arresters
- RC filters
- Chokes
- Synchronous switch-disconnectors and circuit breakers

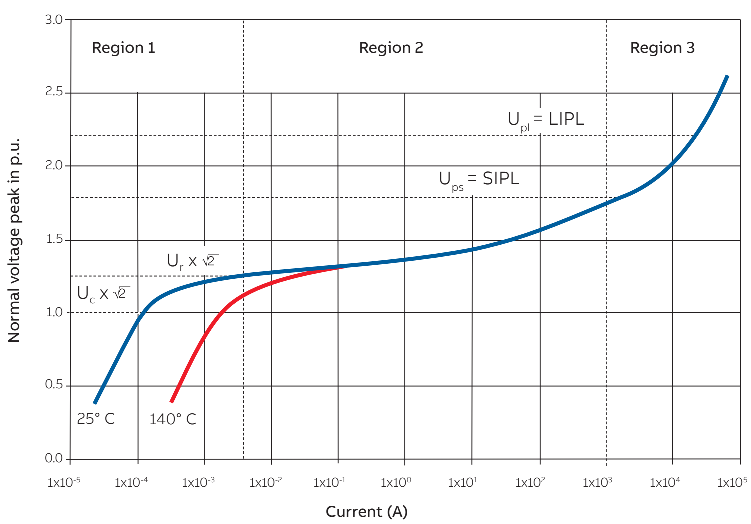


Fig. 5.50

5.3.1 Surge arresters

Proceed as described below when choosing a surge arrester (IEC 60099-5: “Surge arresters – Part 5: Selection and application recommendations”):
- the continuous service voltage of the surge arrester must be at least equal to the highest service voltage of the installation;
- establish the rated voltage of the arrester with reference to the forecast overvoltage;
- estimate the magnitude and likelihood of currents discharged via the arrester and then select the rated discharge current;
- establish the protection characteristic of the arrester's switching impulses so that it is coordinated with the electrical system: to do this, consider that the inception voltage for switching impulses of around 100 µs should be higher than the peak switching value of the TRV, which can reach 2.08 times the rated voltage. In addition, the residual voltage for switching impulses (at the highest discharge current values, thus around 10 kA) should be less than 70% of the impulse withstand voltage;
- the reference curves provided by manufacturers are similar to those illustrated by the Standard in fig. 5.50, where region 1 is the pre-discharge region characterized by low currents for stationary operations, region 2 features a non-linear trend and is typical of currents associated with transient overvoltages and switching impulses and region 3 is characterized by currents exceeding 1 kA generated by rapid impulses (e.g. atmospheric discharge). In addition, U_c is the continuous service voltage, U_r the rated voltage, U_{pl} (or LIPL) is the maximum residual voltage at rated discharge current for atmospheric discharge and U_{ps} (or SIPL) is the maximum residual voltage at rated discharge current for switching impulses;
- the energy absorbed determines the type of arrester with 200 to 1000 A peak currents for multiple re-ignitions, or 10 kA or more for atmospheric discharge impulses;
- position the arrester as near as possible to the apparatus that must be protected;
- the best protection is obtained by connecting the arresters between adjacent phases and between all the phases and earth;
- the connection to the surge arrester must be as short as possible and must have the same earth

5. Switching overvoltages

as the apparatus that must be protected. In the example in fig. 5.5.1 below (taken from the Standard) there are three cases of protection of a transformer T where case 3 guarantees excellent protection since there is only one earth and connection b is short and less than connection a.

This type of protection is limited by the fact that it is only effective for circuit breakers which produce overvoltage of a higher value than the level of protection of the surge arrester. In addition, re-ignitions could occur with values up to twice the protection value and without any reduction in the frequency of the overvoltage.

The phenomenon of re-ignitions before and after application of a surge arrester is illustrated in figures 5.52 and 5.53.

Using RC filters, which will be discussed in the next section, the result would be as follows (figure 5.54):

Overhead line

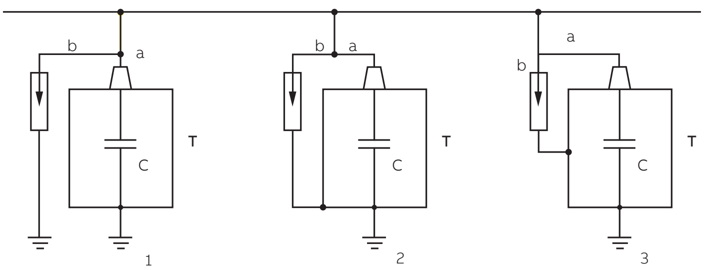


Fig. 5.51

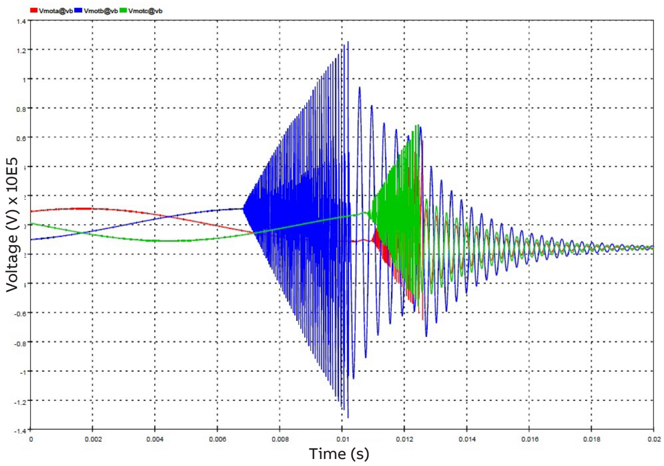


Fig. 5.52

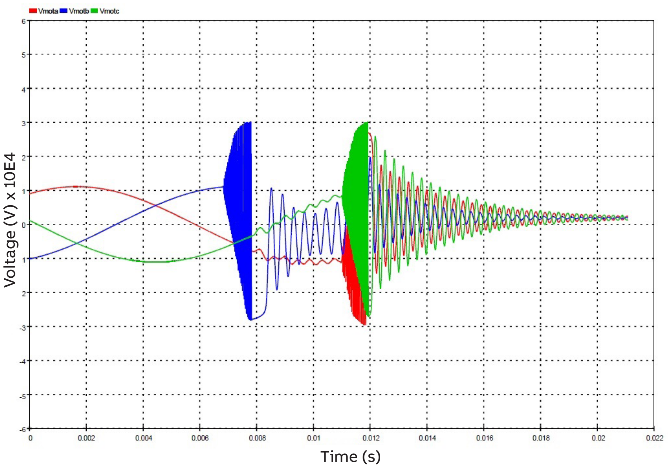


Fig. 5.53

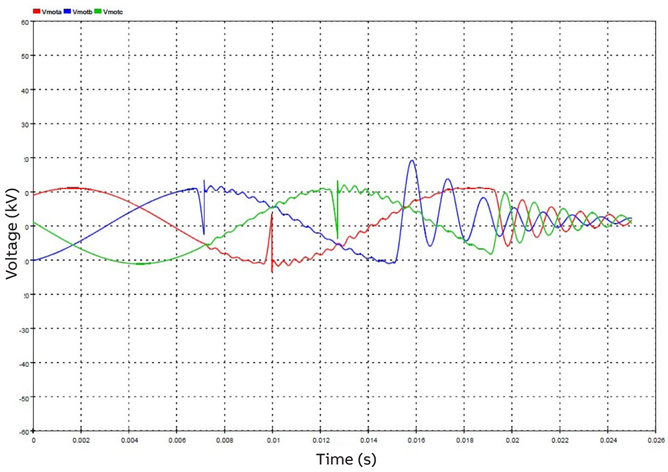


Fig. 5.54

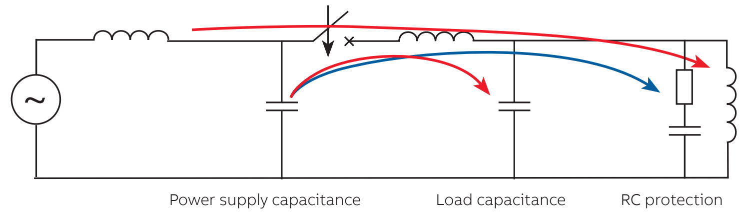
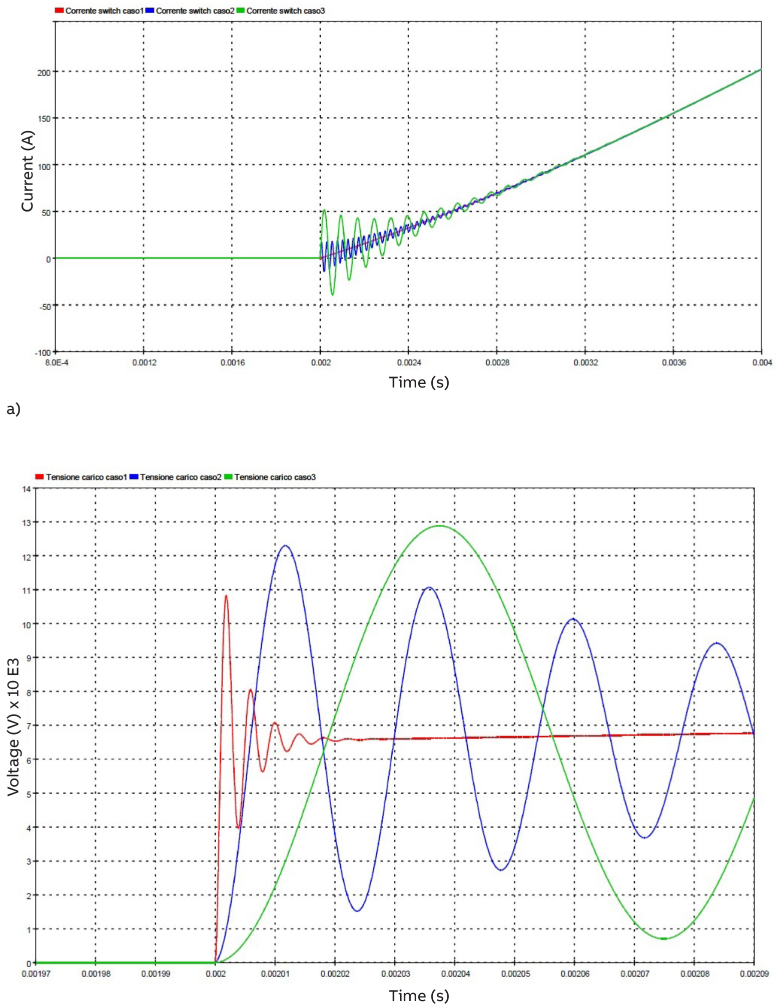


Fig. 5.55



a)

b)

Fig. 5.56

5.3.2 RC filters

RC filters consist of a capacitor in series with a resistor connected between line and earth to the terminals of the load that needs to be protected. RC filters are used in addition to surge arresters mainly to protect inductive loads. As already explained, this is due to the fact that surge arresters do not trip due to overvoltage rate of rise and therefore do not fully protect the windings of motors, generators, reactors and transformers since they are subjected to an uneven distribution of the voltage in the windings.
This protection is able to prevent pre-strikes on closing and multiple re-ignitions on opening of the circuit breaker since it reduces the rate of rise of the TRV.
Chapter 5.1.7 dealt with the subject of re-ignitions and the relative overvoltages and explained how a re-ignition causes a high-frequency current that superimposes the fundamental. The RC filter effectively tends to dampen high-frequency currents, thereby preventing multiple re-ignitions from occurring. In the oscillogram of figs. 5.56 a) and b), the damping effect is clearly evident with two different impedance values, with respect to the green curve in the simulation circuit of fig. 5.55 given as an example.

However, one must consider that, similarly to surge arresters, a centralized protection cannot be obtained but that all devices connected to the same busbar - motors and transformers - must still be protected against overvoltage.
In the example of fig. 5.57, both transformers are protected by surge arresters and RC filters to prevent damage due to overvoltage.

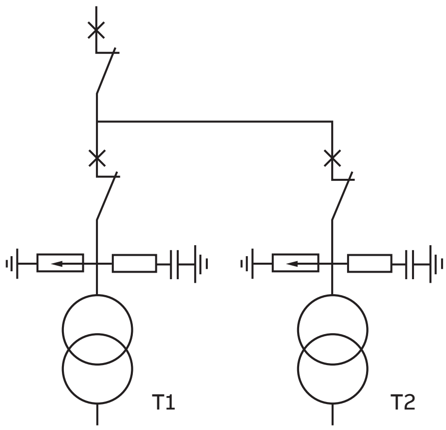


Fig. 5.57

5. Switching overvoltages

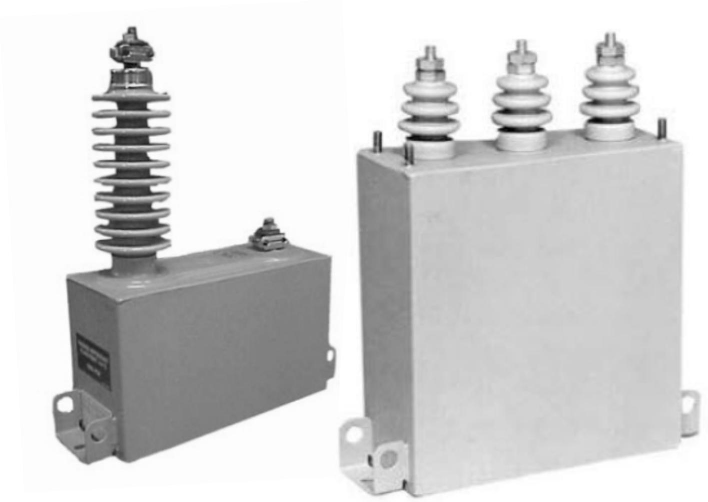


Fig. 5.58: examples of RC filters

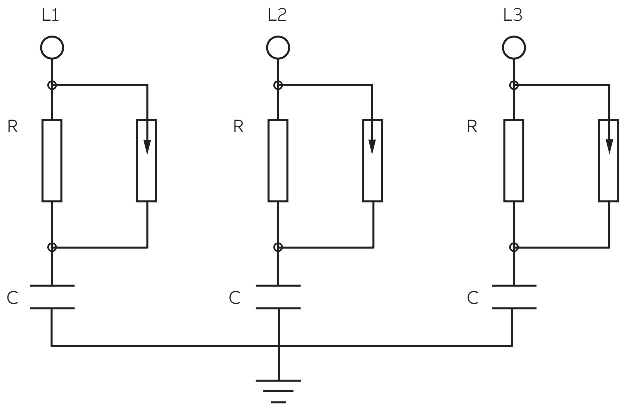


Fig. 5.59

Capacitance C must be chosen so that it is much larger than the capacitance of the connection cable between circuit breaker and transformer (or to all events, of the device that needs to be protected).
Typical values range from 0.1 to 0.25 μF. Specific capacitors are available on the market. They are known as surge capacitors and are able to support even high overvoltage. Thus they are suitable for this type of use. ABB proposes single- or three-phase surge capacitors for voltage values up to 13.8 kV, and 0.08 to 0.75 μF capacitance.

On the other hand, to prevent wave reflections in the cable, the resistance must be chosen so that it is identical to the transient impedance of the cable itself. The resistance must also dampen the high frequency oscillations of the current. Note that in the case of several cables in parallel, the cable impedance diminishes and the resistance of the RC filter must diminish at the same time. The resistance must have a low inductance, the same impulse withstand voltage as the installation and must have sufficient power to support the dissipated power caused by the current at rated frequency and by potential harmonics.
Integrated devices called ZORC are also available on the market. These devices house surge arresters, capacitors and resistors in a single enclosure (fig. 5.59). Integrated solutions up to 40 kV are available.

The disadvantages of these solutions are the cost of losses in the resistor and the design engineering costs, since each installation must be treated in a different way and it is therefore difficult to use standard devices.

5.3.3 Chokes in series

When it comes to damping voltage transients, blocking reactances, or chokes, are an alternative to RC filters. As can be seen in fig. 5.60, they are installed in series between the circuit breaker and apparatus that needs to be protected.

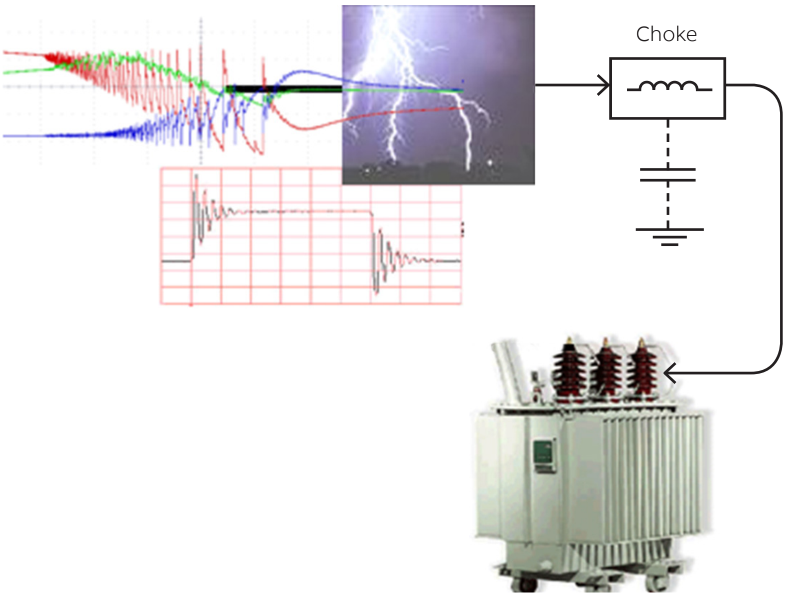


Fig. 5.60

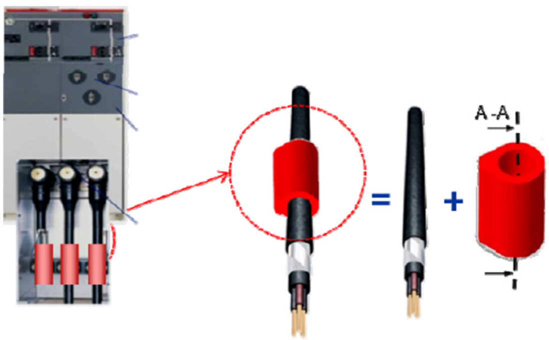


Fig. 5.61

Depending on the load downstream, chokes may or may not require damping capacitors to be installed between the terminals and earth, e.g. in the case of a dry-type transformer connected directly to the protection circuit breaker. It has been experimentally demonstrated that 100 μH inductances dampen overvoltage to a significant extent, especially when used in conjunction with 10 nF capacitors. The resistance in parallel with the inductance also ensures that the oscillating circuit formed by the inductance of the device and the supply side capacitances is also damped. The typical resistance values vary from 30 to 150 W. In practice, this protection must meet the following requirements:

- it must have a high impedance at frequencies between 100 kHz and 1 MHz;
- grid frequency (50-60 Hz) transparency is required;
- voltage drops, thus losses, must be as few as possible.

The advantages can be interesting since both a reduction in the rate of rise and a limitation of the peak value of the overvoltage can be effectively obtained. In addition, re-ignitions in the circuit breaker on the supply side are less probable. The reduction in losses can be obtained by optimizing the magnetic core and relative winding. One of the advantages of coil chokes (fig. 5.61) is that they are easy to install, since they can be fitted onto the conductors that connect to the transformer.

The disadvantage of the solution with chokes in series is that multiple re-ignitions cannot be completely prevented (unless capacitors are also added). In addition, the solution is not widely used in power installations except in Japan, where it is limited to applications up to 6.6 kV. The cost of losses and the noise produced must also be considered. Here again, the best results are obtained by optimizing the protection of each individual apparatus. Thus, every installation must be treated in a different way and use of standard devices becomes hardly feasible.

5. Switching overvoltages

5.3.4 Synchronous switch-disconnectors and circuit breakers

These devices were already mentioned in chapter 3.5 as part of the explanation on breaking techniques and will be discussed again in chapter 9.2.4 in relation to capacitor switching.
Synchronized switching makes the previously described traditional solutions (damping of overvoltage generated by re-ignitions) obsolete since it tackles the root of the problem. Bear in mind that not only is the cost of the traditional solution, using RC filters for example, comparable to or higher than that of a synchronous switching device, but it also poses the problem of size, safety (if used in old installations, since the devices must be fitted to the terminals of the apparatus that must be protected) and standardization.
On the other hand, synchronous switching devices are installed in MV switchgear just like the other apparatus, circuit breakers and switch-disconnectors, in a modular way and in the safest possible manner. The basic principle is to allow current to flow into the individual poles until natural zero crossing and to then open the circuit. This effectively prevents re-ignitions from occurring since the contacts do not separate until that moment.
We will now examine the operating principle in a single-phase circuit and compare it to classic circuit breaker closing.

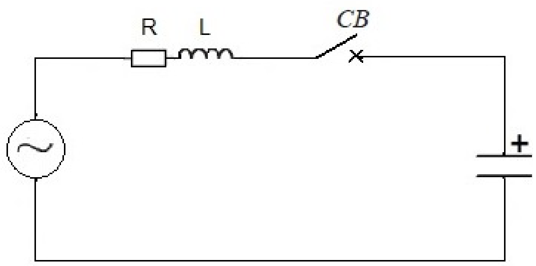


Fig. 5.62

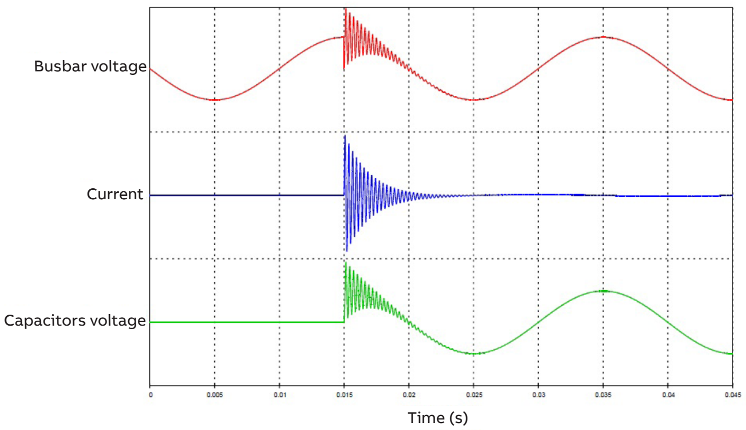


Fig. 5.63

In the example in figure 5.62, the overcurrent peak can reach over 10 p.u. (fig. 5.63) and this can cause:

- considerable voltage drops resulting in the connections being oversized;
- problems with the torque of electric machines (bear in mind that for induction machines, torque varies with the square of the voltage);
- problems concerning electric power quality.

The solution adopted to date has been to use limiting reactors which, by their presence, limit the amplitude of the overcurrent and frequency.
Obviously, this solution:

a) is not economical, since the limiting reactor is a costly item;
b) is bulky, since these reactors are generally air reactors and take up a lot of space;
c) short-circuit faults can occur between the limiting reactor and capacitor bank, resulting in high TRV values.

When a capacitor bank opens, having been switched by conventional circuit breakers or switch-disconnectors, appropriately sized surge arresters are typically required to limit potential overvoltage due to restriking, and this involves higher costs for the customer.
A synchronous solution free from restrikes allows capacitor banks to be switched-in and out by means of diode technology. This eliminates overvoltage (even in the back-to-back configuration) and the risk of restrikes during opening.

With reference to the closing stage and the equivalent circuit in figure 5.64, the DS1 functions in the following way:

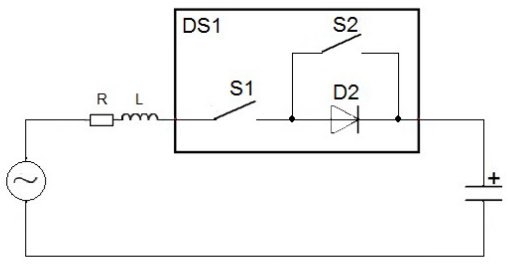


Fig. 5.64

1. DS1 closes contact S1 during the negative half wave of the voltage on the busbar;
2. the diode is then reverse biased for as long as the voltage remains negative. The diode begins to conduct as the voltage crosses zero. The capacitor is therefore switched in at zero voltage, thereby minimizing the overcurrent;
3. since there is a 90° phase shift between the current and voltage, contact S2 is closed before they become negative again;

In conclusion, the capacitor will have been switched in without overcurrent having been generated (fig. 5.65).

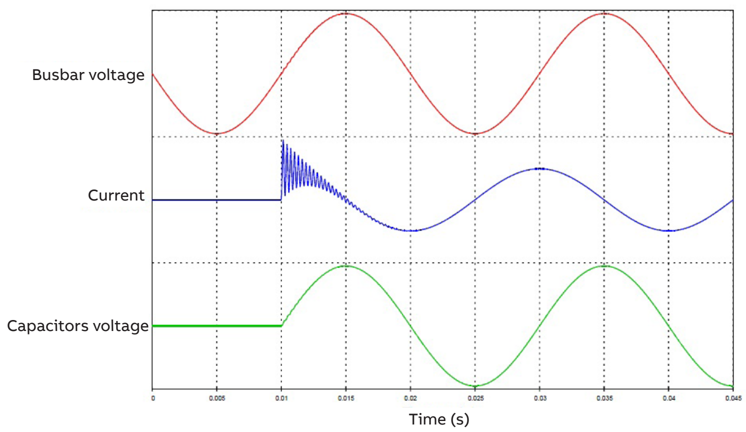


Fig. 5.65

Regarding the opening stage and the equivalent circuit of figure 5.66, the sequence is:

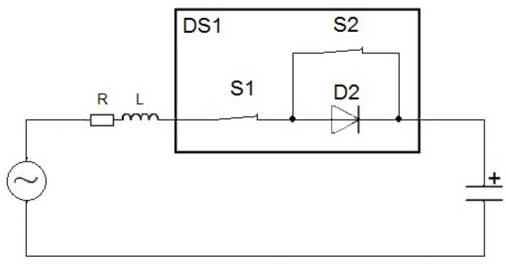


Fig. 5.66

1. contact S2 is opened when the current and voltage are positive, allowing current to pass into the diode;
2. the moment in which the current reaches zero, the diode turns off and is reverse biased. Current consequently stops flowing;
3. lastly, contact S1 is opened

6. Mechanical specifications

6.1 Mechanical operating sequences

The operating mechanism in modern medium voltage circuit breakers that provides mechanical energy for separating the contacts is strongly integrated into the structure, of which it is an integral and fundamental part.
The operating mechanism must be designed to optimize the mechanical energy with which the poles are supplied so as to allow these latter to function properly. This must be done by applying the required separation speed to the contacts but without supplying too much power, thus preventing damage to the mechanical components and allowing the required number of switching operations to be achieved.
Product Standard IEC 62271-100 divides circuit breakers into two classes:

- class M1 for circuit breakers with a normal mechanical endurance, able to perform 2,000 operating sequences;
- class M2 for circuit breakers with extended mechanical endurance, able to perform at least 10,000 operating sequences. These circuit breakers must be designed to require only limited maintenance, such as lubrication of certain parts.

The mechanical operating mechanism is the stored energy type charged in the manual mode or by the motor of the closing spring. The opening spring is loaded during the closing operation. The opening and closing operations take place at speeds that are independent from the operator and the operating mode (manually using local or remote push-buttons or by means of the opening and closing shunt releases).
When it is not equipped with a geared motor for loading the closing springs, the operating mechanism can enable the following sequences:

- with circuit breaker open and closing spring loaded: C – O;
- with circuit breaker closed and closing spring loaded: O - C - O.

When equipped with a geared motor for loading the closing springs, the operating mechanism can perform repeated reclosing operations thanks to automatic reloading after each closing sequence.
Circuit breakers with permanent magnet operating mechanisms are a different case since this mechanism is very simple. It reduces the number of mechanical components to the minimum, thereby also reducing the amount of maintenance work required. In this case, the number of operating sequences is decidedly higher, although always limited by the mechanical endurance of the vacuum interrupters.
Switch-disconnectors are governed by Standard IEC 62271-103, which also provides for two classes: M1 for 1,000 operating sequences and M2 (extended mechanical endurance) for 5,000 operating sequences.
The reference Standard for disconnectors is IEC 62271-102 and comprises three classes: M0 for normal mechanical endurance and 1,000 operating sequences, class M1 for extended mechanical endurance in conjunction with a circuit breaker with 2,000 operating sequences and class M2, again for extended mechanical endurance in conjunction with a circuit breaker, for 10,000 operating sequences.
Lastly, contactors are governed by Standard IEC 62271-106. According to this Standard, the manufacturer must declare the number of no-load operating sequences in millions of operating sequences, preferably using the following numbers: 0,01 - 0,03 - 0,1 - 1 - 3.
The following tab. 7 outlines the number of mechanical operating sequences per type of switching device.

Apparatus	Contactor	Circuit breaker				Multifunction apparatus						Capacitor switch
						HySec			GSec			
	VSC	HD4	VD4	VM1	Vmax	Circuit breaker	Line disconnector	Earthing switch	Line disconnector Op. mech. S1 Single spring	Line disconnector Op. mech. S2 Double spring	Earthing switch	DS1
Max. numb. op.sequences	1000000	10000	30000 (*)	30000 (*)	10000	10000	1000	1000	5000	1000	1000	50000
Class	n.a.	M2	M2	M2	M2	M2	M0	M0	M2	M1	M0	M2
IEF ref. standard	IEC 62271-106	IEC 62271-100	IEC 62271-100	IEC 62271-100	IEC 62271-100	IEC 62271-100	IEC 62271-102	IEC 62271-102	IEC 62271-103	IEC 62271-103	IEC 62271-102	IEC 62271-103

(*) 30,000 operating sequences up to 17.5 kV - 2500 A - 31.5 kA and up to 24 kV - 2500 A - 25 kA; 10,000 operating sequences for higher ratings.

Tab. 7

6.2 Static and dynamic loads during switching

The maximum static load of the circuit breaker approximately equals the weight of the apparatus itself. On the other hand, the dynamic load is about double the weight of the circuit breaker. Since circuit breakers are normally installed in one of the units of a switchgear (fixed or withdrawable), in this case the dynamic load will range approximately from 10 to 15% of the total weight of the unit.

6.3 Climatic conditions

The normal operating conditions are defined for all the apparatus in Standard IEC 62271-1.
For indoor apparatus, the Standard specifies that:

a) the ambient temperature must not exceed 40 °C and its average value, measured over a period of 24 hours, must not exceed 35 °C.
   The minimum ambient temperature must be chosen from among certain preferred values which, in our case, is -5 °C. On request, ABB can provide apparatuses able to operate at lower minimum temperatures;
b) the altitude must not exceed 1,000 m a.s.l;
c) the ambient air must not be polluted by dust, smoke, inflammable or corrosive gas, vapors or salt;
d) the humidity conditions must be the following:
   - the average relative humidity value measured over a period of 24 hours must not exceed 95%;
   - the average water vapor pressure value measured over a period of 24 hours must not exceed 2.2 kPa;
   - the average relative humidity value measured over a period of one month must not exceed 90%;
   - the average water vapor pressure value measured over a period of one month must not exceed 1.8 kPa;

Bear in mind that condensation could occasionally form in these conditions and in the presence of rapid temperature changes.

7. Temperature specifications

7.1 Temperature limits and derating due to ambient temperature

If the ambient temperature exceeds 40 °C (the limit specified by Standard IEC 62271-1 for normal operation), the rated current of the apparatus must be appropriately derated. However, derating may not be necessary if margins with respect to the admissible maximum values are discovered during the temperature-rise tests required by the Standard. Since ambient temperature refers to the temperature of the air around the circuit breaker, the characteristics of the circuit breaker compartment in the switchgear are of fundamental importance when defining the ΔT with respect to 40 °C. Lastly, one must consider that when high temperatures are involved, the operating mechanism requires more frequent maintenance if lubrication problems are to be avoided.
Vice versa, although the rated current need not be derated because of the temperature, temperatures of less than -5 °C could affect the mechanical characteristics in a negative way. HD4 and VD4 circuit breakers have passed the low temperature test, but the problem must still be faced case by case.

7.2 Temperature-rise test

The temperature-rise test is a mandatory test required by Standard IEC 62271-1. This test attests to the capability of the apparatus to carry its rated current for an indefinite time and is performed by assessing compliance with the maximum temperatures allowed by the Standard in various points of the apparatus. The test must be performed with sinusoidal current and the frequency must be declared. The test must last long enough for the temperature to be able to reach a stable value. This normally occurs when the temperature rise does not exceed 1 K in 1 hour. This happens when the test lasts 5 times the thermal-time constant of the tested apparatus. Fig. 7.1 illustrates the typical temperature test trend of a circuit breaker where θ_c is the temperature of the tested apparatus and θ_a is the temperature of the air.

In the absence of ferrous materials alongside the path of the current, the test conducted at 50 Hz can also be considered for 60 Hz, so long as the temperature values reached do not exceed 95% of those specified by the Standard as admissible maximum values. Particular attention must therefore be paid if the tests performed in the switchgear are extended. Vice versa, rating being equal, tests performed at 60 Hz can also be considered valid at 50 Hz.

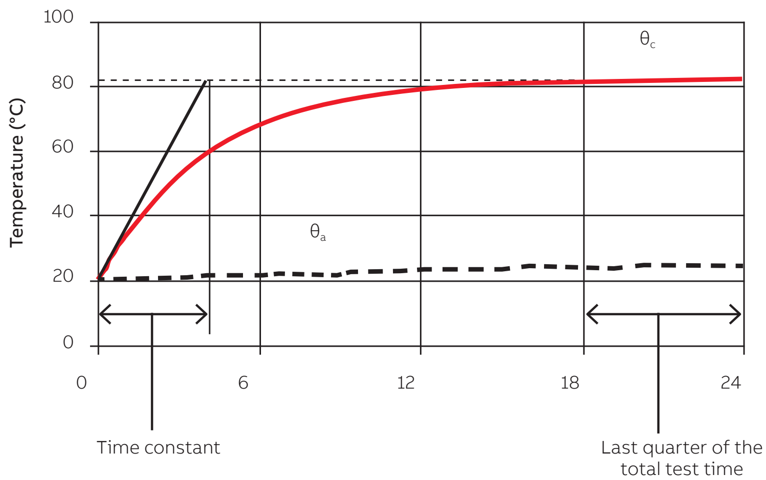


Fig. 7.1

7.3 Temperature rise due to an overload

If an apparatus has been used at a current value that is less than its rated current I_r, the load current can be increased to a value able to ensure that the admissible temperature limit established by the Standard is not exceeded. Technical Guide IEC/TR 62271-306 deals with the subject in detail.
There are certain factors which influence the length of the period of time t_s relating to overcurrent I_s.
These are:
- the value of the current I_s itself;
- the value of the continuous current I_i carried before the overload;
- the thermal-time constant of the apparatus τ obtained from the type tests;
- the ambient temperature before and during the overload.

The time during which overcurrent I_s can be applied can be calculated in the following way:

$$t_S = \tau\left[-\ln\left\{1 - \frac{\theta_{max} - Y - \theta_a}{Y\langle (I_S/I_i)^{1,8} - 1\rangle}\right\}\right]$$

with

$$Y = (\theta_{max} - 40)\cdot\left(\frac{I_i}{I_r}\right)^{1,8}$$

where:

- θmax is the temperature limit of the hottest point in °C, in accordance with Standard IEC 62271-1;
- θa is the ambient temperature in °C;
- I_i is the initial current in A, that is, the maximum current carried by the circuit breaker during the 4 hours prior to application of overcurrent I_s;
- I_s and I_r are expressed in A and τ in hours;
- t_s is the time in hours in which current I_s is allowed to flow at the temperature of θa and after I_i;
- Y is a coefficient given in K.

Thus calculated, time t_s will not cause the temperature limit to be exceeded so long as:
1. the apparatus, and especially the contacts, are new and in an excellent state;
2. I_i is effectively the current carried by the circuit breaker during the 4 previous hours. It is advisable to make a recording during this period;
3. at the end of period t_s, the current drops to a value $\leq I_r$;
4. the value of I_s is in no case more than twice I_r.

For example, supposing that there is an overload in a 1250 A circuit breaker (at 40 °C) due to the I_s=6125 A starting current of a motor. The initial current prior to the overload is I_i=370 A with θ_{max} of the circuit breaker equal to 105 °C. The ambient temperarture is θ_a=40 °C and lastly, the time constant of the circuit breaker is typically τ=0.5 h. The results obtained by applying the formula are:

$$Y = (105 - 40)\cdot\left(\frac{370}{1250}\right)^{1,8} = 7,26$$

$$t_S = 0,5\cdot\left[-\ln\left\{1 - \frac{105 - 7,26 - 40}{7,26\cdot\langle (6125/370)^{1,8} - 1\rangle}\right\}\right] = 0,026\ h$$

in other words 1 min and 35 sec.

When choosing the setting of the protection relay of the medium voltage apparatus, one must consider the potential overloads that affect the electrical installation so as to protect the load and the circuit breaker itself.

8. Insulation characteristics

8.1 Insulation co-ordination

Standard IEC 60071-1 Insulation co-ordination, Part 1: Definitions, principles and rules, establishes how insulation must be co-ordinated and explains "selection of the dielectric strength of equipment in relation to the operating voltages and overvoltages which can appear in the system for which the equipment is intended and taking into account the service environment and the characteristics of the available preventing and protective devices, where dielectric strength of the equipment is meant here its rated or its standard insulation level".

The amplitude, form and duration of the voltages and overvoltages which stress the insulation must be determined by means of an analysis of the system, which must also include the choice and location of the devices for preventing and limiting overvoltages.

After this, a representative voltage and overvoltage must be chosen on the basis of the previous analysis for the purpose of associating a standard withstand voltage test. Lastly, the Standard requires that the highest voltage be used for establishing the insulation of the equipment by choosing from among the standard withstand voltages that characterize the insulation of the equipment in the specific application.

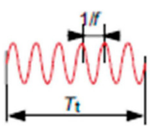
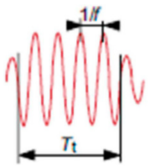
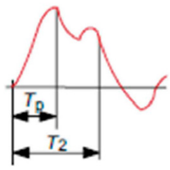
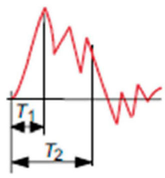
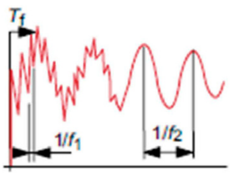
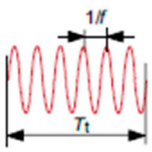
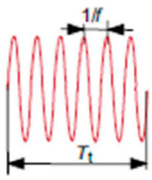
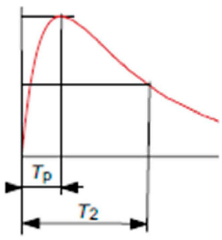
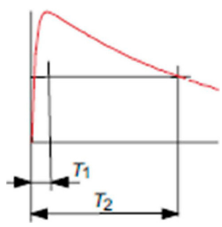
The process for defining the choice of rated or standard insulation level is described in the Standard.

8.2 Over-voltages

Standard IEC EN 60071-1 (see tab. 8) groups all the voltages and over-voltages that may be present in an installation into classes of defined shape and duration, but with amplitudes that depend on the installation itself and on the limiting devices.

Almost all the classes refer to standard voltage shapes and the relative standard withstand voltage tests to which reference should be made.

For medium voltage installations and apart from the last class, over-voltages can be the lightning impulse type (column 4) or temporary over-voltage at power frequency (column 2). The slow-front transients concern HV systems at Um > 245 kV.

Category	Low frequency		Transient		
	1) Continuous	2) Temporary	3) Slow front	4) Fast front	5) Very fast front
Voltage or over-voltage shapes					
Range of voltage or overvoltage shapes	f = 50 Hz or 60 Hz $T_t \geq 3600s$	10 Hz < f < 500 Hz $0.02s \leq T_t \geq 3600s$	$20\ \mu s < T_p \leq 5000\ \mu s$ $T_2 \geq 20\ ms$	$0,1\ \mu s < T_1 \leq 20\ \mu s$ $T_2 \geq 300\ \mu s$	$T_1 \leq 100\ ms$ $0.3\ MHz < f_1 < 1000\ MHz$ $30\ kHz < f_2 < 300\ kHz$
Standard voltage shapes	 f = 50 Hz or 60 Hz T_t (a)	 48 Hz ≤ f ≤ 62 Hz $T_t = 60s$	 $T_p = 250\ \mu s$ $T_2 = 2500\ \mu s$	 $T_1 = 1,2\ \mu s$ $T_2 = 50\ \mu s$	
Standard withstand voltage test		Short-duration power frequency test	Switching impulse test	Lightning impulse test	

Tab. 8

8.3 Insulation level

The standard insulation levels for medium-voltage circuit breakers are given in tab. 9 (IEC 62271-1):

Rated voltage U_r **kV (root mean square value)**	**Rated short-duration power-frequency withstand voltage** U_d **kV (root mean square value)**		**Rated lightning impulse withstand voltage** U_p **kV (peak value)**	
	Common value	**Across the isolating distance**	**Common value**	**Across the isolating distance**
(1)	(2)	(3)	(4)	(5)
3.6	10	12	20	23
			40	46
7.2	20	23	40	46
			60	70
12	28	32	60	70
			75	85
17.5	38	45	75	85
			95	110
24	50	60	95	110
			125	145
36	70	80	145	165
			170	195

The withstand voltage values apply towards earth, between the poles and between the terminals of the open switching device.
The “on isolating distance” values only apply to apparatus designed to comply with the functional requirements of the disconnectors.

Tab. 9

8.4 Circuit breaker dielectric tests

The purpose of conducting insulation type tests is to make sure that the apparatuses comply with the insulation levels specified in the previous tab. 9.
The tests required for MV apparatuses are:
- short-duration power-frequency voltage withstand tests;
- lightning impulse voltage test.

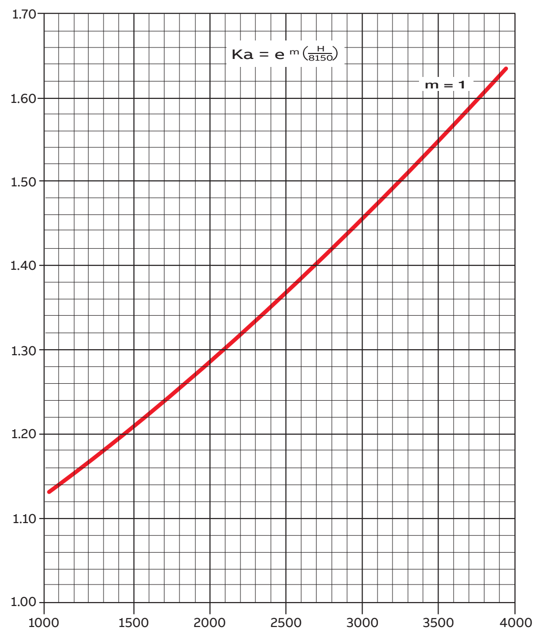
The tests are performed at standard atmospheric values:
- Temperature t_0 = 20 °C;
- Absolute pressure p_0 = 1 013 hPa (1013 mbar);
- Absolute humidity h_0 = 11 g/m^3.

Correction factors can be applied if the values deviate from those above. A short-duration power-frequency voltage withstand tests should be performed as one of the routine tests, according to the values in table 9 (column 2). The circuit breaker could also be subjected to a further dielectric test if, following agreements between the switchgear manufacturer and user, the voltage test on the main circuit is repeated in-site after installation. In this case, the test voltage will be 80% of the rated value (IEC 62271-200).
Standard IEC 62271-1 also requires tests to be performed on low voltage circuits, such as control circuits, motors, anti-condensation heaters, etc. The short-duration power-frequency voltage withstand tests is normally conducted between the auxiliary and control circuits connected together and the structure of the apparatus.
The value envisaged by the Standard for the type test is 2 kV for 1 min., while the voltage drops to 1 kV for 1 s for the routine test.

8. Insulation characteristics

8.5 Altitude correction factor

The insulating properties of the air diminish as altitude increases. This must be taken into account for the external insulation of the equipment (insulation inside the pole is not subjected to variations as it is sealed).
This phenomenon must always be taken into account when the insulating components of equipment that must be installed over 1000 m above sea level is designed.
A correction coefficient must be used in this case. This coefficient can be obtained from the graph on the following page, created in accordance with the indications provided by Standard IEC 62271-1 (which refers the reader to IEC 60071-2).
The example below gives a clear interpretation of the indications above:
- installation altitude 2000 m;
- use at 12 kV rated voltage;
- power frequency withstand voltage 28 kV rms;
- impulse withstand voltage 75 kVp;
- Ka factor found from graph 1.27.



H = altitude in meters;
m = value with reference to power frequency, lightning impulse withstand and line-to-line voltages.

Fig. 8.1

In view of the aforementioned parameters, the equipment must withstand (during tests at zero altitude, i.e. at sea level):
- power frequency withstand voltage:
  28 · 1,27 = 36 kVrms;
- impulse withstand voltage equal to:
  75 · 1,27 = 95 kVp.

It will be apparent from the above that equipment with 17.5 kV rated voltage characterized by 38 kVrms power frequency insulation levels and 95 kVp impulse withstand voltage is required for installations at an altitude of 2000 m above sea level with 12 kV operating voltage.

8.6 Other tests: X-ray emission

For vacuum circuit breakers, IEC 62271-1 requires a test to be performed to make sure that the X-ray emission levels produced by interrupters do not exceed the maximum admissible limits. These maximum limits are (fig. 8.2):
a) 5 μSv per hour at a distance of 1 m at maximum operating voltage U_r;
b) 150 μSv per hour at a distance of 1 m at a voltage equal to the value of the short-duration voltage at power frequency.

Tests performed by ABB have shown that the X-ray emission values of its interrupters are well below those specified.

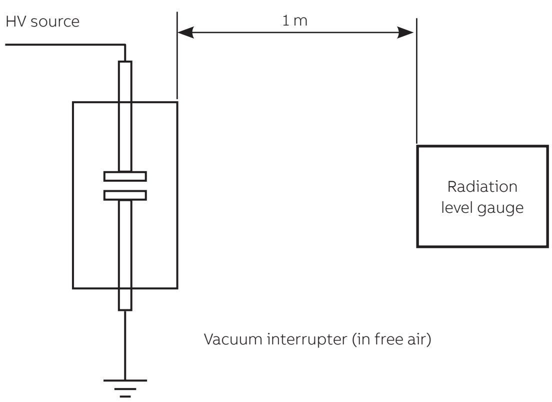


Fig. 8.2

8.7 Effects of the outdoor environment: specific climatic conditions

When the environmental conditions are particularly aggressive during service, manufacturers of circuit breakers for indoor use should be consulted about every special service condition, e.g. in the presence of dust, smoke, corrosive gas, vapours or salt, etc. However, IEC 62271-1 gives specific indications about switchgear and controlgear.
Chapter 4.2 "Special service conditions" and in particular in section 4.2.3 "Exposure to pollutions" the user is asked to define the site pollution severity (SPS) class according to IEC TS 60815-1. Furthermore, appendix K includes descriptions of the classes "Very light", "Light" and "Medium" and suggestions for the minimum nominal specific creepage distance by pollution level to be adopted in these cases. For indoor applications up to 52 kV the IEC Standard IEC 62271-304 "High voltage switchgear and controlgear - Part 304: Design classes for indoor enclosed switchgear and controlgear for rated voltages above 1 kV up to and including 52 kV to be used in severe climatic conditions" can also be used.

By and large, a correct assessment of the environmental conditions must be based on a set of historical data recorded daily, monthly or on a seasonal basis (as appropriate). Surveys prior to installation dedicated to a specific situation may not be sufficiently comprehensive to determine whether the environment-product are compatible. The switchgear and controlgear manufacturers must be consulted after these analyses have been conducted, especially if the service conditions are more severe than normal.

9. Applications

9.1 Circuit breakers for protecting transformers

Fig. 9.1: example of an MV distribution transformer

Transformers are basically inductive loads, especially compared to the other components in the installation, such as lines and cables. Thus, in certain rare cases, the impedance of the transformer is predominant and influences the short-circuit trend with a time constant of the direct component, which could acquire higher values than the standard 45ms. For example, this happens when the transformer is connected directly to the busbars or installed in close proximity to the point of generation, thus with a small capacitive contribution from the cables and lines.

In these cases, Standard IEC 62271-100 specifies a higher time constant, i.e. 120 ms (fig. 9.2) for voltage up to 52 kV. Note that the direct component percentage is much higher than the maximum value defined by the Standard, equal to 20% for the 45 ms standard time constant.

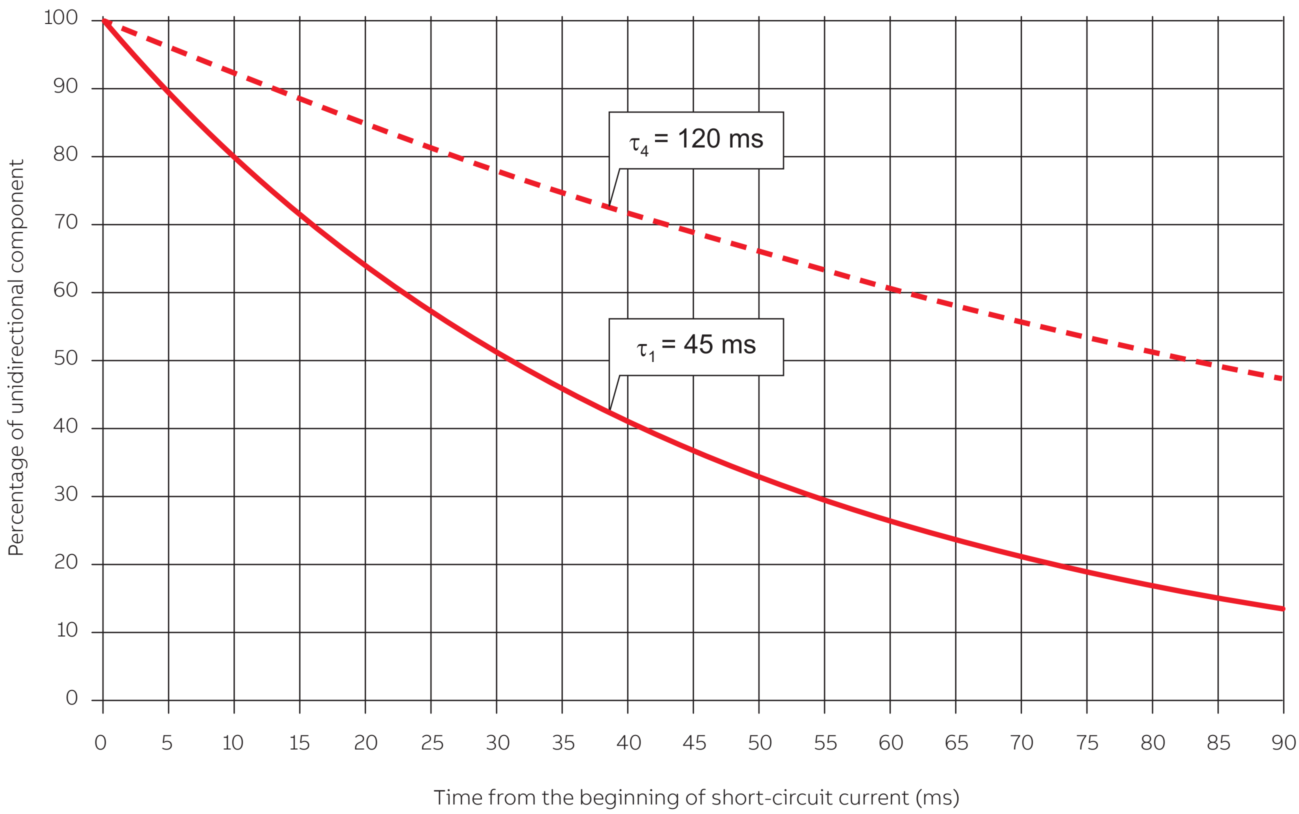


Fig. 9.2

In these cases, the circuit breaker may not be suitable for breaking short-circuit current. Generally speaking, when there are doubts about a high direct component, it is advisable to conduct simulation studies of the installation and to specifically analyze the point in which the circuit breaker is installed, using dedicated software like EMTP (Electromagnetic Transient Program).
Another case to consider is when the circuit breaker closes and supplies a no-load transformer. Indicative values of the inrush currents and relative time constants for oil-immersed and dry transformers are given in the next table, depending on their power. When it comes to step-up transformers with no-load supply on the LV side the phenomenon is even more evident, with higher ratios and lower time constants.

These currents are not a problem for the circuit breakers but must be considered when the protection relays are chosen owing to their direct component and relative harmonic content.
To protect the transformer with a different device from a circuit breaker in conjunction with a fuse, the chosen fuse must be able to protect the transformer against short-circuits but without tripping in the case of inrush current due to no-load switching. Tab. 12, with the choice of ABB fuses to use in conjunction with VSC contactors and tab. 13, with the choice of fuses for GSec switch-disconnectors, are included below.

Power in kVA	100	160	250	315	400	500	630	800	1,000	1,250	1,600	2,000	2,500	3,150
$n_{rush} = \frac{\hat{I}_{rush}}{I_n}$	14	12	12	12	12	12	11	10	10	9	9	8	8	8
τ_{rush} in seconds	0.15	0.20	0.22	0.24	0.25	0.27	0.30	0.30	0.35	0.35	0.40	0.45	0.50	0.55

Tab. 10: Typical inrush currents for medium voltage supply in the case of MV/LV oil-immersed transformers.

Power in kVA	160	250	400	630	800	1,000	1,250	1,600	2,000
$n_{rush} = \frac{\hat{I}_{rush}}{I_n}$	10.5	10.5	10	10	10	10	10	10	9.5
τ_{rush} in seconds	0.13	0.18	0.25	0.26	0.30	0.30	0.35	0.40	0.40

Tab. 11: Typical inrush currents for medium voltage supply in the case of MV/LV dry transformers.

Rated voltage of transformer	**Rated power of transformer**																		**Rated voltage of fuse**
	25	**50**	**75**	**100**	**125**	**160**	**200**	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**	**2500**	
[kV]	Rated current of fuse																		[kV]
3	16	25	25	40	40	50	63	80	100	125	160	200	250	315	2x250[1]	2x315[1]			3.6/7.2
5	10	16	25	25	25	40	40	50	63	80	100	125	160	200	250	315	2x250[1]	2x315[1]	
6	6	16	16	25	25	25	40	40	50	63	80	100	125	160	200	250	315	2x250[1]	
10	6	10	16	16	16	20	20	25	31.5	40	50	63	80	100	125	160	200	2x250[1]	12
12	6	6	10	16	16	16	20	20	25	40	40	50	63	80	100	125	160	200	

Use CMF fuses
([1]) An external fuse holder must be used

Tab. 12: Choice of fuse coordinated with VSC for transformer protection

9. Applications

Rated voltage of transformer [kV]	Rated power of transformer																Rated voltage of fuse [kV]
	25	50	75	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	
	Fuse CEF In [A]																
3	16	25	25	40	40	50	63	80	100	125	-	-	-	-	-	-	3.6/7.2
5	10	16	25	25	25	40	40	50	63	80	100	125	-	-	-	-	
6	6	16	16	25	25	25	40	40	50	63	80	100	125	-	-	-	
10	6	10	16	16	16	20	20	25	31.5	40	50	63	80	100	125	-	12
12	6	6	10	16	16	16	20	20	25	40	40	50	63	80	100	125	
15	6	6	10	10	16	16	16	20	20	25	40	40	50	63	80	80	17.5
20	6	6	6	10	10	16	16	16	20	20	25	31.5	40	50	63	80	24
24	6	6	6	6	10	10	16	16	16	20	20	25	40	40	50	63	

Tab. 13: Choice of fuses coordinated with GSec for transformer protection

Lastly, when it comes to breaking the magnetizing current in the case of no-load transformers, one must first bear in mind that there are no type tests for this operation, first because it is less severe than others and second because it would be difficult to reproduce in a model.

Fig. 9.3: ABB MV fuses

This task is not particularly challenging for oil-immersed transformers. The current amplitude is negligible. It can be less than 1 A in modern, low loss transformers. Both SF_6 and vacuum circuit breakers can be easily used for these types of transformers.
In dry transformers, the main problem when the vacuum current is opened concerns over-voltages due to the chopping current and multiple re-ignitions (chap. 5.1.7 and 5.1.9). From this standpoint, SF_6 circuit breakers function in a better way compared to vacuum circuit breakers. Whatever the case, over-voltages depend on the length of the cables that connect the circuit breaker to the transformer, so the longer the cable, the less over-voltage there will be. 3.5 p.u. is the maximum value the overvoltage can reach, so careful assessments must be made when these transformers are used and devices able to limit the over-voltages must be installed when necessary (chap. 5.3).

9.1.1 Protection relays for transformers

Power transformer switching is one of the typical and most frequent applications for medium voltage circuit breakers. Circuit breakers are normally required to perform a very limited number of operations, only a few each year in many cases. However, there can be exceptions, such as pumping stations and arc furnaces where a high number of switching operations is required. If a short circuit occurs on the load side of the transformer, the fault is normally eliminated by low voltage circuit breakers. This is especially true for transformers that supply several users and correct coordination of the protections guarantees

selectivity, thus maximum continuity of service. However, the medium voltage circuit breaker may also be required to operate following a fault in the actual transformer or medium voltage riser and for putting back into service after an opening due to a fault or maintenance.
The protections required on a power transformer and that can cause the circuit breaker to open are:

- relay 49 thermal overload protection;
- relay 51 inverse time overcurrent protection;
- relays 51 or 50 overcurrent protection for short-circuit on secondary side;
- relay 50 overcurrent protection for short-circuit on primary side;
- relay 87T residual-current protection of transformer;
- relay 51G-MV overcurrent protection for earth fault on primary side;
- relay 51G-LV overcurrent protection for earth fault on secondary side;
- relay 26 temperature-rise protection;
- relay 63 over-pressure protection (only for oil-cooled/insulated transformers).

A few transformer protection system configurations are illustrated in fig. 9.4.
In this case, the recommended relays are: REF 601, REF 615, RET 615, RET 620, RET 630 (fig. 9.5).

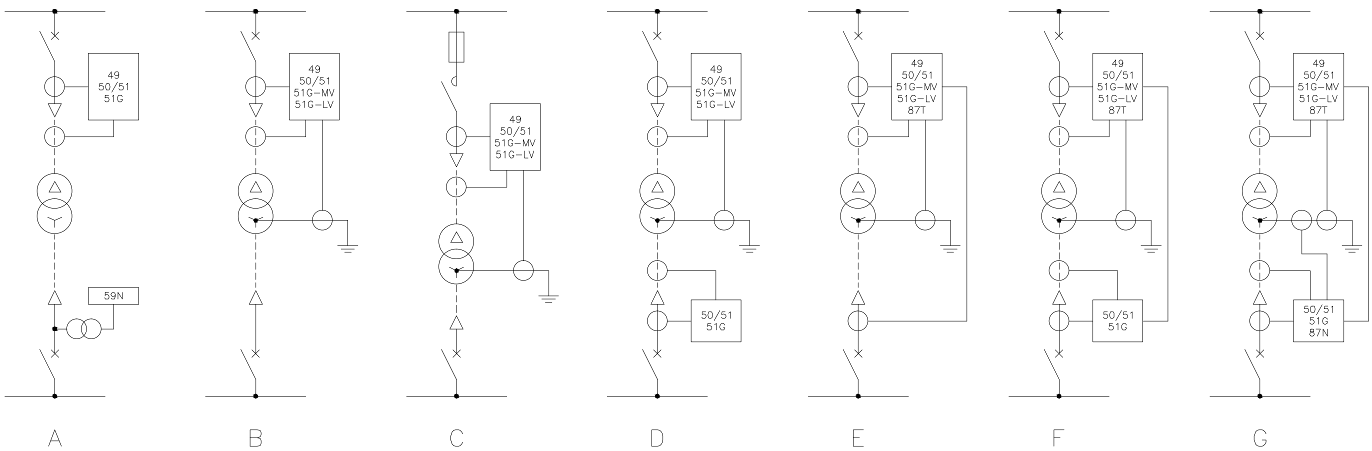


Fig. 9.4


Fig. 9.5

Refer to the Technical Guide entitled “Protection criteria for medium voltage networks” for further details.

9. Applications

9.2 Capacitor switching and protection apparatus

As mentioned previously, switching capacitor banks is a delicate operation both on opening (chap. 5.1.4) and closing for switching-in (chap. 4.2.1).
Standard IEC 62271-100 (tab. 14) establishes preferential values for switching capacitive currents. The preferential value for current interruption in single or back-to-back banks is 400 A for all voltage values.

Fig. 9.6: examples of capacitors

	Line	**Cable**	**Single bank of capacitors**	**Back-to-back capacitor bank**		
Rated voltage	**Rated line-charging breaking current**	**Rated cable-charging breaking current**	**Rated single capacitor bank breaking current**	**Rated back-to-back capacitor bank breaking current**	**Rated back-to-back capacitor bank inrush making current**	**Frequency of the inrush current**
U_r **kV, rms**	I_r **A, rms**	I_c **A, rms**	I_{sb} **A, rms**	I_{bb} **A, rms**	I_{bi} **kA, peak**	f_{bi} **Hz**
3.6	10	10	400	400	20	4 250
4.76	10	10	400	400	20	4 250
7.2	10	10	400	400	20	4 250
8.25	10	10	400	400	20	4 250
12	10	25	400	400	20	4 250
15	10	25	400	400	20	4 250
17.5	10	31.5	400	400	20	4 250
24	10	31.5	400	400	20	4 250
25.8	10	31.5	400	400	20	4 250
38	10	50	400	400	20	4 250

Tab. 14: preferential values of capacitive switching currents

Regarding inrush current, the Standard governing circuit breakers does not provide values for single capacitor banks since this condition is not considered critical. On the other hand, 20 kA peak value and 4250 Hz frequency are given as preferential values for back-to-back capacitor banks.
IEC 62271-106, the product Standard for contactors requires manufacturers to provide the breaking currents and withstand current relating to the inrush current for back-to-back capacitors.
When it comes to interrupting capacitive loads and similarly to circuit breakers, there are two classes for contactors regarding their behavior in relation to restrikes:
- class C1: low probability of restrike, demonstrated by type tests
- class C2: very low probability of restrike, here again demonstrated by type tests

The maximum capacitive current for VSC-S contactors (fig. 9.7) is 250 A. In the case of back-to-back capacitor banks, the making capacity with inrush current is 8 kA peak with 2500 Hz maximum frequency.
Certain factors must be considered when defining the type of switching device for rated current. These factors include overvoltage, capacitance tolerance and the presence of a harmonic component. Standard IEC 60871-1 specfifies that the switching and protection devices of capacitor banks must be sized for continuous current 1.43 times the rated current of the capacitor or bank. Not only must this value must be taken into account when choosing the circuit breaker or contactor, but also when the settings of protections, fuses and relays are defined.

Fig. 9.7

9.2.1 Protection relays for capacitors
If circuit breakers and relays are used for protection purposes, faults and abnormal operation of the capacitors can be caused (and consequently recognized by the protection device) by:
- currents higher than the rated value;
- short-circuits;
- earth faults;
- overvoltage;
- unbalanced impedance (fault in the elementary element forming the capacitor).

Abnormal operating conditions can be identified by means of the following protection functions (fig. 9.8):
- relay 51 overcurrent protection;
- relay 50 short-circuit overcurrent protection (can be replaced by fuses);
- relay 51G earth fault overcurrent protection;
- relay 59 overcurrent protection;

relay 46 negative sequence overcurrent protection.

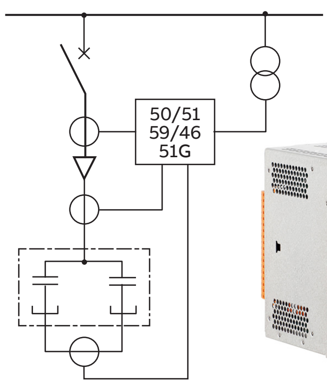


Fig. 9.8

Fig. 9.9

The ABB REV 615 relay is recommended in this case (fig. 9.9).
Refer to the Technical Guide entitled “Protection criteria for medium voltage networks” for further details.

Whether relays are being adjusted or fuses chosen, certain fundamental parameters concerning the switching transient of the capacitor bank must be calculated. These parameters include the value of the inrush current, the frequency of the transient, its duration and the specific let-through energy I^2t. A few examples of how to calculate and size the components are explained below.

9. Applications

9.2.2 Example of how a single capacitor bank is sized

Consider the following example:

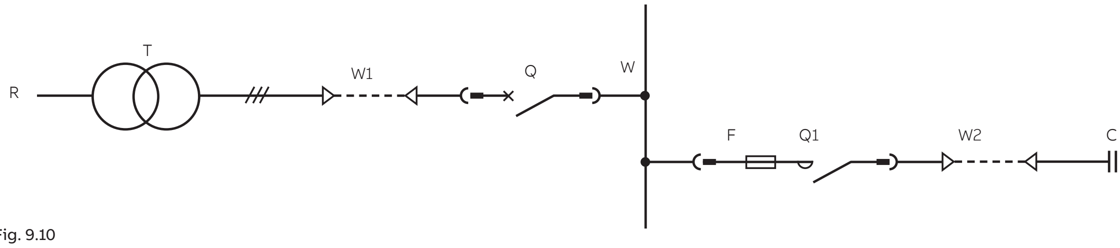


Fig. 9.10

where:

C = capacitor banks with oil and polypropylene dielectric material
F = 12 kV – 63 A ABB CEF fuses
Q = VD4 main circuit breaker 12.06.16 (12 kV -630 A – 16 kA)
Q1 = type VSC-S switching contactors (12 kV – 250 A)
R = HV relay
T = HV/MV power transformer
W = main busbars of MV switchgear with section S=3x(60x5) mm² and length l=10 m
W_1 = connection cable between transformer and switchgear with section S = 2x (3x150) mm² and length l = 20 m
W_2 = connection cable and capacitor bank with section S=3x(1x35) mm² and length l=20m

Further data:

U_n = 10 kV MV side rated phase voltage
f = 50 Hz grid frequency
S''_{kQ} = 3000 MVA short-circuit power of network on supply side
S_{rt} = 10 MVA, u_{kr} = 7%, $\cos\varphi_{cc}$ = 0.1 characteristics of HV/MV transformer
R_{W1} = 1.30 mΩ, L_{W1} = 3.88 µH characteristics of cable W1
R_W = 0.59 mΩ, L_W = 5.30 µH characteristics of busbar W
R_F = 13.70 mΩ, L_F = 0.10 µH characteristics of fuse F
R_{W2} = 11.50 mΩ, L_{W2} = 7.30 µH characteristics of cable W2
Q = 400 kVAR, I_r = 23.1 A characteristics of capacitor

To calculate the frequency of the switching current, first calculate the short-circuit current at the terminals of the capacitor bank. This is done by applying the power method and determining the total inductance of all the components between the transformer and capacitor bank (but not the resistors of the circuit, since X>>R), thus:

S''_{kQ} = 3000 MVA amount from the grid
S_{kT} = $(S_{rT}/u_{kr})\cdot 100 = (10/7)\cdot 100$ = 142.8 MVA amount from the transformer
L_c = $L_{W1}+L_W+L_F+L_{W2}$ = 3.88+5.30+0.10+7.30 = 16.58 µH total inductance of connections
S_{kc} = $U_{n2}/Z_c = U_{n2}/(2\pi f\cdot L_c) = (10\cdot 10^3)^2/(6.28\cdot 50\cdot 16.58)$ =
= 19,208 MVA amount from the connections
S_{kTOT} = S''_{kQ} // S_{kT} // S_{kc} = 1/[(1/3000)+(1/142.8)+(1/19208)]
= 135 MVA Short-circuit power on capacitor bank

The short-circuit current is therefore worth:

I_{SC} = $S_{kTOT}/(\sqrt{3}\cdot Un) = 135/(\sqrt{3}\cdot 10)$ = 7.8 kA

By applying the formula described in chap. 4.2.1:

$$f_i = f_s \sqrt{\frac{I_{sc}}{I_1}}$$

the result is:

$$f_i = 50 \cdot \sqrt{\frac{7.8\ 10^3}{23.1}} = 0{,}919\ kHz$$

The influence of frequency on the inductance considered in the previous calculation could now be assessed. At least, by evaluating just the variation in the inductance of the transformer since the value of the inductance of the connections L_c compared to the former is negligible. To assess the frequency response of the inductance and resistance of a transformer, one needs to know the rating plate data and consult the curves supplied by the manufacturer or available in literature. Generally speaking, this recalculation is unnecessary because variations in the transformer inductance as a function of frequency are limited to a few percentage points. For the sake of thoroughness, the two graphs below illustrate the coefficient of variation α_c (fig. 9.11) of the inductance of three-pole cables with the following curves: a) 3x70 mm² cables, b) 3x95 mm² cables, c) 3x 150 mm² cables

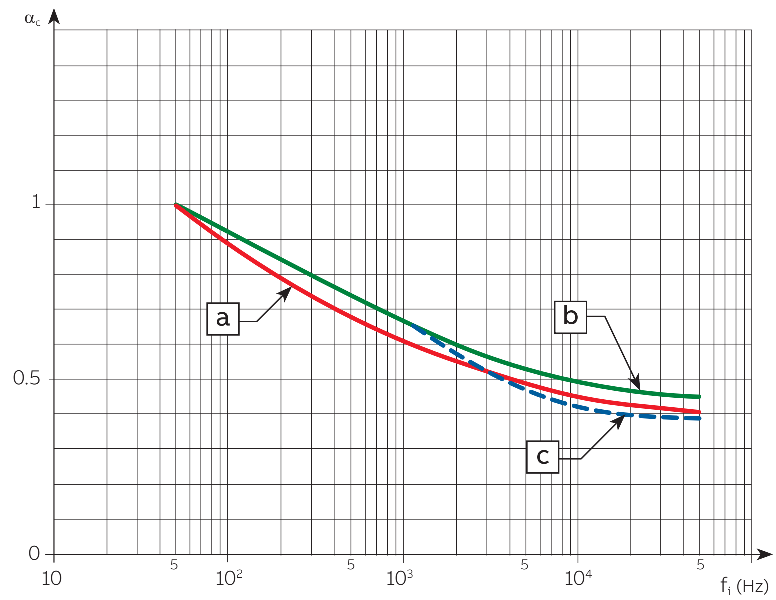


Fig. 9.11

In the case of single-conductor cables on a flat surface, inductance variation with frequency is negligible. The maximum peak transient current will now be calculated using the formula below:

$$i_{imax} = \sqrt{2} \cdot \sqrt{I_{sc} I_1}$$

Thus:

$$i_{imax} = 1{,}41 \cdot \sqrt{7{,}8\ 10^3 \cdot 23{,}1} = 599\ Ap$$

The two values are much lower than the limits established by the Standards, both for circuit breakers and contactors. This is further proof of the fact that switching single banks of capacitors is not considered critical by the Standard.
The ratio k between the maximum peak value of the transient current and the rated current of the capacitor bank is: K = 599/23.1 = 26.
This means that the dynamic-thermal stress to which the capacitor bank is subjected is sensibly lower than the value given as maximum prudential value, i.e. K = 100.
The I^2t, or specific let-through energy of the transient, is calculated to assess whether the correct fuses have been chosen.
Resistances at transient frequency f_i are used in the formula. The resistance of the transformer, busbar and cables will be calculated but without considering the resistances of the circuit breaker and contactor, since their values are negligible.
Beginning with the transformer, resistance R_{trafo} at 50 Hz is calculated in the following way:

$$R_{trafo\ (50\ Hz)} = 10^3\ (U_n^2/S_{rt}) \cdot (u_{kr\%}/100) \cdot \cos\varphi_{cc}$$

with the following result:

$$R_{trafo\ (50\ Hz)} = 10^3\ (10^2/10) \cdot (7/100) \cdot 0.1 = 70\ m\Omega$$

The characteristic resistance/frequency curves supplied by the transformer manufacturer must be available in order to calculate the value of R_{trafo} a f_i. These curves depend on the construction characteristics of the transformer and allow coefficient β_t to be determined as a function of transient frequency. This coefficient can then be used to multiply the resistance at 50 Hz and obtain the resistance at f_i. The curve of coefficient β_t (fig. 9.12) applicable, with fair approximation, to HV/MV and MV/MV oil-immersed transformers from 25 MVA (curve a) to 100 MVA (curve b) is given below:

9. Applications

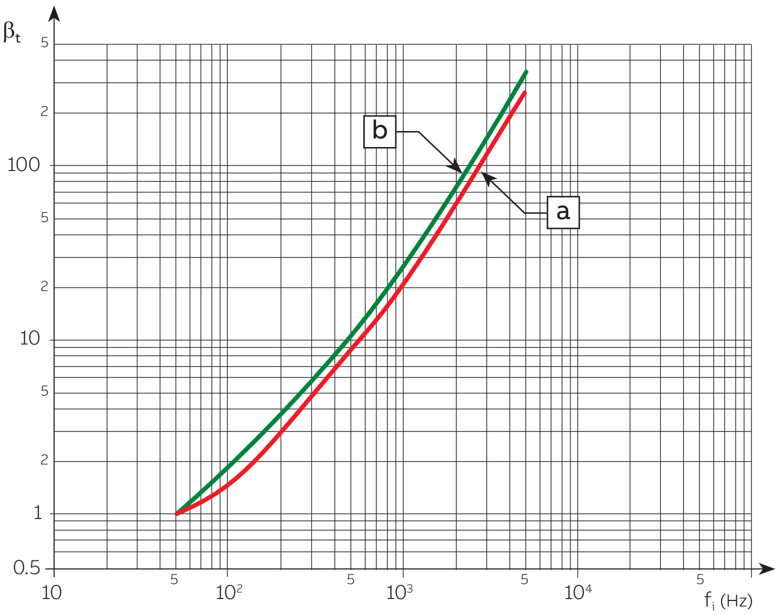


Fig. 9.12

In this particular case, with S_{rt} = 10 MVA and using the nearest curve, i.e. a), at a frequency of f_i = 919 Hz, the result is that β_t = 20.

Thus: $R_{trafo\ (919\ Hz)} = \beta_t \cdot R_{trafo\ (50\ Hz)} = 20 \cdot 70 = 1400\ m\Omega$

The same procedure will now be applied to cable resistance. The curves vary, depending on the type of cable, e.g. three-conductor or single-conductor, and on the voltage. However, since there are only minor differences, a single graph (fig. 9.13) is proposed, with fair approximation, for the purpose of obtaining β_c:

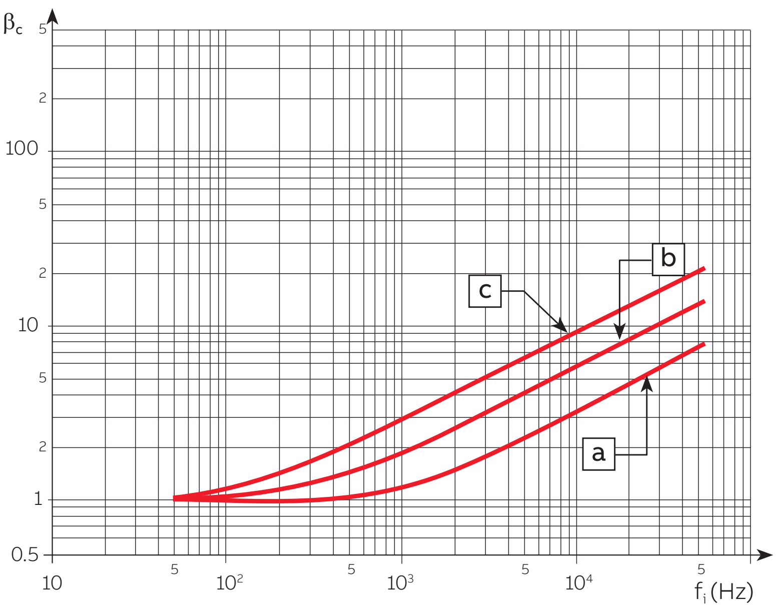


Fig. 9.13

The graph includes three curves: for 50 mm² cables (a), for 150 mm² cables (b) and for 300 mm² cables (c).
Thus, for cable W_1 at 919 Hz, β_c= 2.

Which results in the following:
$R_{W1(919\ Hz)} = \beta_c \cdot R_{W1(50\ Hz)} = 2 \cdot 1.30 = 2.60\ m\Omega$

For cable W2 at 919 Hz β_c= 1.2.
Which means that:
$R_{W2(919\ Hz)} = \beta_c \cdot R_{W2(50\ Hz)} = 1.2 \cdot 11.50 = 13.80\ m\Omega$

The change of resistance of fuse R_F = 13.70 mW as a function of frequency is negligible, as is the value of the resistance of the busbars, given the very short lengths involved.
In conclusion, the resistance of the connections at f_i is:
$R_c = R_{W1} + R_{W2} + R_F = 2.60 + 13.80 + 13.70 = 30.1\ m\Omega$
All that remains to be calculated is the internal resistance of the capacitors. This can be done as a function of tgδ (dielectric loss characteristic) of the capacitor, which depends on the type of dielectric medium. A few typical values for MV capacitors are given below:

Type of dielectric	Typical tgδ_{diel}	minimum tgδ_{diel}
Paper	(1 to 4) · 10^{-3}	–
Paper + polypropylene	(0.5 to 1) · 10^{-3}	–
Polypropylene	(0.2 to 0.4) · 10^{-3}	0.5 · 10^{-4}

Tab. 15

The following formula should be applied:

$R_{cond} = 10^6 \cdot (tg\delta \cdot Un^2)/Q$

Thus:

$R_{cond} = 10^6 \cdot (0.5\ 10^{-4} \cdot 10^2)/400 = 12.5\ m\Omega$

The resistance value of the capacitor does not change much as a function of frequency, thus the same value will also be used for f_i.

The total resistance of the circuit is therefore:

$R_{(919\ Hz)} = R_{trafo} + R_c + R_{cond} = 1400 + 30.1 + 12.5 = 1442.6\ m\Omega$

Given the value of $R_{(919\ Hz)}$, I^2t can now be calculated using the formula:

$I^2t = 53\ 10^3 \cdot Q/(f \cdot R_{(919\ Hz)})$

thus:

$I^2t = 53\ 10^3 \cdot 400/(50 \cdot 1442.6) = 294\ A^2s$

This value should be compared to the pre-arc values of I^2t provided by fuse manufacturers. The values of ABB CEF fuses are given in tab. 16:

In [A]	I^2t [A^2s]
6	20
10	30
16	120
20	365
25	500
31.5	610
40	1000
50	2500
63	4500
80	9200
100	15000
125	20000
160	35000
200	100000

Tab. 16

This shows that transient value I^2t is widely supported by the 63 A fuse.
The following formula can be used to calculate the duration of the transient, useful for adjusting the setting of a protection relay:
$t = 955\ 10^3 \cdot Un^2/(f \cdot S_{kTOT} \cdot R_{(919\ Hz)})$
thus:
$t = 955\ 10^3 \cdot 10^2/(50 \cdot 135 \cdot 1442.6) = 9.8$ ms

9.2.3 Example of how a capacitor bank is sized when other banks are already connected

The case of switching-in a capacitor bank C_1 when another, identical one C_2 has already been switched-in back-to-back will now be examined (fig. 9.14):

where:
C_1 and C_2 = capacitor banks with oil and polypropylene dielectric material
F_1 and F_2 = 12 kV – 100 A ABB CEF fuses
Q = VD4 main circuit breaker 12.06.16 (12 kV – 630 A – 16 kA)
Q1 and Q2 = type VSC-S switching contactors (12 kV – 250 A)
R = HV grid
T = HV/MV power transformer
W = main busbars of MV switchgear with section S=3x(60x5) mm^2 and length l=10 m
W1 and W2 = connection cables between switchgear and capacitor banks with section S=3x50 mm^2 and length l=20 m

Further data:
U_n = 10 kV MV side rated phase voltage
f = 50 Hz grid frequency
S''_{kT} = 500 MVA short-circuit power of network on supply side of transformer
$R_{W1,W2}$ = 8 mΩ, $L_{W1,W2}$ = 7.45 µH characteristics of cables W1 and W2
R_W = 0.11 mΩ, L_W = 2.30 µH characteristics of busbar W
R_F = 6.70 mΩ, L_F = 0.10 µH characteristics of fuse F
Q = 400 kVAR, I_r = 23.1 A characteristics of capacitor banks C1 and C2

To use the formulas described in chap. 4.2.1 when there are two identical banks, i.e.:

$$f_t = 13{,}5\sqrt{\frac{f_s U_r}{L_{eq} I_1}}\ kHz \quad \text{e} \quad i_p = 9545\sqrt{\frac{U_r I_1}{f_s L_{eq}}}\ Ap$$

first, the inductance Leq between the two capacitor banks must be calculated.

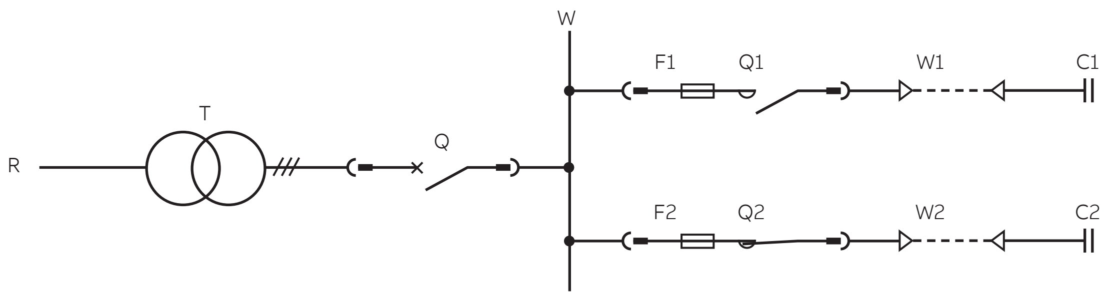


Fig. 9.14

9. Applications

$L_{eq} = L_{W1} + L_F + L_W + L_F + L_{W2} =$
$= 7.45 + 0.1 + 2.3 + 0.1 + 7.45 = 17.4$ µH
where the values of the switching devices will continue to be ignored since they are negligible.
The following can now be calculated

$f_i = 13.5 \cdot \sqrt{(50 \cdot 10 / 17.4 / 23.1)} = 15.057$ kHz

In this case, the inductance of the cables at transient frequency must be recalculated since the variation is far from negligible (as in the previous case with the transformer), so the graph will be used to calculate α_c as explained in the previous section.
For 3x50 mm² three-conductor cables, the value is $\alpha_c = 0.45$. Consequently:
$L_{W1(15kHz)} = L_{W1} \cdot \alpha_c = 7.45 \cdot 0.45 = 3.35$ µH

The new inductance value is:
$L_{eq} = L_{W1(15kHz)} + L_F + L_W + L_F + L_{W2(15kHz)} =$

$=3.35 + 0.1 +2.3 + 0.1 + 3.35 = 9.20$ µH

When the calculation is repeated, the result is:

$f_t = 13.5 \cdot \sqrt{(50 \cdot 10 / 9.2 / 23.1)} = 20.708$ kHz

However, there is also a transient at a lower frequency, supplied by the grid in a similar way to when a single capacitor bank is energized. In the majority of cases, the inductance between capacitor banks is less than 1% compared to the inductance of the feeder, thus the amount the grid adds to transient current can be neglected. In this particular example, the value will be calculated since the amount is somewhat higher.
As explained in the previous section, to calculate this frequency it is first necessary to calculate the short-circuit current. Thus:
$I_{SC} = S''_{kT} / (\sqrt{3} \cdot Un) = 500/(\sqrt{3} \cdot 10) = 28.9$ kA
when the formula described in chap. 5.2.1. is applied to the sum I_t of the two capacitor banks:

$$f_i = f_s \sqrt{\frac{I_{sc}}{I_t}}$$

the result is:

$$f_i = 50 \sqrt{\frac{28{,}9 \cdot 10^3}{23{,}1 + 23{,}1}} = 1250\ Hz$$

As shown in the previous example, variations of the inductance of the transformer as a function of frequency are negligible, thus there is no need to recalculate.
The peak value is obtained as the sum of the values of the two transients at different frequencies.

$$i_p = 9545 \sqrt{\frac{U_r \cdot I_1}{f_s \cdot L_{eq}}} + \sqrt{2}\ \sqrt{I_{sc} \cdot I_t} \cdot \left(\frac{I_1}{I_2 + I_1}\right)^2$$

$$i_p = 9545 \sqrt{\frac{10 \cdot 23{,}1}{50 \cdot 9{,}2}} + \sqrt{2}\ \sqrt{28{,}9\ 10^3 \cdot 46{,}2} \cdot \left(\frac{23{,}1}{46{,}2}\right)^2 = 7171\ A$$

The K ratio in this case of back-to-back switching-in is K=7171/23.1=310
The stress is therefore too high for both the capacitors and contactors.
As described previously, Standards IEC 62271 recommend 20 kAp short-time peak current at 4250 Hz frequency for the circuit breaker and 8 kAp short-time peak current at 2500 Hz frequency for the contactors.

This means that additional inductors in series must be used to limit them.
The limiting inductance value can be obtained by applying the previous formulas in reverse, beginning with the limits recommended by the Standard.
In this case, a value of approximately 100 µH in series can reduce the peak current and frequency values to below the required limits.

A formula similar to the one for the single bank is used to calculate I^2t, but it is applied by taking the second, back-to-back bank C2 into account:

$$I^2 t = 53\ 10^3\ \frac{Q_1}{f\ (Q_2 + Q_1)} \times \left(\frac{Q_2}{R_b} + \frac{Q_1}{R_r}\right)$$

Where R_b is the overall phase resistance of all the components between the banks at transient frequency and R_r is the overall resistance of all the grid components up to the connection point of the banks at the lowest transient frequency.
When calculating, one must consider the 100 µH additional limiting inductance, which has an 0.8 mΩ resistance R_{ind} at 50 Hz, the value of which changes with the frequency, as shown by the curve of fig. 9.15:

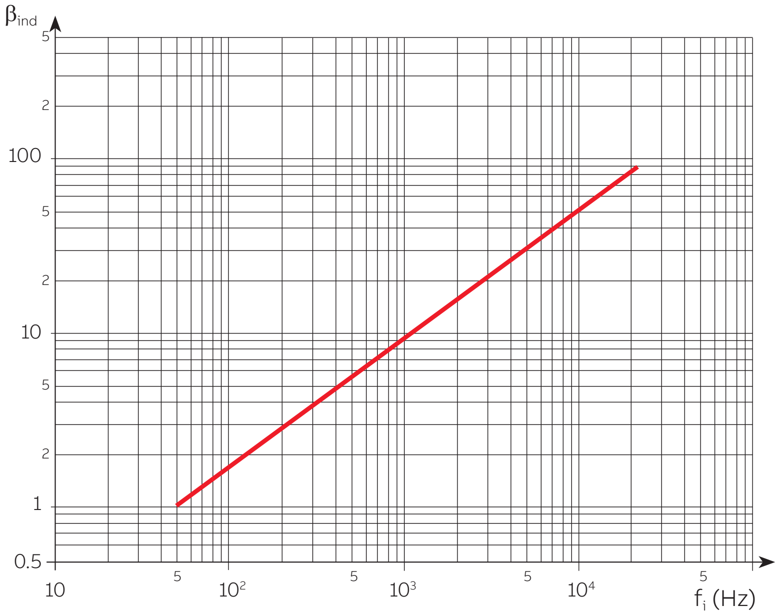


Fig. 9.15

Value which the chosen ABB CEF fuses are well able to support:

In [A]	**I²t [A²s]**
6	20
10	30
16	120
20	365
25	500
31.5	610
40	1000
50	2500
63	4500
80	9200
100	15000
125	20000
160	35000
200	100000

Tab. 17

At 4.3 kHz, β_{ind} = 25. Thus R_{ind} = 0.8 · 25 = 20 mΩ
As explained in the previous chapter, R_{W1} and R_{W2} of the cables must be recalculated with β_c, which equals 2 (see fig. 9.13 in the previous chapter).
Thus: $R_{W1} = R_{W2} = 2 \cdot 8 = 16$ mΩ
while the resistances of the busbars and devices will not be considered. Lastly,
$R_{cond} = 10^6 \cdot (tg\delta \cdot Un^2)/Q = 10^6 \cdot (0.5\ 10^{-4} \cdot 10^2)/400 =$ 12.5 mΩ
Which obtains the following result:
$R_b = R_{cond1} + R_{ind1} + R_{W1} + R_{F1} + R_{F2} + R_{W2} + R_{ind2} + R_{cond2} =$ 12.5 + 20 + 16 + 6.7 + 6.7 + 16 + 20 + 12.5 = 110.4 mΩ

The resistance of the grid components, in practice that of the transformer, is:
$R_r = 10^3\ (U_n^2/\ S''_{Kt}) \cdot \cos\varphi_{cc} = 10^3\ (10^2/500) \cdot 0.1 =$ 20 mΩ
Since at 4,3 kHz β_t = 30 (see fig. 9.12 in the previous chapter), the result is:
R_r = 20 · 30 = 600 mΩ
Since all the data required for the above formula are now available:

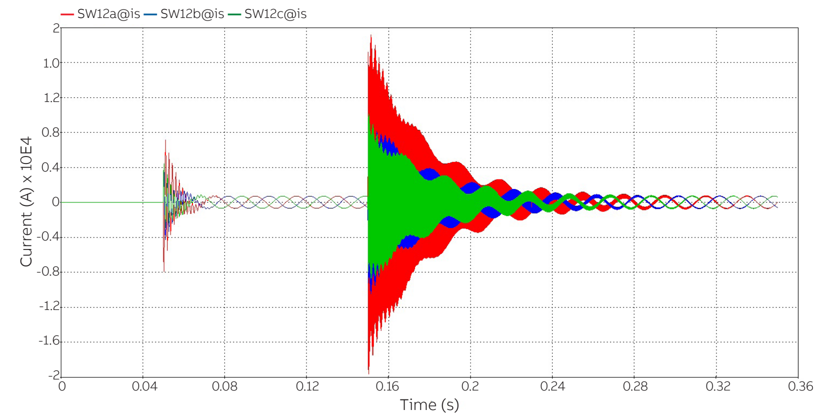
$$I^2t = 53\ 10^3\ \frac{400}{50\ (400+400)} \cdot \left(\frac{400}{110{,}4} + \frac{400}{600}\right) = 2274\ A^2s$$

The final calculation concerns the duration of the transients. Using one of the previous formulas, the following is obtained for the lowest frequency:
$t_r = 955\ 10^3 \cdot Un^2/(f \cdot S''_{Kt}\ R_{r(4.3\ kHz)}) =$
$= 955\ 10^3 \cdot 10^2/(50 \cdot 500 \cdot 600) = 6.4$ ms
while the formula below is used for the highest frequency between banks:
$t_b = 6\ L/R_b$
thus: $t_b = 6\ L_{eq}/R_b = 6 \cdot 217/110.4 = 11.8$ ms

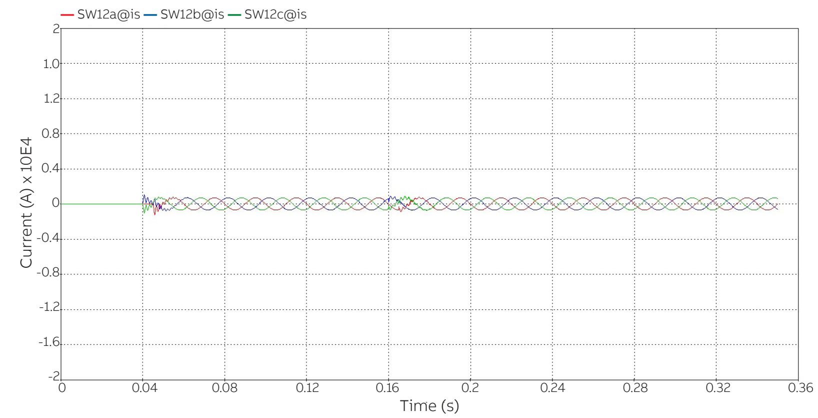
9. Applications

9.2.4 Synchronous switching of capacitors

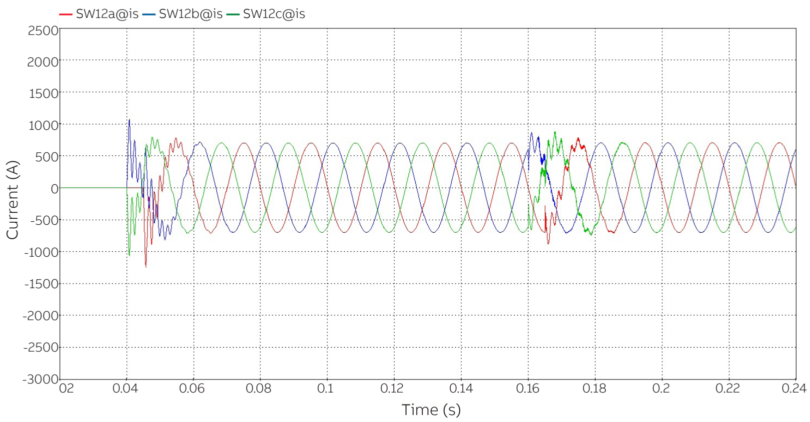
Another solution able to resolve this problem in a technically brilliant way is to use a synchronous switching device, such as DS1 by ABB, which solves the problem at its source. The previously illustrated and commonly adopted formulas are based on the assumption that when they close, capacitor banks are fully discharged and that closing occurs the moment in which the inrush current is at its maximum. This happens when the switching device, circuit breaker or contactor, closes with the line voltage at its maximum.
During switching transients, capacitors act like a short-circuit where only the inductors of the power supply grid limit the current, with the consequent current peaks and oscillation frequencies described in the previous chapters.
Controlling the closing operation so as to supply the capacitor bank at zero voltage allows the transient phenomenon (which is dangerous for the components of the electrical installation) to be eliminated.
We will now consider using a DS1 to switch two capacitor banks in the back-to-back configuration. Closing of the first circuit breaker creates a transient, the frequency and amplitude of which are a function of the grid inductance and the power of the bank. The randomness of the instant in which a conventional circuit breaker closes can cause an overcurrent, the consequences of which are listed in section 5.3.4.
Energizing of the second bank connected in parallel causes a considerably higher inrush current than that of the previous switching operation. This requires the use of limiting reactors connected in series to each individual bank for the purpose of mitigating the phenomenon, but this solution is not without disadvantages, such as size and cost. Figure 9.16 illustrates the transient caused by switching-in two banks with a conventional circuit breaker a) and with a DS1 b), this latter enlarged in c).



a)



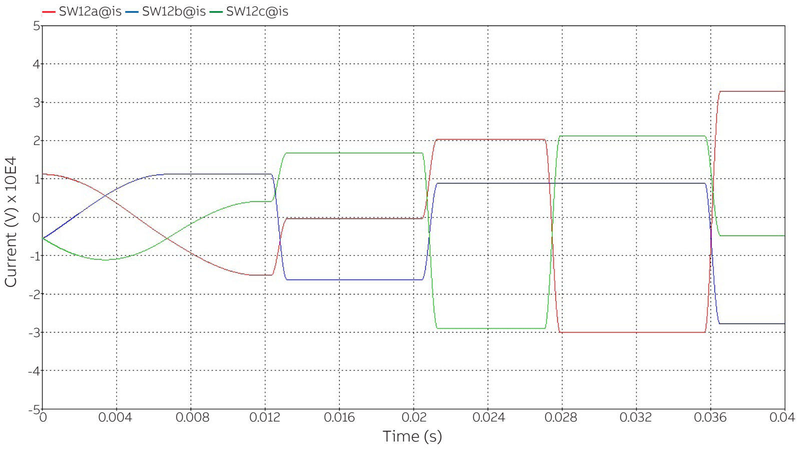
b)



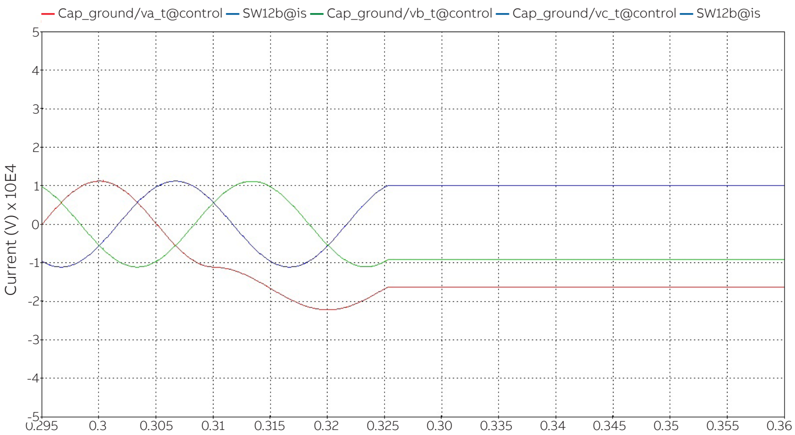
c)

Fig. 9.16

When it comes to opening, note how the presence of restrikes can lead to a rise in voltage at each restrike. Figures 9.17 a) and b), with and without DS1, show how the effect of opening with DS1 is free from restrikes and consequent over-voltages. Consequently, there is no need to use surge arresters.



a)



b)

Fig. 9.17

Thus use of DS1 allows systems for protecting against over-voltages or the installation of limiting inductors to be avoided, as in the example in the previous section.
DS1 is available for currents up to 630 A at 17.5 kV, 50 Hz

Electrical specifications		DS1 50	DS1 60
Rated frequency	Hz	50	60
Rated voltage	kV	17.5	15
Rated current	A	630	600

Tab. 18

Fig. 9.18: DS1

9. Applications

9.3 Circuit breakers for protecting lines and cables

Fig. 9.19: example of cable marking

We will now calculate the charging current of a medium voltage cable.
A single-conductor cable type RG7H1M1 12/20kV with 1·50 mm² section will be used as an example. We will also assume that the operating voltage is 17.5 kV at a frequency of 50 Hz and that the cable is 2 km in length.

The following formula will be applied:

$$X_C = \frac{1}{\omega C} = \frac{U}{\sqrt{3} \cdot I}$$

where:

X_C is the capacitive reactance of the cable,

C' is is the cable capacitance in µF/km

U is the line-to-line voltage of the network in V

I is the charging current of the cable in A

Supposing that the capitance value provided by the manufacturer is, for the cable in question, 0.25 µF/km

The result will be: $I = 2\pi \cdot f \cdot C \cdot E$

and thus: $I = 2\pi \cdot 50 \cdot 0.25\ 10^{-6} \cdot 2 \cdot 17.5\ 10^3 / \sqrt{3} = 1.6$ A

Thus calculated, the charging current should be compared to the preferential value specified in the Standard (see table in previous section), which is 31.5 A for the voltage value in question but, above all, it must be compared to the value supplied by the circuit breaker manufacturer.

Consider that in DY800 “Secondary substations 24 kV prefabricated switchgear and controlgear in internal arc-proof metal enclosures with circuit breaker (ICS)”, Public Utility Company ENEL Distribution requires 16 A rated breaking current for no-load cables.

9.3.1 Protection relays for cable lines

If line protection is performed by a circuit breaker with protection relay, bear in mind that line protection is adequate when protection against overloads is ensured and when polyphase short-circuit faults and single-phase earth faults can be identified. This means that the protection is extremely simple and generally limited to the following protection functions:

- relay 49 thermal overload protection;
- relay 51 overcurrent protection;
- relay 50 short-circuit overcurrent protection;
- relè 87L line residual current protection, applicable when selective protection is required in a particular part of the distribution network (e.g.: in industrial installations with ring networks);
- relay 50N earth fault protection.

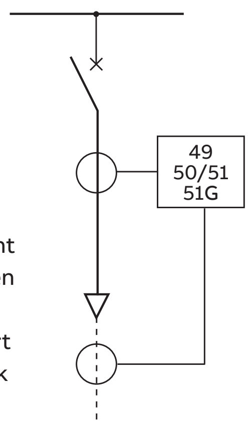


Fig. 9.20

A typical configuration is illustrated in fig. 9.20.
In this case, the recommended relays are:
REF 601, REF 611, REF 615, REF 620, REF 630, RED 615 (fig. 9.21).

Fig. 9.21

Refer to the Technical Guide entitled “Protection criteria for medium voltage networks” for further details.

9.4 Motor switching and protection apparatus

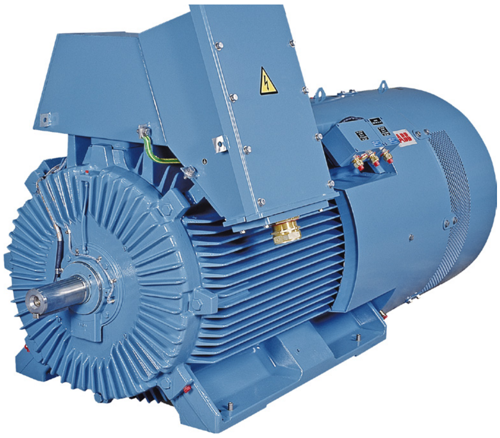


Fig. 9.22: example of an ABB MV motor

9.4.1 Example of motor starting

A practical example (illustrated in fig. 9.23) will now be discussed for the purpose of highlighting the criteria for choosing switching and protection apparatus.

- F = 7.2 kV ABB CEF fuses
- Q = type VD4 12.06.20 main circuit breaker (12 kV – 630 A – 20 kA)
- Q1 = type VSC switching contactor (7.2 kV – 400 A)
- R = HV grid
- T = HV/MV power transformer
- W = main busbars of MV switchgear with section S=3 x (60 x 5) mm² and length= 10 m
- W_1 = connection cable between transformer and switchgear with section S = 2 x (3 x 150) mm² and length l = 20 m
- W_2 = connection cable between contactor and motor with section S = 3 x(1 x 50) mm² and length l = 210 m

Further data:

- U_n = 6 kV MV side rated phase voltage
- f = 50 Hz grid frequency
- S''_{kQ} = 200 MVA short-circuit power of network on supply side of transformer
- R_{W1} = 1.173 mΩ, X_{W1} = 1.978 mΩ characteristics of cable W_1
- R_{W2} = 74 mΩ, X_{W2} = 27 mΩ characteristics of cable W_2
- M = ABB HXR medium voltage three-phase squirrel-cage motor.

The main data of the motor are:
Rated voltage U_r = 6000 V
rated frequency f = 50 Hz
rated speed 1500 rpm = 4 poles
Rated power P_r = 1250 kW
Efficiency at full load η= 97.5%
Power factor at full load cosφ = 0.88
Rated current I_N = 140 A
Starting current/rated current ratio
I_A/I_N = 6.5
Rated torque T_n = 7994 Nm
Starting torque/rated torque ratio
T_s/T_n = 0.8
Maximum torque/rated torque ratio
T_M/T_n = 2.3
Rotor inertia J_M = 63.3 kgm²
We will also assume that load starting torque cannot be less than 0.2 Tn (breakaway torque).
We will begin by calculating certain general data:
Grid reactance is:

$$X_Q = \frac{1{,}1 \cdot U_n^2}{S''_{KQ}} = \frac{1{,}1 \cdot 6^2}{200} = 0{,}198 \quad \Omega$$

Motor reactance at start-up is:

$$X_M = \frac{U_n^2 \cdot \cos\varphi \cdot \eta}{\frac{I_S}{I_n} \cdot P_r} = \frac{6^2 \cdot 0{,}88 \cdot 0{,}975}{6{,}5 \cdot 1{,}2} = 3{,}96\ \Omega$$

The most economical solution is certainly direct starting, so we will begin with this case.

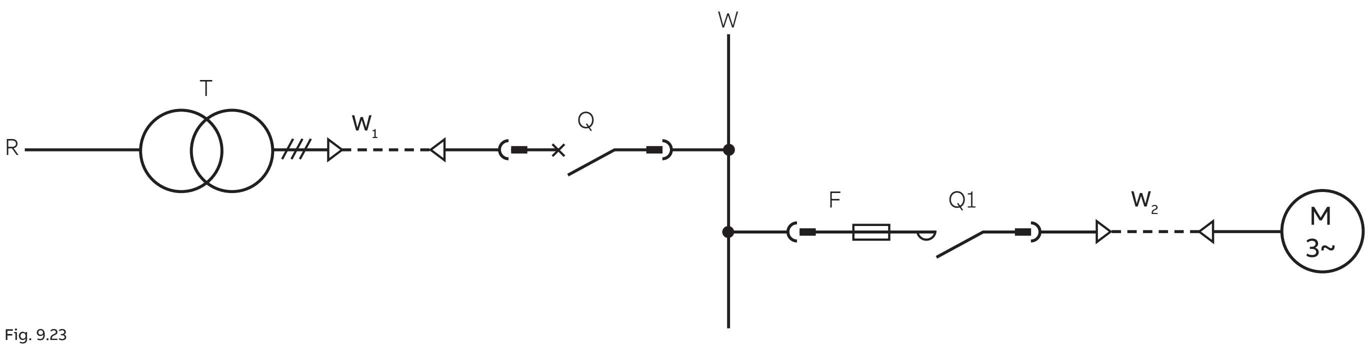


Fig. 9.23

9. Applications

Using the formulas in chap. 4.2.3 and since the reactances of cable W1, busbars W and the fuse are negligible:

$$\frac{I_{A1}}{I_N} = \frac{I_A}{I_N} \cdot \frac{X_M}{X_M + X_{W2} + X_Q} = 6{,}5 \cdot \frac{3{,}96}{3{,}96 + 0{,}027 + 0{,}198} = 6{,}15$$

$$\frac{T_{s1}}{T_n} = \frac{T_s}{T_n} \cdot \left(\frac{X_M}{X_M + X_{w2} + X_Q}\right)^2 = 0{,}8 \cdot \left(\frac{3{,}96}{3{,}96 + 0{,}027 + 0{,}198}\right)^2 = 0{,}72$$

The voltage at the terminals of the motor on start-up is:

$$\frac{U_s}{U_n}\% = \frac{X_M}{X_M + X_{W2} + X_Q} \cdot 100 = \frac{3{,}96}{3{,}96 + 0{,}027 + 0{,}198} = 95\%$$

And the voltage drop is:

$$\Delta U_n\% = \frac{X_Q}{X_M + X_{W2} + X_Q} \cdot 100 = 4{,}73\%$$

In this case, direct starting is possible since the voltage drop is acceptable and the starting torque higher than the breakaway torque of the load (0.72>0.2).

9.4.2 How to choose fuses

ABB CMF fuses conform to DIN 43625 Standards and are suitable for protecting motors. They must be chosen by assessing the service conditions, i.e.

- supply voltage;
- starting current;
- starting time;
- number of starts/hour;
- full load current of motor;
- short circuit current of installation.

Protection against short-circuits is provided by the fuses. Always choose fuses with a higher rated current than the motor, to prevent them from tripping when the motor starts. This prevents them from being used for protection against overloads, a function for which fuses are generally unsuitable.
This means that it is always necessary to use them in conjunction with an inverse time relay for protection against overloads. This protection must be coordinated with the function provided by the fuse so that the curves of the relay and fuses intersect in a point enabling:

1) protection of the motor against overcurrents provided by indirect relays and which act on the contactor, as described further on;
2) protection of the circuit against fault currents which exceed the breaking capacity of the contactor, up to the maximum admissible fault current. Protection provided by the fuse.

Proceed in the following way to assess the service conditions (see IEC 60644 “Specification for high-voltage fuse-links for motor circuit applications” and Technical Report IEC/TR 62655 “Tutorial and application guide for high-voltage fuses”):

- Rated voltage Un. must be the same as the operating voltage of the installation or higher. Also make sure that the insulation level of the electrical system is higher than the value of the switching over-voltage generated by the fuses which, for the fuses used by ABB, is well below the limit established by the IEC 60282-1 “High-voltage fuses-– Part 1: Current-limiting fuses” Standards illustrated in tab.19.

Rated voltage kV	Maximum switching overvoltages kV
3.6	12
7.2	23
12	38
17.5	55
24	75
36	112

Tab. 19

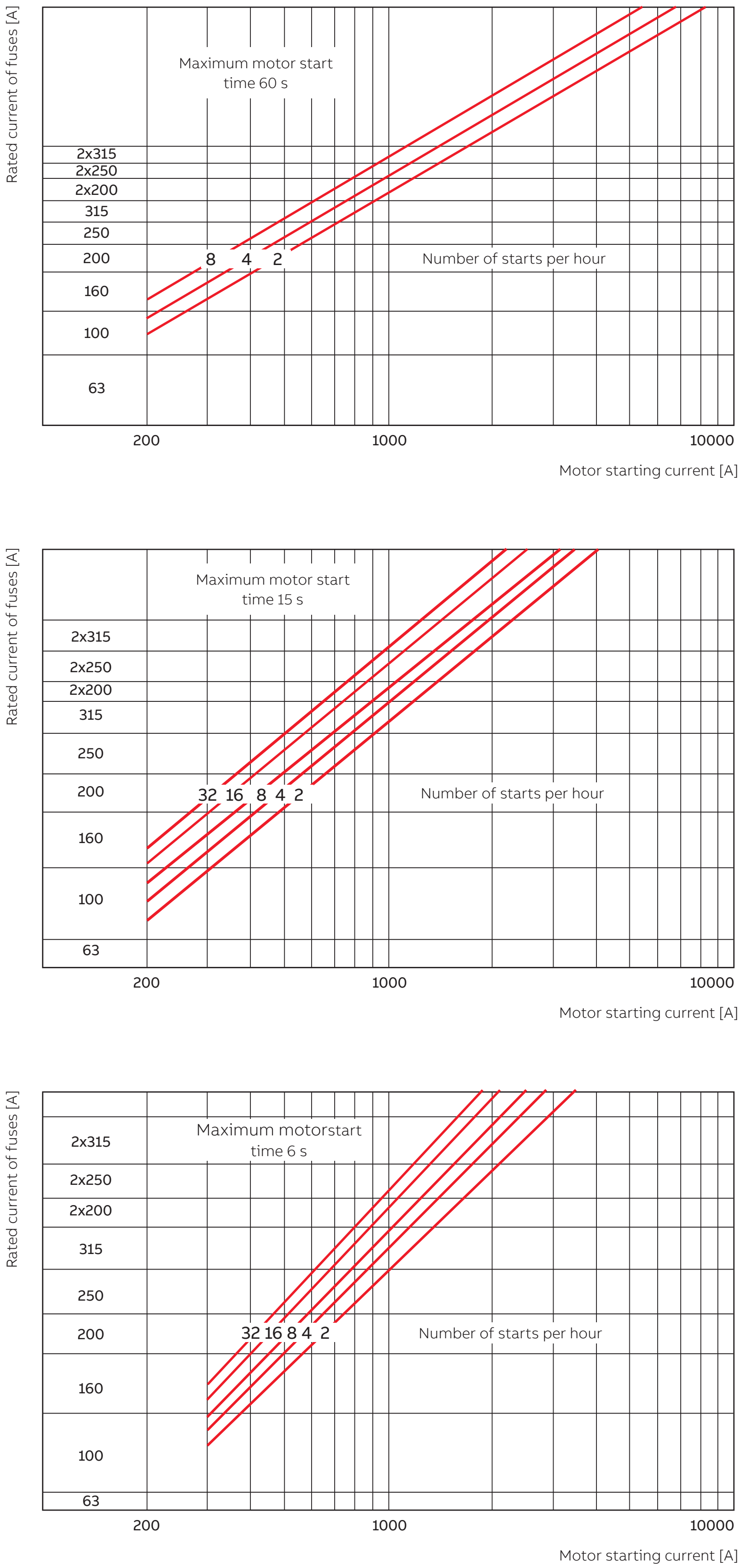


Fig. 9.24

- Rated current In. Must be chosen by consulting the diagrams, which refer to starting at uniform intervals of time, with the exception of the first two starts of each hourly cycle, which can take place in immediate succession. Each diagram (fig. 9.24) refers to a different starting time, i.e.: 60 s - 15 s - 6 s respectively.
  If there are very brief intervals between starts, it is advisable to check again to make sure that the starting current does not exceed $I_f \cdot K$, where I_f is the fusing current of the fuse at the starting time of the motor and K is a factor less than 1, a function of the In of the fuse, as shown in tab. 20 for CMF fuses.

Un	In	K *)	Minimum $I^2 \times t$
[kV]	[A]	–	[$A^2 \times s$]
3.6	100	0.75	1.4×10^4
	160	0.7	3.8×10^4
	200	0.7	7.6×10^4
	250	0.6	14×10^4
	315RC280	0.6	21×10^4
7.2	63	0.75	0.48×10^4
	100	0.75	1.40×10^4
	160	0.7	3.8×10^4
	200	0.7	7.6×10^4
	250	0.6	14×10^4
	315RC280	0.6	21×10^4
12	63	0.75	0.48×10^4
	100	0.75	1.4×10^4
	160	0.7	3.8×10^4
	200	0.7	9.3×10^4

*) The K factor refers to the mean value of the current 315RC280, fuse with typical time-current characteristic for 315 A but with 280 A maximum rated current.

Tab. 20

- Breaking capacity. The breaking capacity of the fuse (or rated maximum breaking current) must be higher than the short-circuit current of the installation. In addition, the short-circuit current limiting curves provided by the manufacturer allow short-current limitation on the supply side of fuses affected by faults to be ascertained. This means that sizing the switchgear and controlgear on the load side will be less problematical.

9. Applications

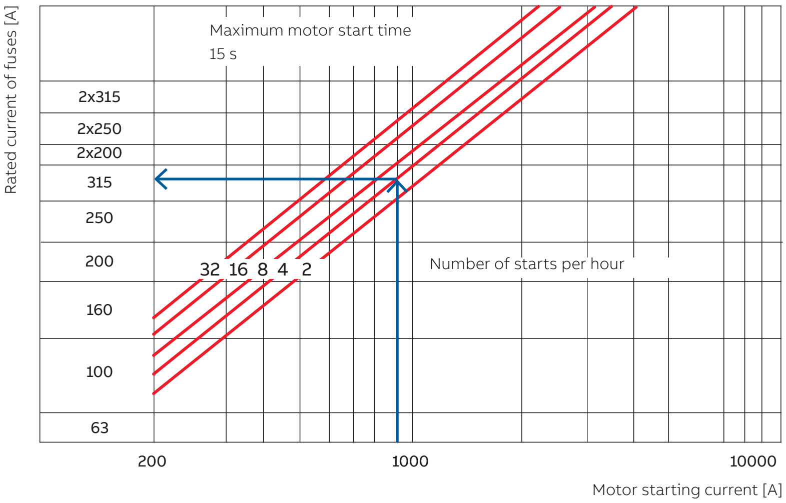


Fig. 9.25

In the example that has just been described and since the grid operating voltage Ur = 6000 V, we will choose 7.2 kV as the rated voltage of the fuse. Start time t_a is calculated with the formula described in chap. 4.2.3, assuming that the load torque is T_L = 8000 Nm with K_L = 1 constant torque, J_L = 230 kgm^2 moment of inertia of the load and with T_s = 6395 Nm, T_M = 18386 Nm:

$$T_{acc} = (T_M - T_L) = 0{,}45 \cdot (6395 + 18386) - 1 \cdot 8000 = 3151\ Nm$$

$$t_a = \frac{2\pi \cdot 1500 \cdot (63{,}3 + 230)}{60 \cdot 3151} = 14{,}6\ s$$

For this reason, we will use the graph with start time t_a=15s and at inrush current I_s= 6.5 · 140 = 910 A with 4 starts an hour, the result is a 315 A fuse.

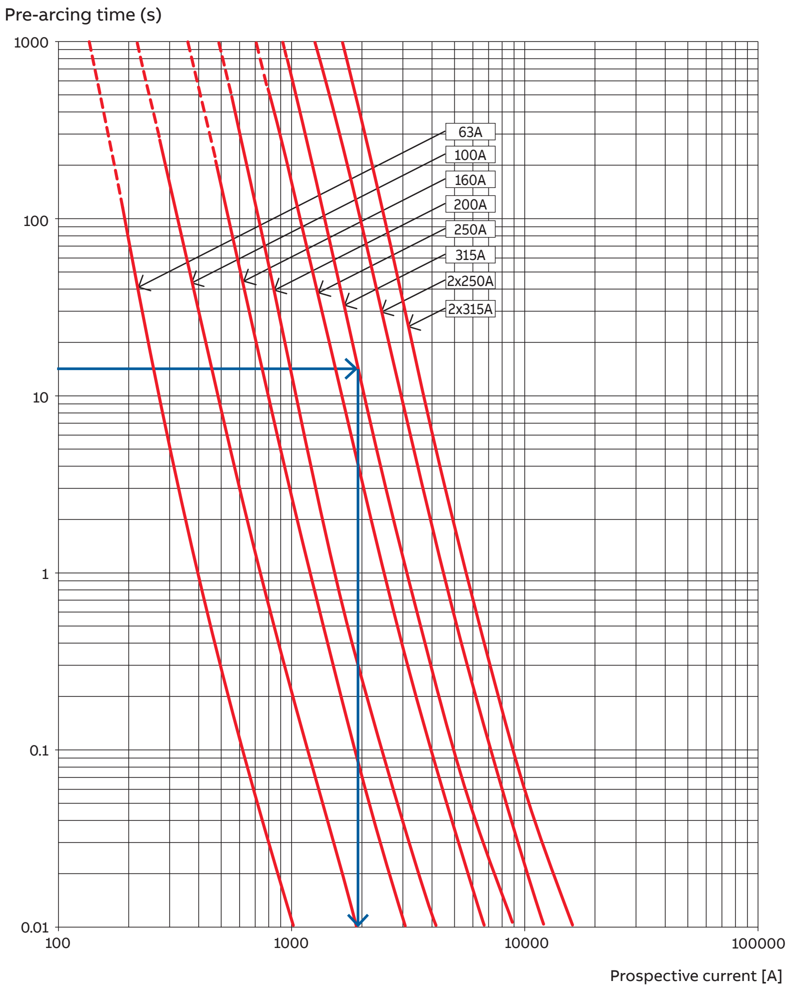


Fig. 9.26

We will now proceed with the next assessment. According to tab. 20 with the K factors, the value of K for a 7.2 kV, 315 A fuse is 0.6.
In addition, the fusing-time curve in fig. 9.26 shows that at 14.6 s (start time), the 315 A fuse blows if crossed by current at approx. 2000 A. The resulting value is therefore I_f · K = 1200 A.
This value is higher than the starting current (910 A), thus use of a 315 A fuse is also correct with regard to this condition, which concerns the possibility of brief intervals between starts.

9.4.3 Example of coordination between fuse - inverse time relay for protection against overloads

The need for an inverse time-delay or independent time relay for protection against overloads can be appreciated by observing the fusing curve of the 315 A fuse. Prolonged overtemperature, beyond the temperature specified for the insulation class, is harmful and seriously compromises the life of electric machines.
Generally speaking, the following steps are taken to coordinate the two devices (indicated in IEC 60644 and with reference to fig. 9.27):

1. when multiplied by the K factor, the time-pre-arcing current characteristic of the fuse must be to the right of the motor start current;
2. the switching device must be able to support the conditions defined by the combination of the two protections;
3. the rated current of the fuse must be chosen so that when it is in its service state, the fuse is able to continuously carry full-rate operating current without temperature rises;
4. the current corresponding to the point of intersection between the curve of the fuse and that of the relay must be less than the breaking capacity of the switching device;
5. the minimum breaking current of the fuse should not exceed the minimum take-over current indicated by the letter B;
6. if an instantaneous protection is used, intersection point B moves to C. Attention must therefore be paid to the fact that the switching device could open to a current higher than its breaking capacity;
7. the limited current of the fuse at the maximum fault current of the system should not exceed the withstand current of the switching device for the break time of the fuse, typically a half-cycle or less;
8. the minimum breaking current of the fuse should preferably be as low as possible, in any case equal to the locked-rotor current of the motor;
9. the cable withstand curve must remain to the right of the resulting trip curve of the protections. If this is not the case, the cable section may have to be increased.

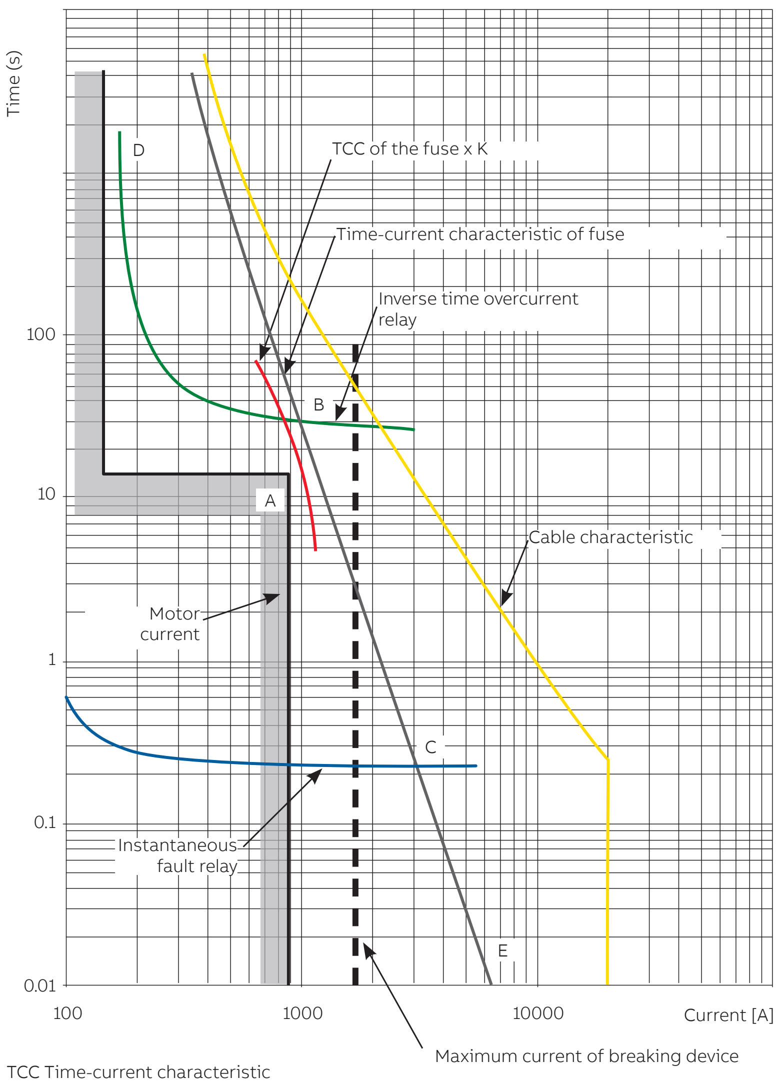


Figura 9.27: explanatory graph given in IEC 60644

In our example, illustrated in the time-current graph of fig. 9.30, step 1 has already been assessed 1 (curve d').
Compliance with the condition required by step 2 is confirmed, since coordination of contactor VSC7 with the chosen fuse has already been verified by the manufacturer.
Step 3 has been amply fulfilled since the fuse value is 315 A with 140 A rated current of the motor.
The current of the intersection point between the curve of the relay and the fuse is 2000 A less than the breaking capacity of contactor VSC 7, equal to 5 kA (line e), denoting compliance with the condition described in point 4.
The minimum breaking current of the fuse is 950 A (given by the fuse manufacturer), therefore less than the current in the point of intersection (2000 A): compliance with the condition described in point 5.
Step 6 does not apply to the example in question.

9. Applications

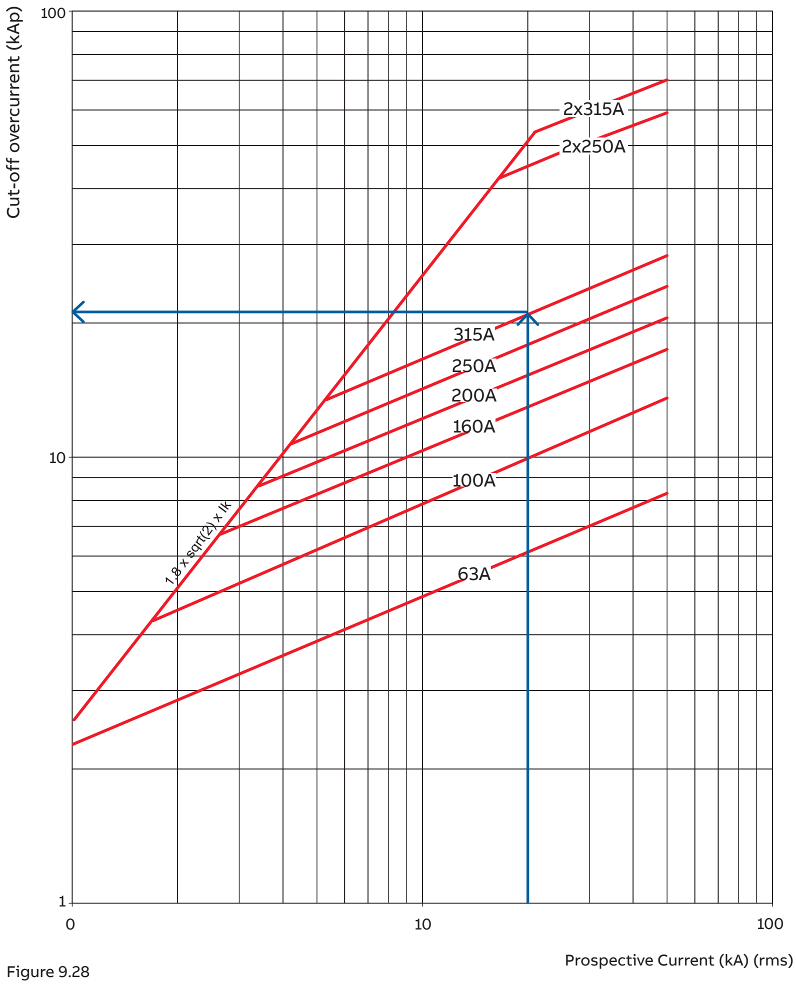


Figure 9.28

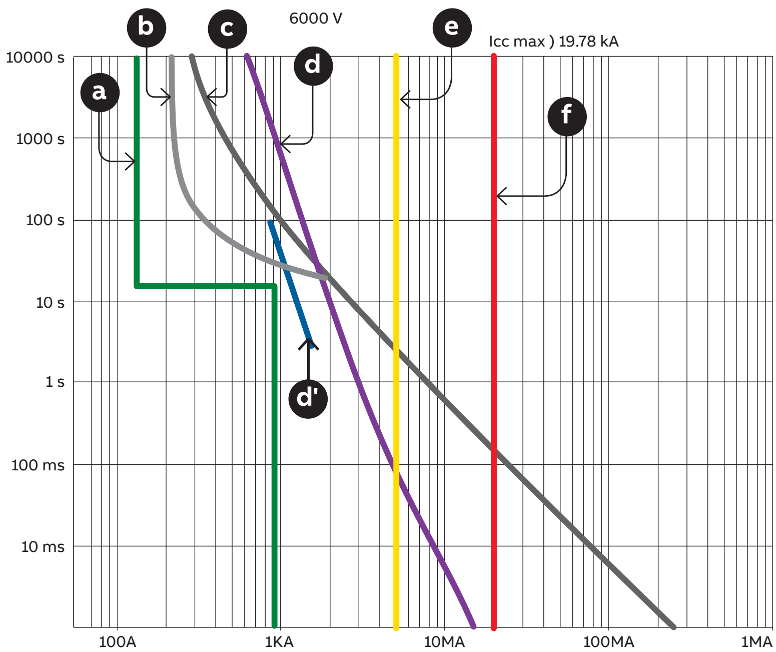


Figure 9.30

As to step 7, the curves provided by the fuse manufacturer given in fig. 9.28 show that at 19.8 kA maximum short-circuit current, the limited current is 22 kAp. In this particular case, coordination between VSC contactor and 315 A fuse is guaranteed by the manufacturer up to 50 kA. Thus compliance with the condition specified in this step has been verified.

Regarding step 8, we can affirm that the locked-rotor current for the motor in question exceeds 900 A and is therefore practically the same as the minimum breaking current of the fuse. However, locked-rotor protection of the motor is provided by the protection relay (function 51LR) rather than by the fuse.
Lastly, step 9 could be critical since the intersection point of the protection curves overlaps the withstand curve of the 50 mm² cable. To be on the safe side, either an additional definite time overcurrent threshold could be introduced or the cable section could be increased, to 70 mm² for example.

Figure 9.29

a - motor current, I_N=140A, I_S=910A
b - relay REF 615 inverse time maximum current protection
c - characteristic of 50 mm² cable
d - TCC of CMF 315 fuse
d' - TCC of the fuse x K
e - breaking capacity of contactor VSC 7
f - short-circuit overcurrent

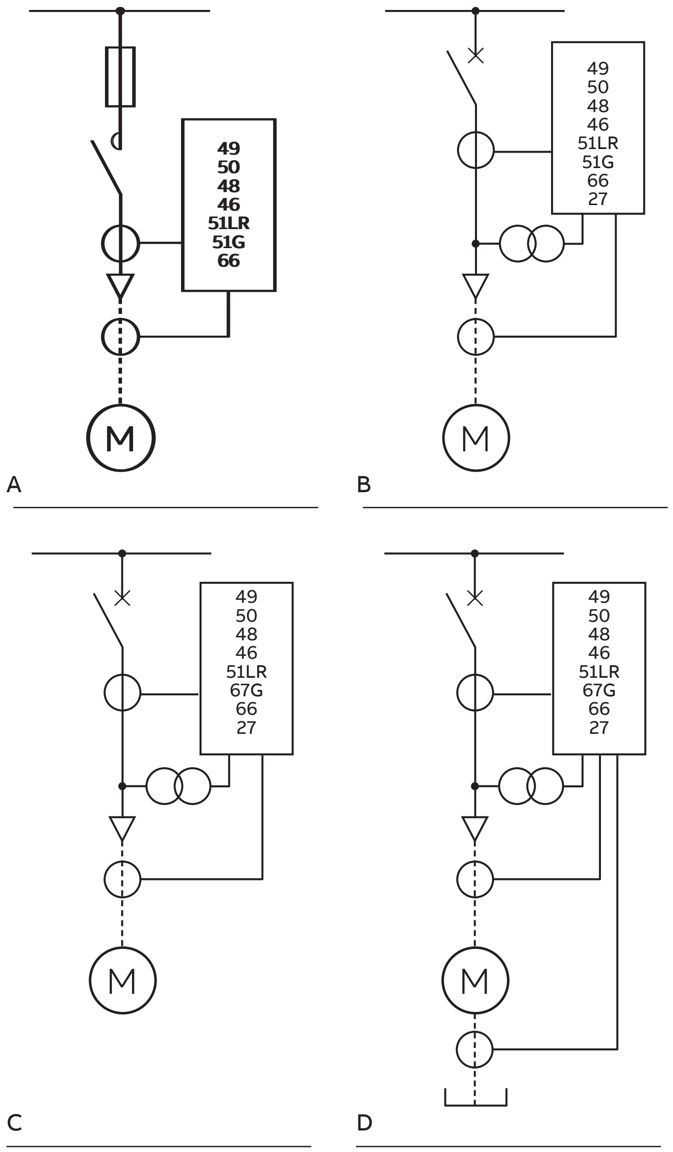


Figure 9.31

9.4.4 Protection relays for motors

If protection is provided by circuit breakers and protection relays, faulty operating conditions can be identified by means of various protection functions, one of which can also be the stand-by of the other, e.g. short-circuits can be identified using overcurrent and/or residual current protections.
The protection functions required for motors are:

- relay 49 thermal image overload protection;
- relay 50 short-circuit overcurrent protection (can be in conjunction with fuses);
- relay 87M residual-current protection;
- relay 51G earth fault overcurrent protection;
- relay 48 protection against overcurrent for prolonged starting;
- relay 51LR protection against overcurrent for locked-rotor during running;
- relay 46 negative sequence overcurrent protection;
- relay 66 number of starts control protection.

Other protection functions can be included for special applications and are:

- relay 27 undervoltage protection against motor disconnection;
- relay 37 undercurrent protection (typical for submersible pumps);
- relay 78 protection against step loss in synchronous motors.

Some typical protection system configurations are illustrated in fig. 9.31.

In this case, the recommended relays are: REM 611, REM 615, REM 620, REM 630 (fig. 9.32).

Refer to the Technical Guide entitled “Protection criteria for medium voltage networks” for further details.

Fig. 9.32

9. Applications

9.5 Generator protection apparatus

Fig. 9.33: example of an MV generator

The main function of a circuit breaker is to carry the rated current of the generator and break both the short-circuit current supplied by the generator and that supplied by the power grid. Requirements in terms of breaking capacity depend on the amount the installation contributes to the fault current and the location of the actual fault itself. Fig. 9.34 illustrates a typical single-line diagram and two possible points of failure, i.e.:

- fault in A, system-source fault
- fault in B, generator-source fault.

Regarding amplitude, fault current supplied by the grid is almost always higher than that supplied by the generator. This is due to the lower reactance of the transformer and network compared to the transient and sub-transient reactance of the generator.

This is also true of the X/R ratio, which is lower when the fault is supplied by the grid. This current is therefore the requirement that determines the breaking capacity of the circuit breaker. However, when a circuit breaker is chosen for protecting a generator, in accordance with the new Standard IEC/IEEE 62271-37-013 Ed. 1: High-voltage switchgear and controlgear - Part 37-013: Alternating current generator circuit breakers, short-circuit overcurrent is only one of the parameters required for this specific application. One must also consider the fault in B, supplied by the generator, characterized by higher levels of asymmetry and higher time constants (fig. 9.35).

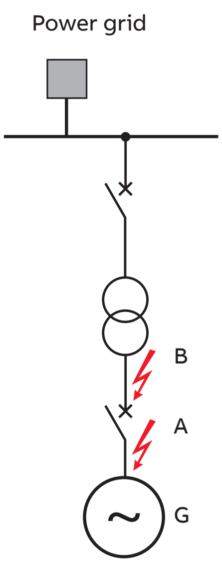


Fig. 9.34

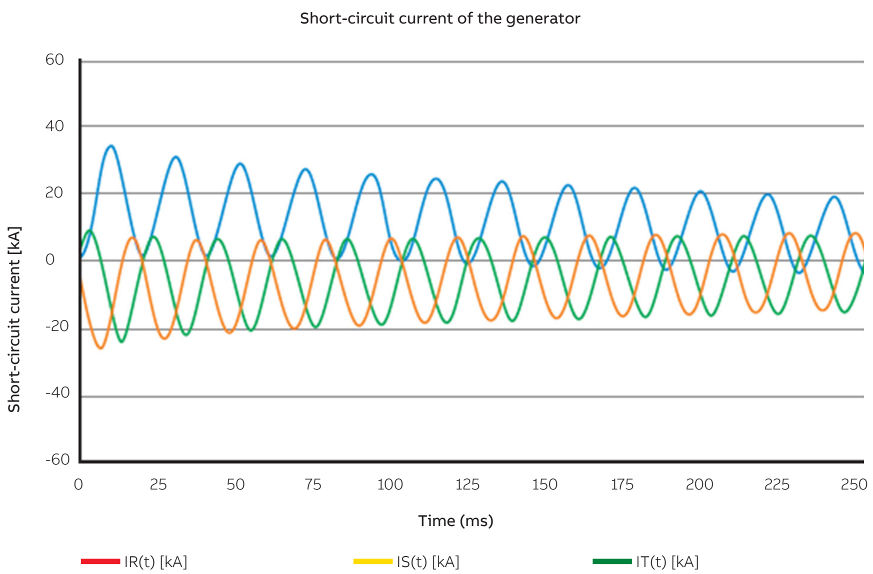


Fig. 9.35: fault in B supplied by generator

Circuit breakers for generators conforming to Standard IEC/IEEE 62271-37-013 are designed to overcome these critical conditions and to withstand longer electric arc duration.
The VD4G family of generator circuit breakers includes three apparatuses: VD4G-50, ill VD4G-40 and VD4G-25 for voltage ratings up to 15 kV, currents up to 4000 A and breaking capacities of up to 50 kA for supply by generator. The circuit breakers all conform to Standard IEC/IEEE 62271-37-013 “High-voltage switchgear and controlgear – Part 37-013: Alternating-current generator circuit breakers". The following table lists the breaking capacities of the family in the three conditions: system-source, generator-source and out-of-phase conditions. In the case of generator-source breaking capacity, the first value refers to maximum breaking capacity with 110% asymmetry and the second to 74% breaking capacity but 130% asymmetry (called class G1 in the Standard). The same value means that the circuit breaker is able to interrupt at maximum breaking capacity with 130% asymmetry (called class G2 in the Standard).

	System-source breaking-capacity [kA]	Generator-source breaking-capacity [kA]	Out-of-phase breaking-capacity [kA]
VD4G-50	50	50/37	25
VD4G-40	40	25/25	20
VD4G-25	25	16/16	12.5

In all cases, if the cause of asymmetry occurs during delays in current zero crossing, it will be necessary to demonstrate that the circuit breaker is able to interrupt the current within the maximum arcing time it is able to sustain.
If the arcing time resulting from the lack of current zeroes were to exceed the maximum arcing time the circuit breaker is able to sustain, a possible solution would be to delay the release signal of the circuit breaker so as to return below that maximum value. This would clearly lengthen the time the installation would be exposed to short-circuit current. For that reason, this solution must be carefully assessed and agreed with the user.
The other differences with respect to interruption of faults supplied by the grid are that the rate of rise of the transient recovery voltage (TRV) is much steeper and there are fault currents due to closing in out-of-phase conditions.
Current interruption due to generator-source faults is an extremely complex phenomenon, considering the differences in the way generators behave due to different design and construction techniques. Since it is very difficult to reproduce these faults in test laboratories, the Standard underscores how the only way to assess the capability of a generator circuit breaker to interrupt a short-circuit current with lack of current zero crossing is by simulation.

Fig. 9.36

9. Applications

9.5.1 Example of how a generator circuit breaker is sized

Two generators connected to the HV grid by means of a transformer with three windings are considered in the installation proposed as an example. The starting condition will be that of an initially no-load generator. A 1.05 voltage factor is considered for this installation.

The main grid data are:
Scc=2000 MVA X/R=10 V_n=150 kV

Transformer with 3 windings:
V_1=150 kV S_1=150 MVA V_{cc_12}=11.5% @ 55 MVA
V_2=11.5 kV S_2=75 MVA V_{cc_13}=11.1% @ 55 MVA
V3=11.5 kV S_3=75 MVA V_{cc_23}=21% @ 55 MVA

Generators:
Sn=75.294 MVA
V_n=11.5kV

X_d=2.26	X_q=2.06	T_d'=0.71	T_q'=0.71
X_d'=0.217	X_q'=0.26	T_d''=0.04	T_q''=0.04
X_d''=0.155	X_q''=0.19	R_a=0.001309	

The reactances and resistances are given in p.u. while the values of the time constants are given in seconds. According to Standard IEC 60034-3, the admissible tolerances can be around ±15%, thus all reactances are decreased by that percentage as a precaution.
We will first analyze the symmetrical current at instant t=0 (i.e. the moment that short-circuit occurs) on the supply side and then on the load side of the generator circuit breaker (GCB). After this, the capability of the circuit breaker to eliminate a three-phase-earth short-circuit in the two above-mentioned points will be assessed.
We will first consider a three-phase-earth fault between the GCB and generator G1. Application of the MVA method allows the value of the short-circuit symmetrical current to be assessed in just a few steps.

First, we must make sure that the v_{cc_12}; v_{cc_13}; v_{cc_23} values are given according to the same basis. After this, the values of the short-circuit impedances for each winding can be obtained from the following relations:

$$v_{cc\_1} = \frac{v_{cc\_12} + v_{cc\_13} - v_{cc\_23}}{2} = 0{,}8\ \% \quad @\ 55\ MVA$$

$$v_{cc\_2} = \frac{v_{cc\_12} + v_{cc\_23} - v_{cc\_31}}{2} = 10{,}7\% \quad @\ 55\ MVA$$

$$v_{cc\_3} = \frac{v_{cc\_23} + v_{cc\_13} - v_{cc\_12}}{2} = 10{,}3\ \% \quad @\ 55\ MVA$$

Now let us suppose that the transformer with three windings is like the one in the equivalent diagram of figure 9.37:

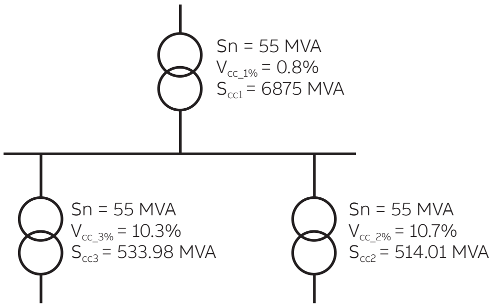


Figure 9.37: Transformer with 3 windings

The MVA method can now be applied to the circuit, as shown in figure 9.38:

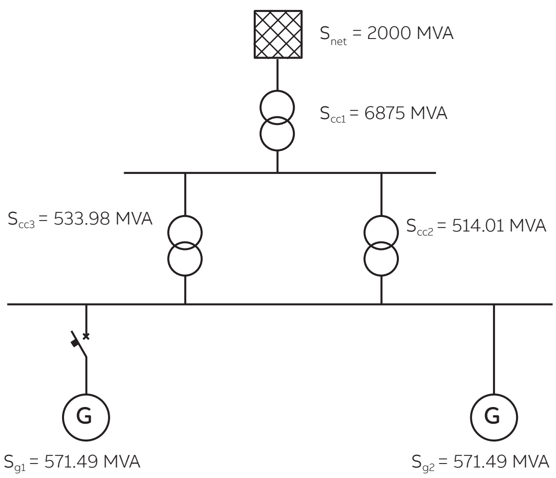


Figure 9.38: layout of the installation

The short-circuit current for a fault between the machine circuit breaker and generator G1 will be calculated first:

$$Scc_k = \frac{1}{\left(\frac{1}{Sg2} + \frac{1}{Scc2}\right)} = 270{,}61\, MVA$$

$$Scc_r = \frac{1}{\left(\frac{1}{Snet} + \frac{1}{Scc1}\right)} = 1549{,}29\, MVA$$

$$Scc_p = Scc_r + Scc_p = 1819{,}90\, MVA$$

$$Scc_{tot} = \frac{1}{\left(\frac{1}{Scc_p} + \frac{1}{Scc3}\right)} = 412{,}84\, MVA$$

The symmetrical short-circuit current at instant t=0 can be obtained from this value.

$$I_k'' = \frac{c * Scc_{tot}}{\sqrt{3} * V_n} = \frac{1{,}05 * 412{,}84 * 10^6}{1{,}73 * 11{,}5 * 10^3} = 21{,}78\, kA$$

I_k'' is the symmetrical short-circuit current value at time t=0. This value acts as a reference for successive simulation performed via computer using EMTP (Electromagnetic Transient Program) software. It also allows an initial estimation to be made of the size of the circuit breaker required. The single-line diagram showing the system-source short-circuit currents for this particular example is given in figure 9.39. Current I_{sff} is the symmetrical short-circuit current to which value I_k'' corresponds at time t=0.

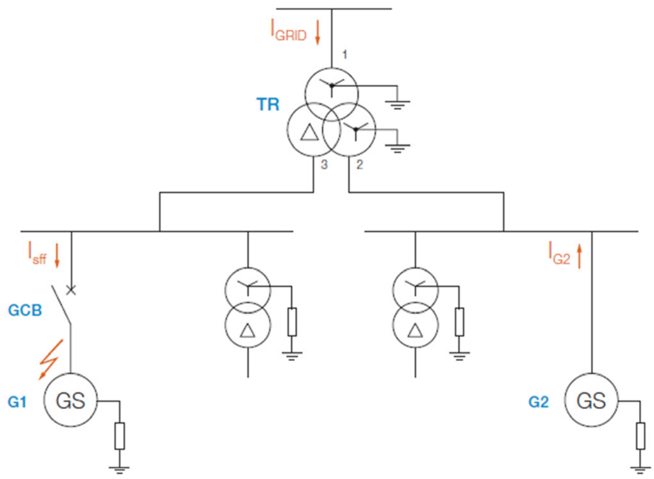


Figure 9.39: Trend of short-circuit currents for a system-source fault

9. Applications

The trend of the short-circuit current in the time calculated with EMTP is illustrated in the graph of figure 9.40.

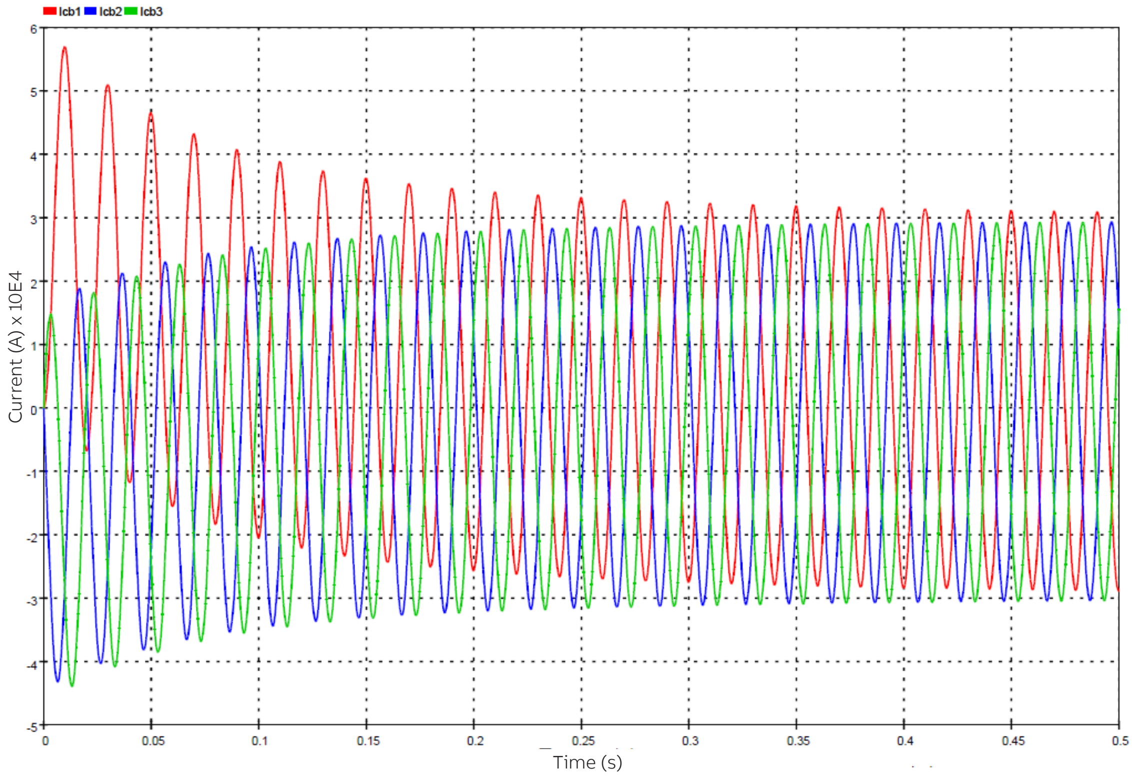


Figure 9.40: Short-circuit current for a system-source fault

The graph shows that the maximum current peak is:

I_p = 56.70 kA

while the remaining current values at instant t = 45 ms are:

I_{ssf_sym} = 21.38 kA

$i_{dc\%}$ = 53,75%

Note that the value of the symmetrical component is slightly different from the one observed at instant t=0. This is due to the contribution from the generator of the right-hand busbar which, in the absence of a constant symmetrical component, also changes the total symmetrical current value, although to a lesser extent.

The next data item to assess is the short-circuit current value in the case of a generator-source three-phase to earth fault, considering the symmetrical component at instant t=0 and -15% tolerance on the reactance as explained previously:

$$Scc_g = \frac{S_n}{x''_d} = \frac{75{,}294}{0{,}155 * 0{,}85} = 571{,}49\ MVA$$

$$I''_{kg} = \frac{c * Scc_g}{\sqrt{3} * V_n} = \frac{1{,}05 * 571{,}49 * 10^6}{1{,}73 * 11{,}5 * 10^3} = 30{,}12\ kA$$

Here again, short-circuit current I''_{kg} acts as the reference value for the following computer simulation. The single-line diagram showing the current flow for generator-source faults (I_{gff}) is given below.

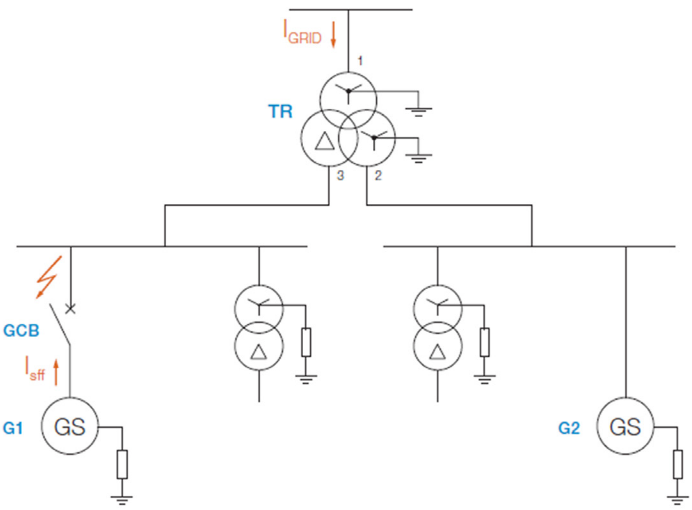


Figure 9.41: Trend of short-circuit currents for a generator-source fault

The graphs in figures 9.42 and 9.43 show the short-circuit current trend for the 90 and 0 degree voltage phase angles, respectively (also calculated with EMTP).

9. Applications

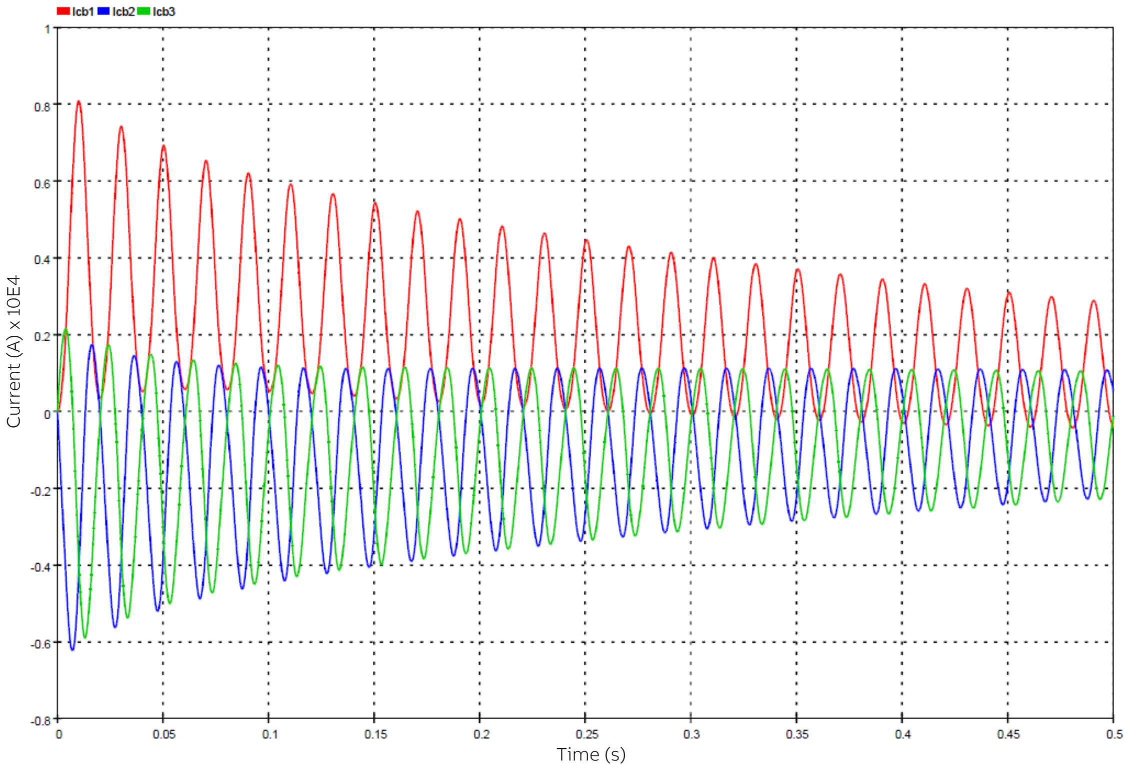


Figure 9.42: Short-circuit current for a generator-source fault, 90° voltage angle

The graph shows that the maximum value of the current peak is:

I_p = 80 kA

Considering a 45ms instant, the remaining current values are as follows:

I_{sym} = 22.52 kA

$i_{dc\%}$ = 118%

This result shows that continued operation can be guaranteed by a class G1 circuit breaker, as is VD4G-50.

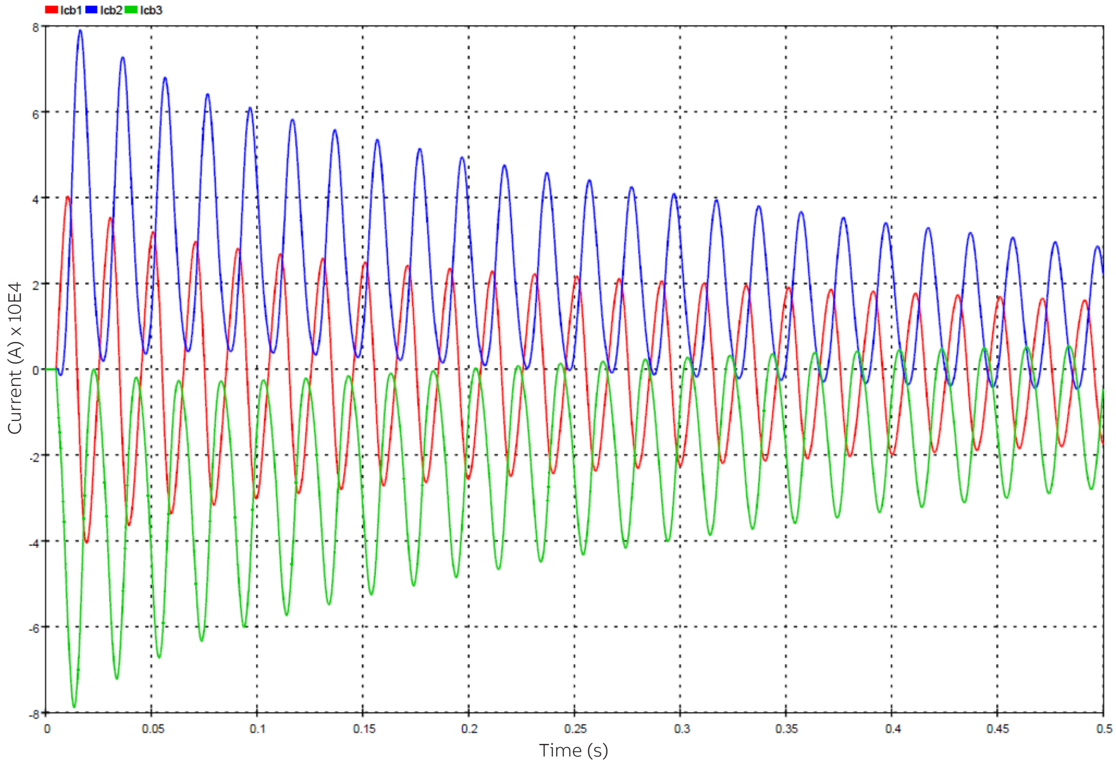


Figure 9.43: Short-circuit current for a generator-source fault, 0° voltage angle

Both the graphs in figures 9.42 and 9.43 show the two asymmetry values that must be considered when choosing the circuit breaker, as clearly suggested by the new Standard for generator circuit breakers (IEC/IEEE 62271-37-013 Annex E). These graphs show that the short-circuit current has a maximum peak value of 80kA and a 22.5 kA symmetrical component. In the case of system-source faults, thus owing to simultaneous contributions from the grid and generator, the ratio between peak value and the real symmetrical component the instant the contacts separate may exceed the value of 2.74 (standardized value for system-source faults, corresponding to a 133 ms time constant of the direct component). Checks based on the peak value mentioned above are therefore necessary when assessing the minimum size that can be selected.
The other limit when the MVA method is used for the calculations is that the symmetrical component of the short-circuit current is calculated at instant t=0. However, this value could be useful in the absence of detailed data. As mentioned previously, the value of the symmetrical component varies over time since a generator, whose symmetrical component is not constant during short-circuits, is involved. This means that it is important to calculate the value of the total symmetrical component the instant the contacts separate, which is less than that calculated with the MVA method, i.e. at t=0, so as to avoid choosing an oversized circuit breaker. However, to calculate the circuit breaker precisely, the exact characteristic parameters of the generator must be known and the technician who performs the calculation must be fully familiar with the use of EMTP software.
Faults due to out-of-phase must also be assessed if the circuit breaker can be closed in the absence of synchronism between the grid and the generator itself, e.g. owing to faulty operation of the parallelled system. The fault current that occurs in this case follows the characteristic trend in figure 9.44, which mainly depends on the inertia of the rotor and relative turbine connected.

9. Applications

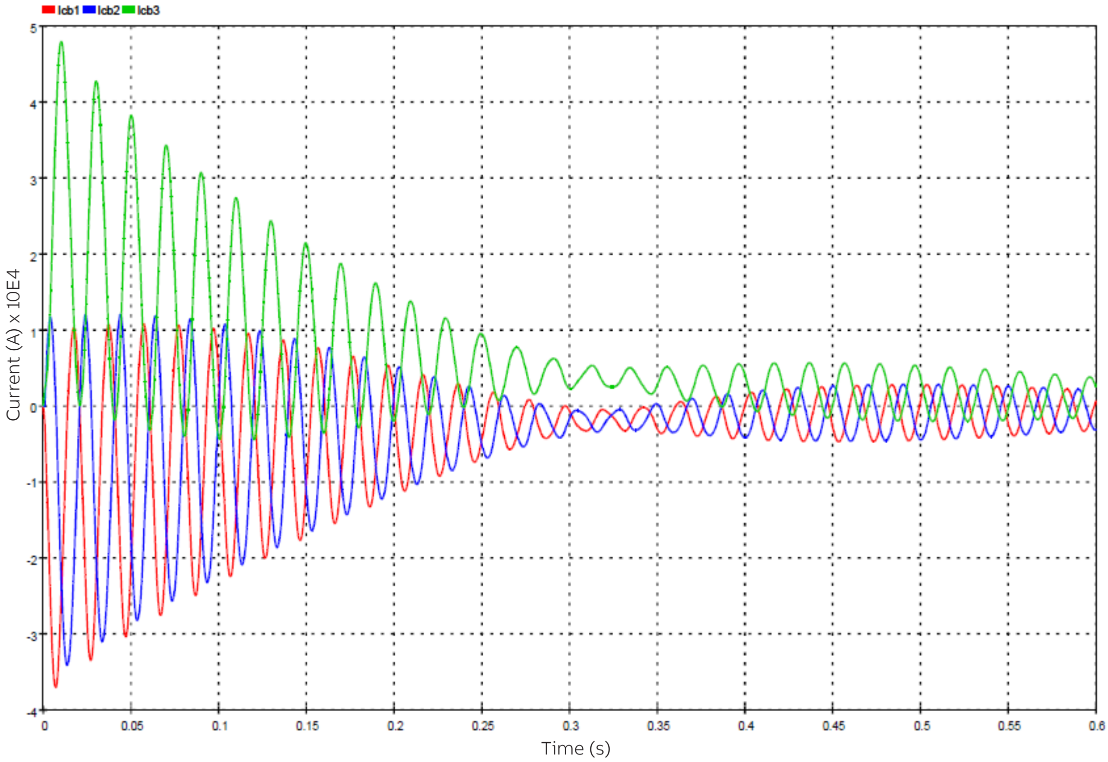


Figure 9.44: Fault current due to circuit breaker closing in out-of-phase conditions at 90° phase difference.

Although it may not seem so frequent, this type of fault must still be considered since its effects can be serious. Thus the capability of a generator circuit breaker to deal with it is of fundamental importance.
This subject is analyzed at depth in technical Application papers No. 22 “Medium Voltage circuit breakers for generators”, which includes an example of a complete calculation in accordance with IEC/IEEE 62271-37-013.

9.5.2 Protection relays for generators

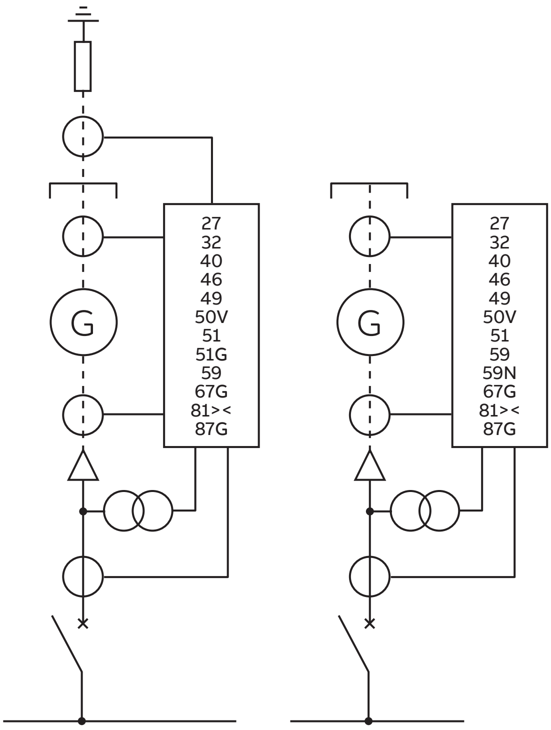
All or only some of the following protection functions can be used for protecting the generator, depending on the rated power of the machine and the type of application:

- relay 87 residual current protection of the generator (sometimes called 87G);
- relay 49 thermal overload protection of stator;
- relay 51 overcurrent protection;
- relay 40 loss of field protection;
- relay 32 reverse power;
- relay 46 negative sequence overcurrent protection;
- relay 21 underimpedance protection (as an alternative to zero-sequence overcurrent protection with voltage control when there is a unit transformer);
- relay 50V overcurrent protection with voltage control (as an alternative to underimpedance protection when there is no unit transformer);
- relay 27 undervoltage protection;
- relay 59 overvoltage protection;
- relay 81 underfrequency and overfrequency protection;
- relay 24 maximum overflux protection;
- relay 64R rotor ground protection;
- relay 64S stator ground protection (function of the type of state of the neutral).

There are other protection functions used for high-power machines, e.g.:

- 5 accidental energization;
- 37 underpower relay
- 49R (51R) rotor overload;
- 60 voltage balance relay;
- 78 ou of step.

A few typical protection system configurations are illustrated in fig. 9.45. Relay REG630 is recommended in this case (fig. 9.46).



Generator with earthed neutral

Generator with isolated neutral

Fig. 9.45

Fig. 9.46

Refer to the Technical Guide entitled “Protection criteria for medium voltage networks” for further details.

9. Applications

9.6 Switching overvoltages: application criteria

As will have been seen in the previous chapters, it is clear that in themselves, circuit breakers are not directly responsible for generating overvoltages or overcurrents. The energy that supplies overvoltages is stored in various components of the power grid, transformers, motors, generators, capacitors, cables, lines, etc., with their inductances and capacitances, and is released throughout the installation from one state to the next.
However, the frequency and entity of the transient phenomena also depend on the behavior of the circuit breaker when it opens and closes, in relation to the type of dielectric medium used and, thus, on the way electric arcs are dealt with.
Chapter 5 describes how chopping currents, virtual chopping currents, single and multiple re-ignitions and restrikes are causes that trigger off the phenomenon.
Without bothering to dwell on breaking techniques using air or oil, which are now obsolete in medium voltage installations, we will now consider the different behavior of the SF_6 and vacuum circuit breaker.
As discussed in chaper 3, we know that owing to its nature, vacuum is an excellent dielectric medium. It is so efficient that when inductive currents below several hundred amperes are interrupted, it tends to quench arcs slightly before natural current zero crossing. The current at which this occurs is called chopping current and in modern circuit breakers is usually about 3.5 A with rare, maximum peaks of 5 A. The phenomenon is practically negligible in SF_6 circuit breakers.
This premature current interruption does not normally subject the installation to significant overvoltage. Only in 10-15% of the interruptions of small inductive currents will overvoltage reach considerable levels and maximum values are only reached in 2% of the cases.

Generally speaking, the following considerations can be made:

- since the phenomenon is statistical, the frequency of the opening operations is a first important data item to consider. Daily or monthly openings on-load can be considered as critical. No-load openings, which are actually more frequent, need not be considered;
- secondly, one must establish which level of overvoltage should be considered as dangerous for the installation. The impulse withstand voltage of the installation components in relation to that of the circuit breaker itself can be a good parameter to use. If, for example, the impulse withstand voltage of a fundamental component like a transformer is less than 70% of that of the protection circuit breaker, it could certainly increase the risk. The age of the components can also represent an aggravating factor, considering the natural ageing process of the insulation;
- another assessment concerning the installation concerns the nature of the currents that must be interrupted. Short-circuit currents are fortunately very rare and are not considered as causes of the phenomenon in question. On the other hand, weak inductive currents between 10A and 50A can be critical. If such loads need to be interrupted frequently, several times a year for instance or anyway, during the life of the installation, then this could also be a critical parameter;
- given that the presence of capacitance in the installation has the effect of damping the entity of the overvoltages, the ratio between supply grid capacitance and that of the load is an important parameter to consider. This ratio is 5:1 on average. If it were higher, 10:1 for instance, this would be a critical aspect;
- the existence of connection cables between the circuit breaker and load can be a positive element owing to the damping effect on the TRV. However, cables shorter than 10 m (or <2nF capacitance) are of no help. Cables between 50 and 100 m in length (or 5 and 10 nF capacitance) provide a positive contribution, while those exceeding 100 m in length (or >15 nF capacitance) provide a significantly positive contribution.

The previous five conditions can therefore raise or lower the probability of significant overvoltages occurring. The result must still be cross-checked with the nature of the load that needs protecting, which is the most important factor since sensitivity to the actual overvoltages themselves is different.
Based on experience acquired in a number of applications and laboratory tests, in the case of vacuum circuit -breakers we can affirm:

1. Small motors, typically with <600 A locked-rotor current, should be protected by voltage surge arresters, especially if the number of operations exceeds 2 starts a day. In addition, if the insulation level fails to conform to Standard IEC 60034-15 or is unknown, or if the motors are very old, then use of RC filters would also be advisable.
2. Small generators, characterized by short-circuit currents I''_K lower than 600 A. What has just been said for motors also applies in this case, i.e., the generators should be protected by voltage surge arresters, especially if the number of operations exceeds 2 starts a day. In addition, if the insulation fails to conform to Standard IEC 60034-15 or is unknown, or if the generators are very old, then use of RC filters would also be advisable.
3. Oil-immersed transformers of both the distribution and power type. The capacitance to earth in these machines is usually sufficiently large in relation to the reactive energy of the magnetizing circuit. This prevents significant overvoltages from forming. Additional protections are unnecessary unless the insulation level is inferior to the value established by Standard IEC 60071-1. The number of operations must also be considered if there are more than 2 a day.
4. Compensation inductors. These reactors are used to compensate the parasitic capacitance in long distribution and transmission lines. The operating voltage is between 20 kV and 40 kV and they are switched at least once a day. In this case, surge arresters are normally applied to the terminals of the circuit breaker on the load side, often in conjunction with RC filters connected to the terminals of the power transformer.
5. Transformers for arc furnaces. In view of the extremely frequent operations involved, surge arresters and RC filters are needed to protect these machines.
6. Dry-type transformers. The parassitic capacitances in these types of transformers are only small. So much so, if there are no connection cables between the circuit breaker and transformer, it is highly probable that overvoltage will occur. Surge arresters and, in the absence of long connection cables (<30m), also RC filters must be installed for all applications, especially in industrial installations where frequent operations are to be expected.
7. Limiting reactors. Surge arresters must be used.

Compliance with these recommendations should resolve the problem of overvoltages caused by vacuum circuit breaker switching operations, or at least, the residual risk should be negligible. In more complex cases or when there are doubts as to whether to apply protections against overvoltages or not, it is advisable to analyze the transient in the specific installation using suitable simulation software (EMTP ElectroMagnetic Transient Program).
On the other hand, vacuum interruption provides a whole set of indisputable advantages compared to other techniques in terms of electrical life. Thus the most suitable breaking technique must be chosen after carefully considering all the requirements and technical characteristics of the installation in question.

10. Conclusions

The ideal switching device for a specific application can only be chosen if all the fundamental data about the installation and the operating specifications of the application itself are available. Even so, the validity of the chosen device often only becomes apparent after it has been in service for some time.

Knowing the most important applications and the main phenomena associated with switching operations allows correct and responsible choices to be made; choices that will prevent damage to the installations and situations which could endanger the operators.

ABB is able to provide a vast range of apparatuses with performance parameters able to cover all the different applications that design engineers, installers and end customers may find themselves having to deal with and manage.

More details

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