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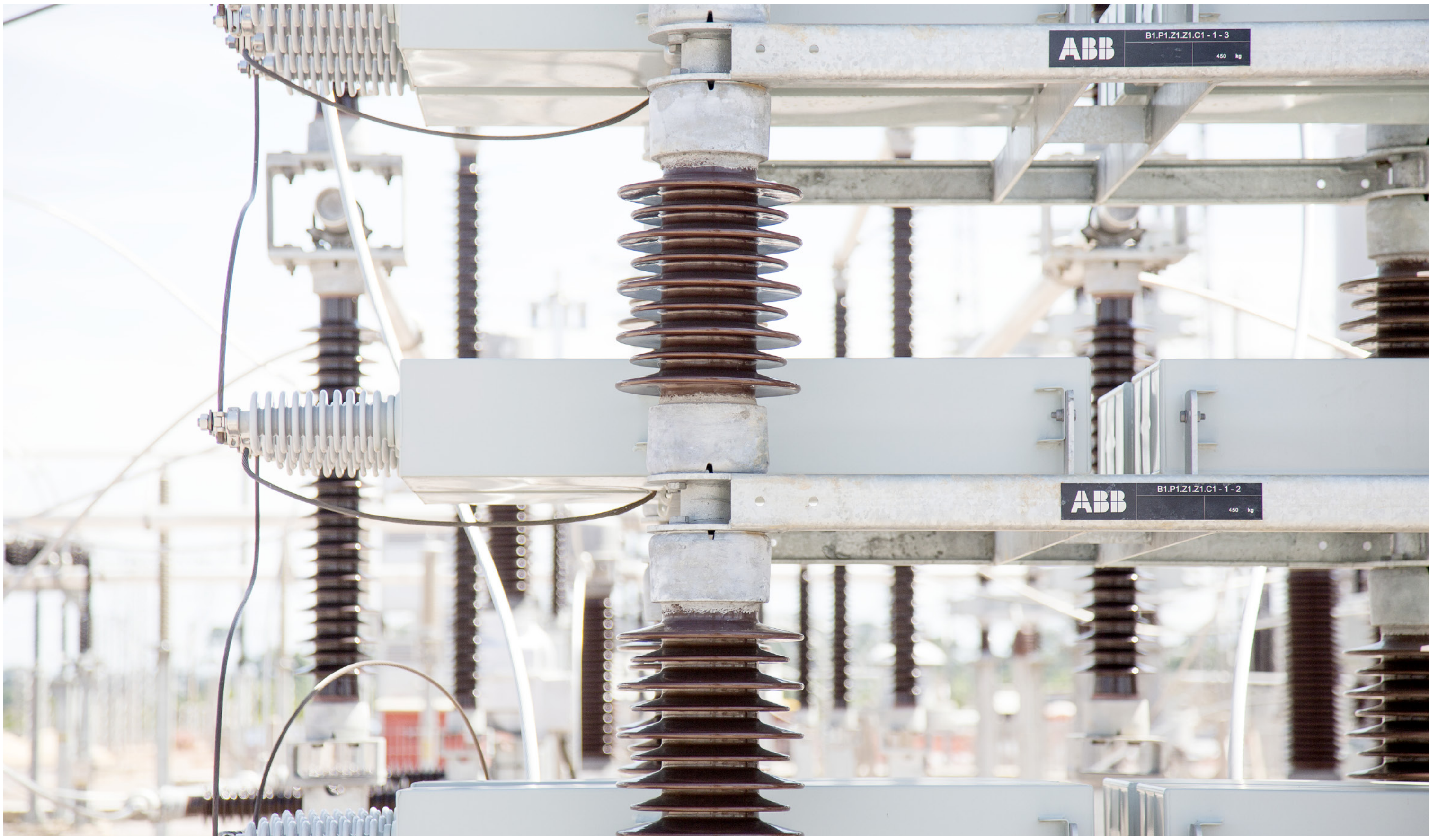
Technical Application Papers No. 23
Medium voltage capacitor switching



Contents

1. Medium voltage synchronous switching: introduction

Between the years 1745 and 1746, a new breakthrough revolutionized the physics of electricity. In order to study the electrification of water, scientist Andreas Cunaeus, who lived in Leiden, Holland, placed the liquid in a small glass jar with a long metal spike through its stopper, which was connected to the terminal of an electrostatic machine. As he held the jar in his hand, the unsuspecting scientist touched the spike and received a shock that was much more powerful than those usually obtained from the electrostatic machine. In January 1746, Pieter van Musschenbroek informed the Academy of Paris about the phenomenon, which was given the name of Leyden jar. This bottle full of water was actually the first capacitor in history.

Abbé Nollet, Professor of Physics at the Collège de Navarre in Paris, updated his demos to a further extent by discharging a battery of Leyden jars through a human chain. But it was Benjamin Franklin's experiments that showed how the water could be eliminated and that the shape of the glass jar was unimportant. His device simply consisted of a piece of glass between two metal plates, called armatures.

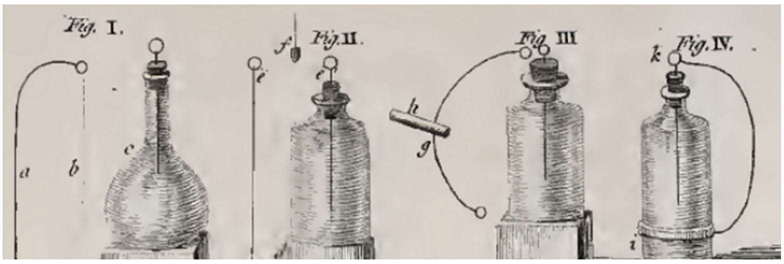


Fig. 1: Leyden jar

Fig. 2: Franklin's experiment

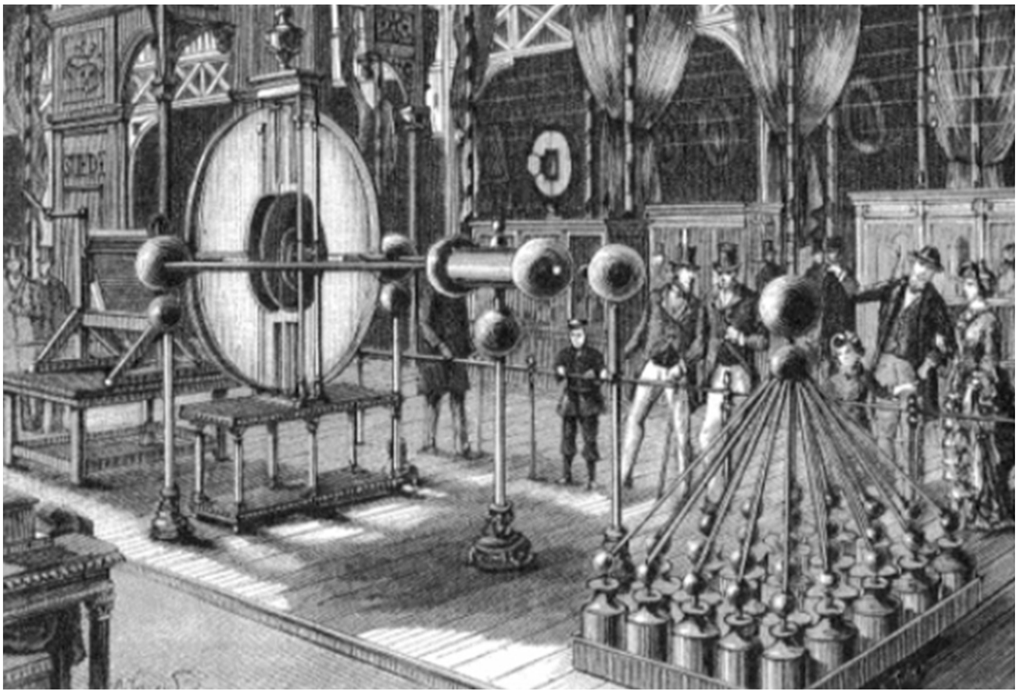


Fig. 3: experiment with several Leyden jars

In December 1773, Edward Nairne, one of Britain's principal manufacturers of scientific instruments, presented a machine comprising more than sixty Leyden jars to the Royal Society while in 1785, in Leiden, Martin van Marun saw to the construction of the largest electricity machine of its time. It featured an array of 100 jars and was able to generate extremely long sparks between its electrodes.

Fig. 4: Volta's condenser

The concepts of capacitance and capacitor were actually introduced during the same period by Alessandro Volta, who can be considered the father of modern electrostatics. An example of Volta's condenser is illustrated in the figure below.

After the victory of alternating current over direct current in the so-called War of Currents in the late 19th century, when there was a rapid expansion of AC electricity transmission and distribution networks, researchers began to address the problem of reducing the amount of reactive power circulating around the lines so as to reduce the consequent losses.
Nowadays, increased efficiency and reduced consumption are strongly encouraged while there is a pressing demand from governments and public opinion for reduced environmental impact. So much so, reactive power (basically of the inductive type) compensation by local installation of capacitor banks is becoming increasingly widespread. In addition, use of power factor correction capacitors provides tangible benefits for consumers since they avoid the fines that would be due should the power factor of their installations be below the contractually established threshold.
Capacitor banks with even high power ratings can be installed in the primary substations of public utility companies or even on individual users (typically motors) in the consumers' factories.

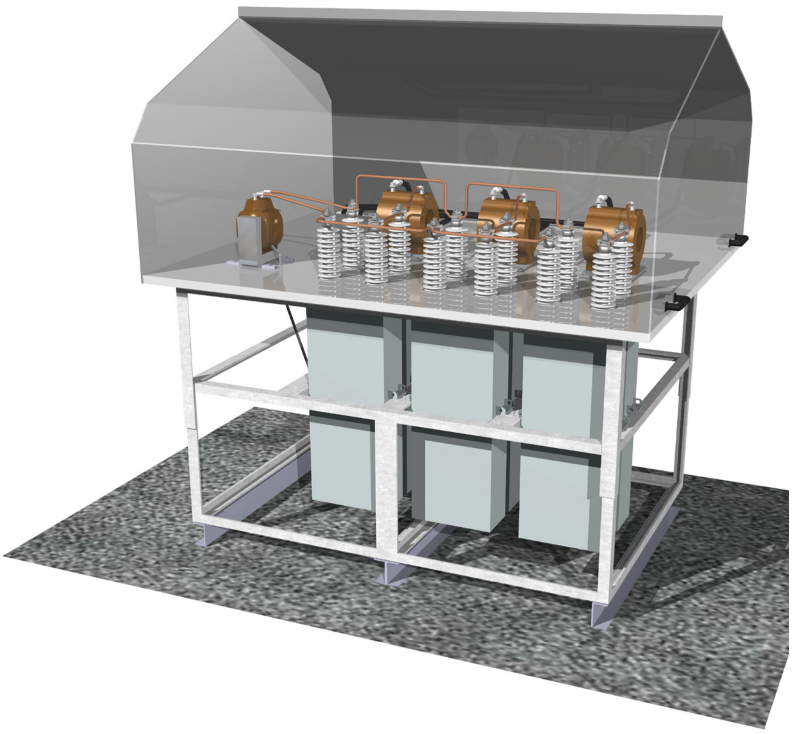


Fig. 5: ABB SIKAP: a compact solution for MV capacitor banks

Since loads fluctuate, capacitor bank switching-in and off operations are frequent, and occur at least daily. Although the capacitive current is normally of a small entity compared to the rated current of the circuit-breaker, capacitor bank switching still creates even considerable transients, which are considered to be one of the possible causes of faults in the capacitors themselves and, more generally, in installations.
Pre-switching of resistors or inductors, fixed inductors and surge arresters are among the possible countermeasures adopted. However, besides taking up space and being often unable to ensure that the phenomenon is completely eliminated, these solutions lead to losses and additional costs.
Synchronous switching is a further solution, developed in recent times. In this case, circuit opening and closing takes place in sync with voltage oscillation so that capacitor bank switching-in and off occurs at zero volts.
Compared to the traditional methods, this solution possesses the undoubted advantage of theoretically eliminating the problem at its origin.
The best way to obtain this result is to operate the poles of the switching apparatus individually and independently.
When it comes to the costs and dimensions of the circuit-breakers and capacitor switches, this solution was initially used at high voltage but recently, thanks to use of electronics in the apparatus and particulatly compact actuators, the principle can now be employed at medium voltage.

1. Introduction

Figure 6: synchronous circuit-breaker in a 420 V substation

According to an investigation conducted by CIGRE, use of synchronous apparatus has rapidly increased since the first experiments in 1990 owing to the good performance achieved in practical situations. As far back as 2001, there were already some 2400 HV synchronous apparatuses and their number was forecast to reach 6700 units in 2009 thanks to reliability improvements due to use of advanced sensors and modern digital technologies.

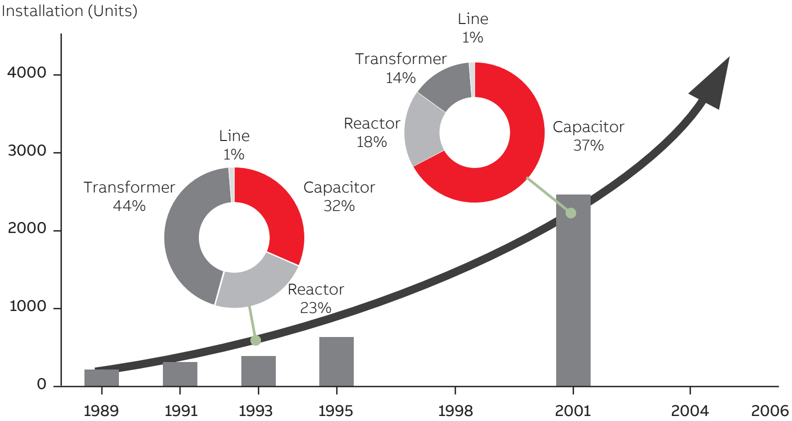


Fig. 7: CIGRE - use of synchronous switching devices over time

As can be seen, the most frequent application has progressively become capacitor bank switching, which already accounted for almost 70% of the applications in 2001. The reason for this success is that concrete savings are obtained through the elimination of pre-insertion resistors and inductors, fixed inductors and surge arresters. In addition, maintenance costs are reduced thanks to the longer electrical life of the switching devices while last but not least, there is less likelihood of faults in the installations.
In medium voltage installations, the circuit-breakers and capacitor switches normally consist of three poles mechanically connected to each other by a single operating mechanism with preloaded springs or by a single magnetic actuator. By contrast, synchronous switching must be performed individually by each pole with respect to its reference voltage, thus an operating mechanism or actuator must be available for each pole. Synchronism is achieved by a control unit so that the switching takes place in the point of the voltage wave that avoids transients caused by arc restrikes, i.e. when voltage crosses through zero.
Clearly the success of synchronized switching does not solely depend on the characteristics of the apparatus, but also on those of the electrical installation. This means that the cause-and-effect relationship between switching and the consequent behavior of the electrical installation must be defined and understood. Vice versa, the characteristics of the electrical installation before switching (e.g. presence of harmonics) may influence the synchronization process.
In addition, the design characteristics of the apparatus must all be constantly monitored to prevent wear or malfunctioning from interfering with the switching operation, e.g. speed of the contacts, state of the voltage sensors, actuators and of the control unit itself.

2. Capacitor bank switching

2.1 Switching-in capacitor banks

Capacitor bank switching is often affected by overvoltages and transient overcurrents.
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. 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.
The inductance of source Ls 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.

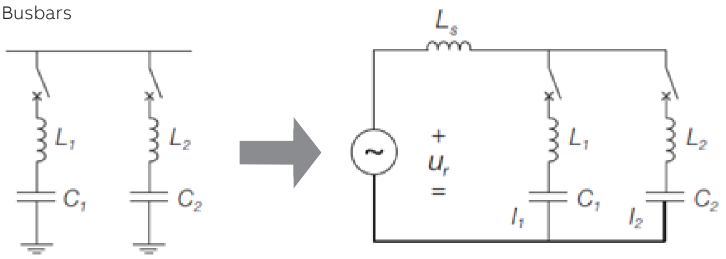


Fig. 8: capacitor switching-in circuit

Thus, for $L_s >> L_1$ there is:

$$\hat{\imath}_i = U_r \sqrt{\frac{2}{3} \cdot \frac{C_1}{L_s + L_s}} \approx U_r \sqrt{\frac{2}{3} \cdot \frac{C_1}{L_s}}$$

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

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:

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

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

If the capacitors are equal to each other and thus $L=L_1=L_2$ and $C=C_1=C_2$, the formulas are simpler and become:

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

In the case of n capacitors already connected:

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

The result is L”= L/n and C”=nC if all the capacitors are the same, so if L_1 is replaced with L” and C_1 with C” in the previous formulas, the result is:

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

By writing L_S in relation to 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 replacing the capacitance with the relative capacitive current:

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

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

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

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

$$i_{\text{peak}} = \sqrt{\frac{10^3 U_r I_1 I_2}{\pi f_s \sqrt{3} \times 10^{-6} L_{eq}(I_1 + I_2)}} = 13\,556 \sqrt{\frac{U_r I_1 I_2}{f_s L_{eq}(I_1 + I_2)}} \approx$$

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

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

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

2. Capacitor bank switching

The simplified formulas are outlined in the table below:

Condition	Quantity	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)	$13{,}5\sqrt{\frac{f_s U_r}{L_{eq} I_1}}$

Table 1. Simplified formulas for switching-in capacitors

For example, let us consider the following electrical circuit where a 6 MVAr capacitor bank at 13.8 kV, 60 Hz supplied by a source with 36 kA symmetrical short-circuit current is switched-in. The impedance of connection LC_1 is 8 μH.

The capacitance and current of the capacitor bank are:

$$C = \frac{Q}{\omega U_r^2} = \frac{6 \cdot 10^6}{2\pi \cdot 60 \cdot (13{,}8 \cdot 10^3)^2} = 83{,}57\mu F$$

$$I_1 = \frac{Q}{\sqrt{3}\, U_r} = \frac{6 \cdot 10^6}{\sqrt{3} \cdot 13{,}8 \cdot 10^3} = 251\ A$$

Thus the inrush current is:

$$i_i = 1{,}41 \cdot \sqrt{I_{sc} \cdot I_1} = 1{,}41 \cdot \sqrt{36 \cdot 10^3 \cdot 251} = 4250\ A$$

With a frequency of;

$$f_i = f_s \cdot \sqrt{\frac{I_{sc}}{I_1}} = 60 \cdot \sqrt{\frac{36 \cdot 10^3}{251}} = 718{,}5\ Hz$$

Special software for simulating the transients (EMTP, ElectroMagnetic Transient Program) can be used to obtain the trend of the inrush current in a phase showing the high frequency oscillation that overlaps the fundamental frequency with damping that depends on the resistors and losses in the system.

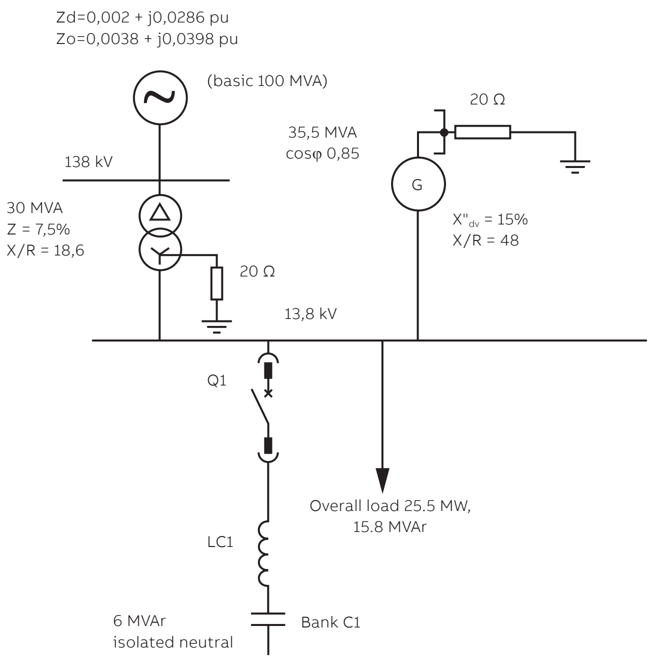


Fig.9: example of a circuit with capacitor banks

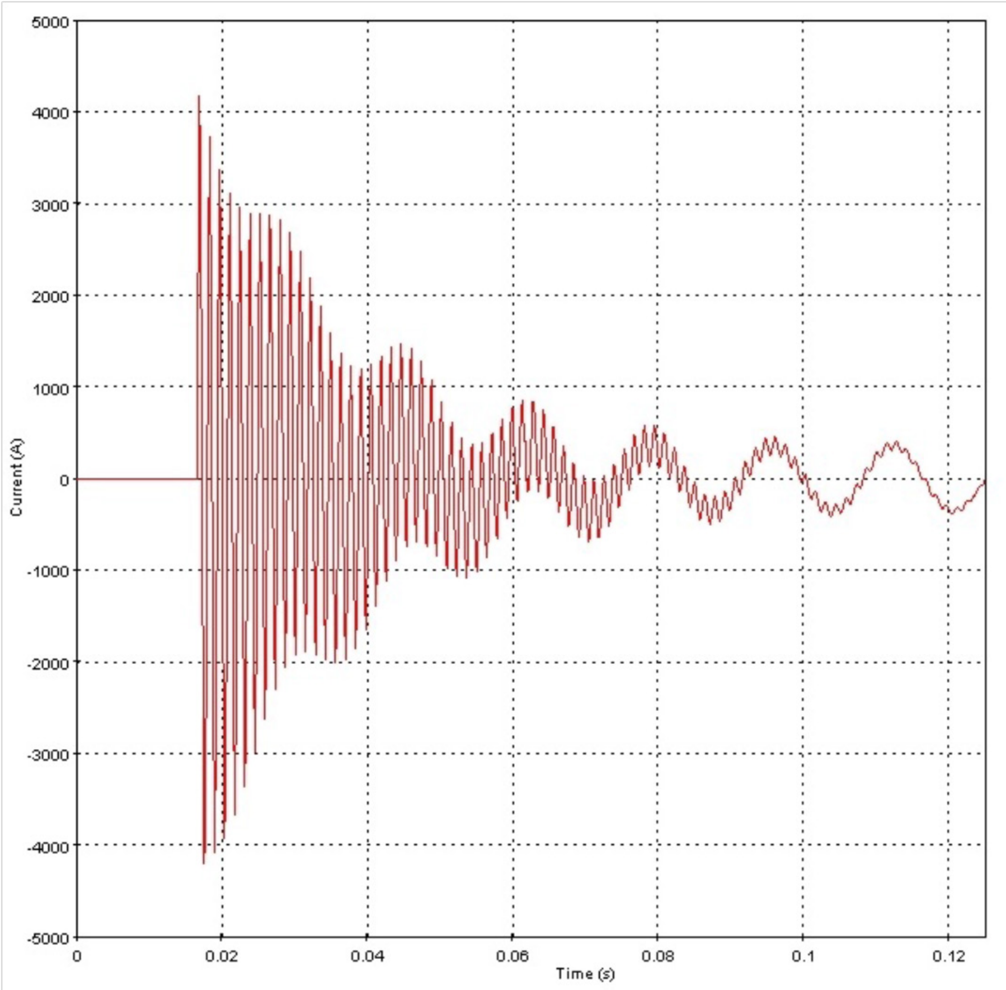


Fig. 10: inrush current for switching-in a capacitor bank

Now let us consider the case of back-to-back switching-in of a second capacitor bank identical to the first one, as shown in the following diagram:

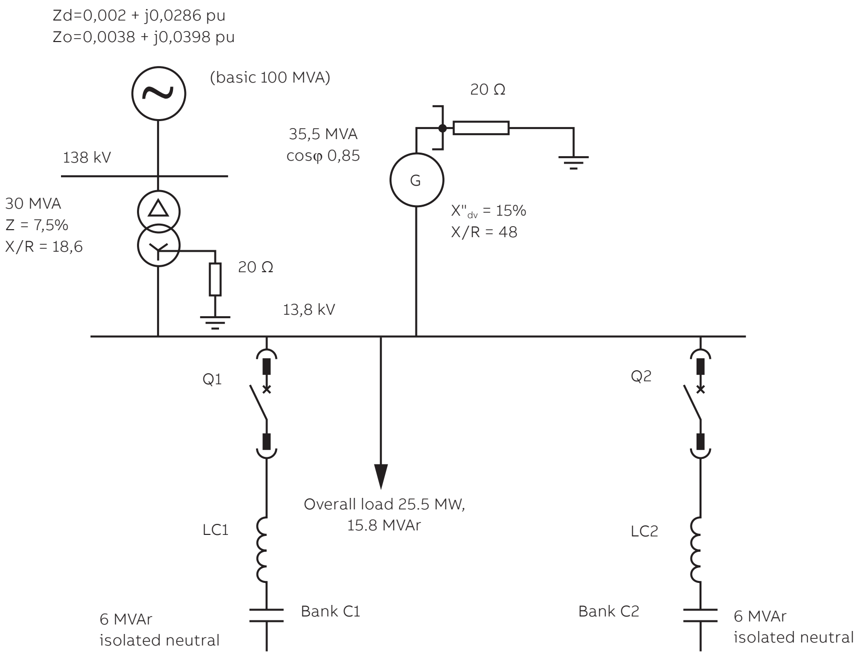


Fig. 11: example of a circuit with two capacitor banks

2. Capacitor bank switching

The results obtained by applying the formula are:

$$i_i = 9545\sqrt{\frac{U_r\, I_1}{f_s\, L_{eq}}} = 9545\sqrt{\frac{13{,}8 \cdot 251}{60 \cdot (8+8)}} = 18{,}1\ kA$$

$$f_i = 13{,}5\sqrt{\frac{f_s\, U_r}{L_{eq}\, I_1}} = 13{,}5\sqrt{\frac{60 \cdot 13{,}8}{16 \cdot 251}} = 6{,}13\ kHz$$

Here again, the trend of inrush current in a phase can be obtained using EMTP software. Note that oscillation reaches a considerably higher peak and frequency than in the previous case where a single capacitor bank was switched in.

In this case, the inrush current exceeds the values recommended by IEC 62271 for capacitive current switching by the circuit-breaker and contactor (20 kAp short-time peak current at 4250 Hz frequency for the circuit-breaker and 8 kPa 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 Standards:

$$i_i = U_r\sqrt{\frac{C}{6\, L_{eq}}} \leq 20\ kA$$

$$f_i = \frac{1}{2\pi\sqrt{L_{eq} C}} \leq 4250 \cdot 1{,}3\ Hz$$

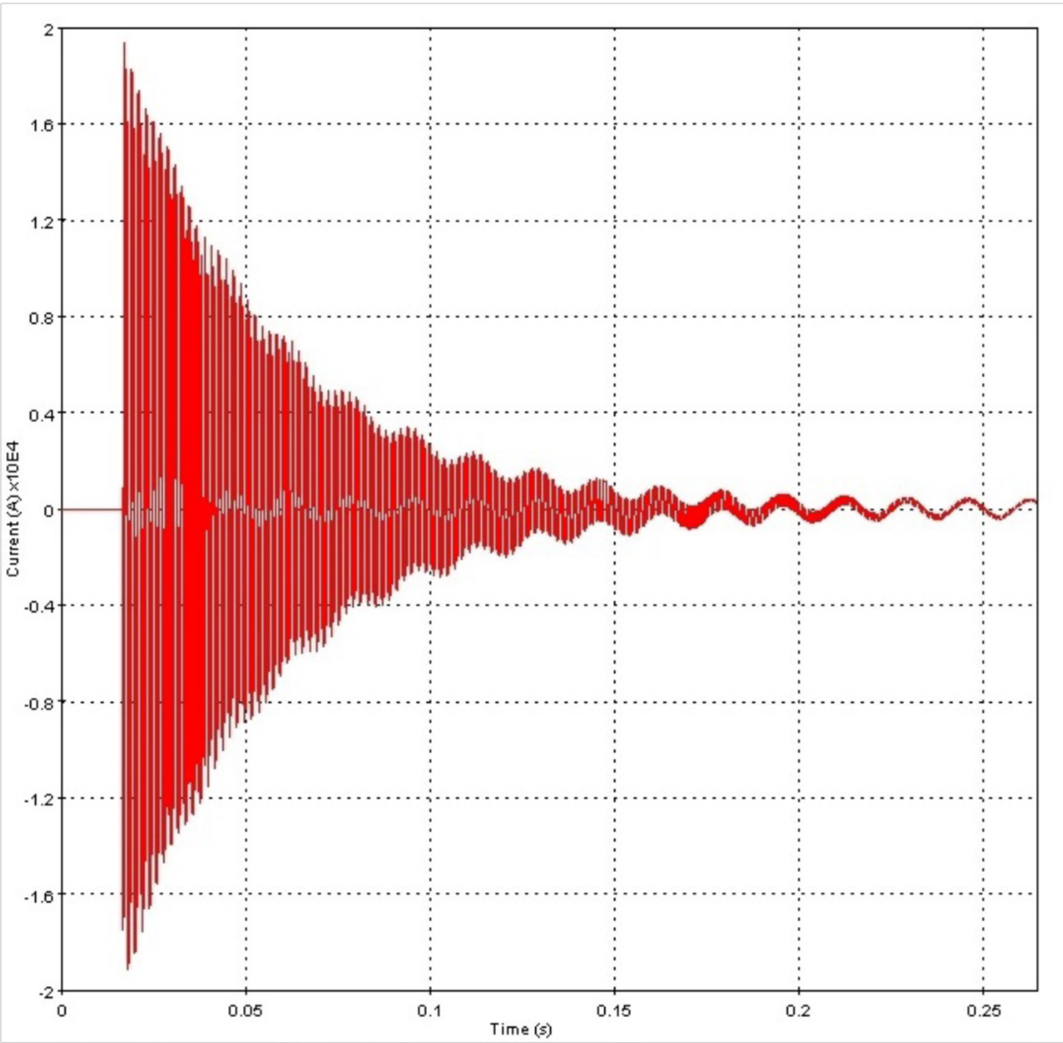


Fig. 12: inrush current for back-to-back switching-in of a second capacitor bank

where 1.3 is a coefficient suggested by the Standard allowing for +130% tolerance on the permissible frequency of the inrush current under service conditions.

Thus:

$$L_{eq} \geq \frac{1}{C\ (2\pi \cdot 4250 \cdot 1{,}3)^2} = 9{,}929\mu H$$

i.e. at least 1.929 additional μH. Moreover, with this value, the peak value would drop to 16.3 kA. As to the positions of the limiting inductors in relation to the switching device and capacitor, theoretically there is no difference to their limiting effect so long as they are installed on each phase and in series with the capacitors.
In some case, inductors are also installed on the neutral terminal of the capacitor. However, this is not the most widely used configuration.
When limiting inductors are installed for the purpose of limiting inrush current, the risk is of a fault occurring in such a way that the inductor limits the fault current interrupted by the circuit-breaker owing to the low capacitance of the circuit and increases the TRV imposed by the contacts to an excessive extent. In the examples shown in the figure, the TRV caused by the fault can often exceed the permissible limits of the circuit-breaker, a phenomenon very similar to that of short line interruption.

Installation of an inductor in series with a capacitor creates a resonant circuit. So much so, it is advisable to check for the presence of harmonics, normally of the high-order type, which could energize the circuit and cause undesired overloading of the inductor and capacitor. Once the capacitance of the capacitor bank is known, the value of the inductance for a determined order-n harmonic can be found so as to prevent resonance:

$$L = \frac{1}{n^2 \omega^2 C}$$

One approach could be to set the inductor to harmonic values that are much higher than those in the installation, e.g. above the thirteenth harmonic. Particular attention should be paid if there are inverters in the installation.
The major disadvantage in using limiting inductors is certainly their cost: the initial outlay, the cost of mitigating the TRV if necessary, and the installation costs.
Inductors also cause additional losses due to their resistance. Lastly, one must also bear in mind that the voltage increase due to large inductors being installed can lead to oversizing of the rated voltage of the capacitors as well as a variation in the power they provide.

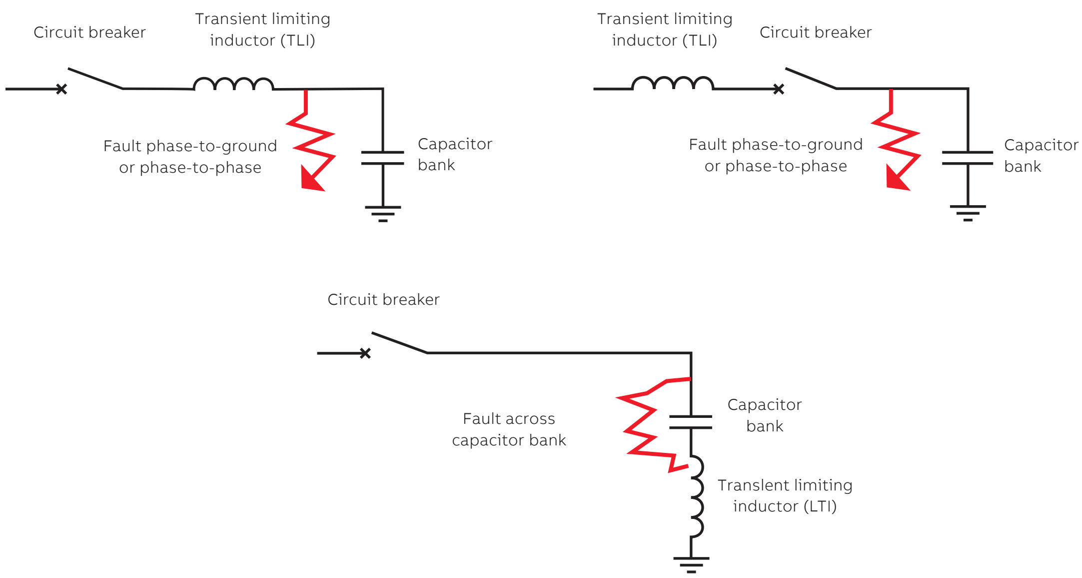
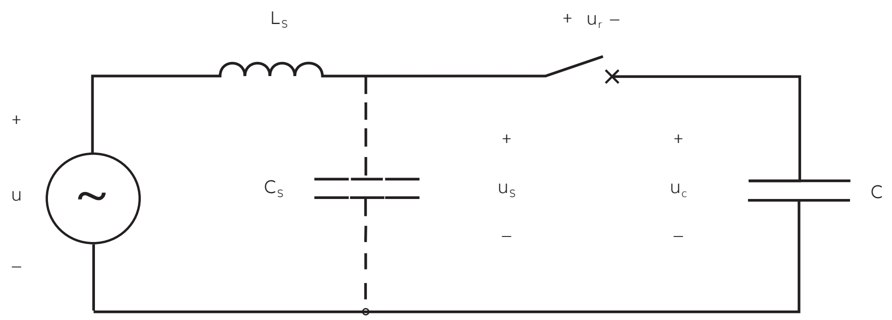


Fig. 13: Examples of limiting inductors in different positions

2. Capacitor bank switching



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

Fig. 14: simplified circuit for capacitive load interruption

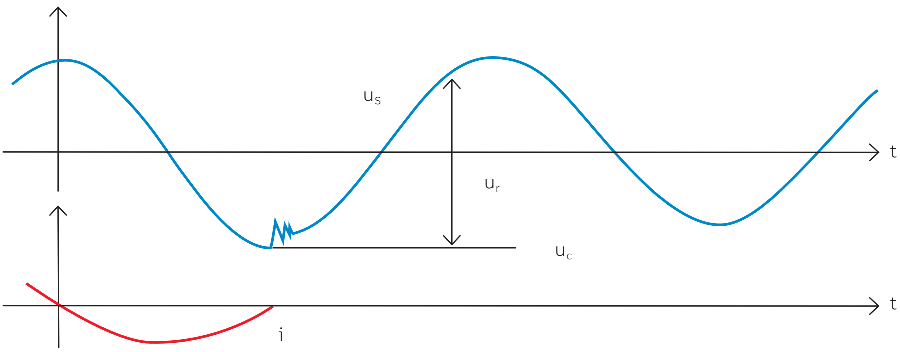


Fig. 15: voltage and current trend upon interruption of a capacitive load

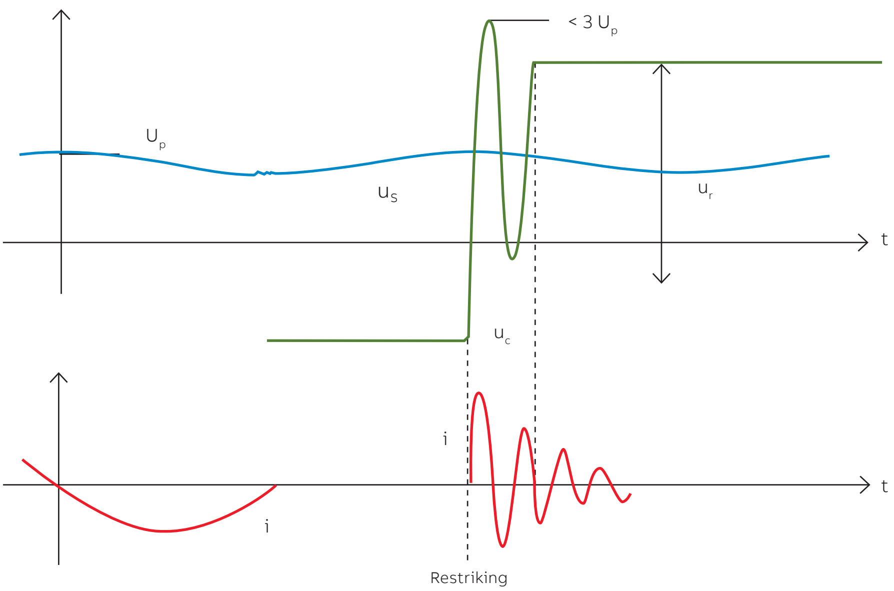


Fig. 16: voltage and current trend in the case of restriking

2.2 Interruption of capacitive loads

With reference to the next figure 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.

Supply voltage u_s remains practically unchanged after the interruption 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. However, the discharge time constant of the capacitors is around 40s, so their residual charge decreases slowly.

Half a cycle after the interruption, the TRV thus reaches a level equal to twice the peak value of the supply voltage.

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. Since the TRV is also higher, the switching device must be properly sized with respect to the single-phase system, so as to cope with opening the first pole. The next figure shows the value of TRV for opening the first pole when a capacitor bank with isolated neutral is opened.

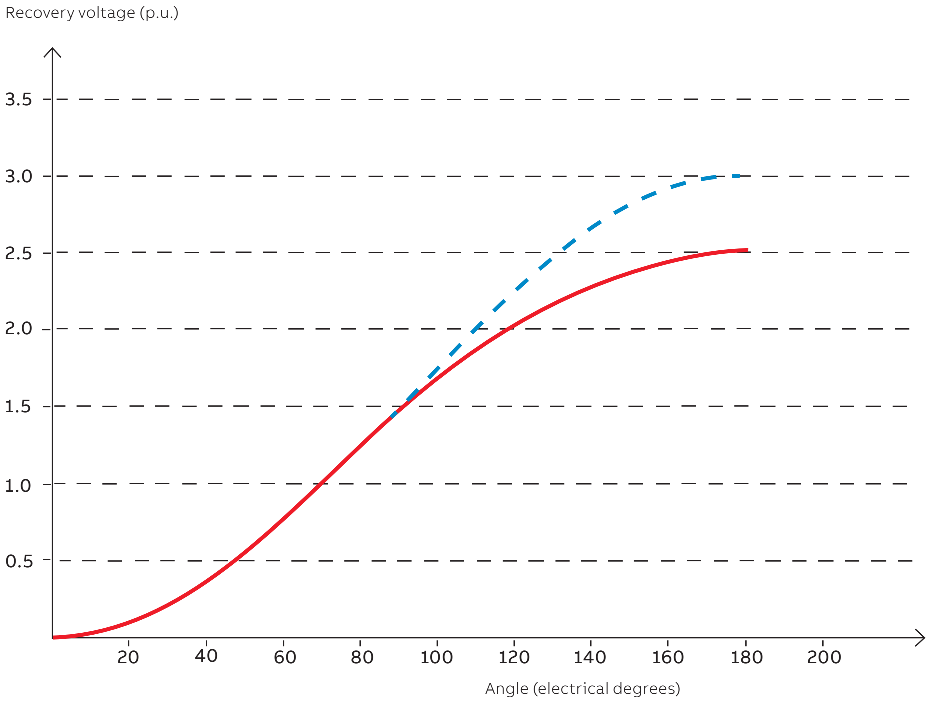


Fig. 17: TRV trend

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 fourth 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 for circuit-breakers, depending on their 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 when overhead lines L and cables C are powered-up), 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.

2. Capacitor bank switching

2.3 Further methods for reducing switching transients

There are several methods for reducing inrush current or TRV in the switching device itself:
- installation of limiting inductors so as to reduce the peak current and frequency of the inrush current;
- addition of pre-insertion resistors or reactors in the switching devices;
- capacitor switching in the incremental mode;
- use of surge arresters (metal oxide varistors – MOVs);
- use of sycnrhonous switching devices in both closing and opening phases;

The effectiveness of these methods depends on the characteristics of the electrical installation, thus the most appropriate choice must be made after detailed research into the behaviour in transient conditions. Each of these methods has different advantages and disadvantages as to reductions in overvoltage, costs, installation requirements, maintenance and reliability. Use of limiting inductors is described in chapter 2.1.

2.3.1 Pre-insertion resistors or reactors

Pre-insertion resistors or reactors are a very effective way for reducing switch-in transients. They are connected before the capacitor bank is energized and then short-circuited after the transient has been damped, obviously giving rise to a second transient. The resistor and inductor must be sized on the basis of the switch-in transient values of the capacitor banks and the successive bypass transient.

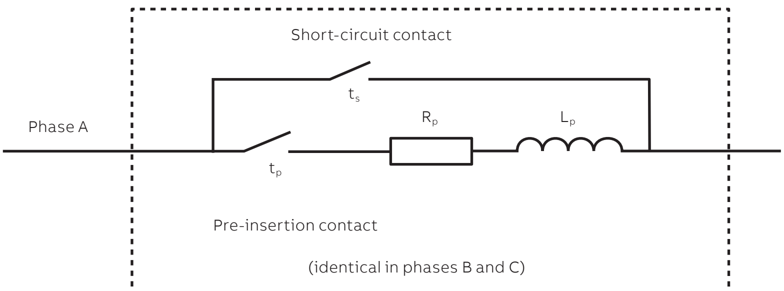


Fig. 18: pre-insertion circuit

The value of resistance R_p mainly depends on the size of the capacitor bank and on the grid parameters. It can be calculated using the following formula:

$$R_p = \sqrt{\frac{L_s}{C}}$$

Where L_s is the grid inductance (positive sequence) and C is the capacitance of the capacitor bank.
E.g. L_s can be calculated in the following way for the example described in chap. 2.1:

$$L_s = \frac{U_r}{\sqrt{3} \cdot \omega \cdot I_{sc}} = \frac{13{,}8}{\sqrt{3} \cdot 2\pi f \cdot 36} = 0{,}588\ mH$$

And since the capacitance of the capacitor bank was:

$$C = \frac{Q}{\omega U_r^2} = \frac{6 \ \cdot 10^6}{2\pi \cdot 60 \cdot (13{,}8 \cdot 10^3)^2} = 83{,}57 \mu F$$

The result is:

$$R_p = \sqrt{\frac{L_s}{C}} = \sqrt{\frac{0{,}588 \cdot 10^{-3}}{83{,}57 \cdot 10^{-6}}} = 2{,}65\ \Omega$$

As already explained for the limiting inductor, the pre-insertion inductor also reduces the inrush current as well as contributing towards limiting transient overvoltages. This effect depends on the system's inductance value and is effective for values that are the same or higher than this latter. A high resistance also helps by increasing the damping effect on voltage wave oscillation. When this solution is adopted, it is obviously necessary to calculate the peak current and frequency of the oscillation both before and after pre-insertion, as described in chap. 2.1.

2.3.2 Surge arresters (metal oxide varistors – MOVs)

Surge arresters limit switching overvoltage to the value of the maximum residual voltage (typically 1.8 p.u.) in the application point.
Proceed as described below when choosing a surge arrester (IEC 60099-5: “Surge arresters – Part 5: Selection and application recommendations”):
- the continuous operating voltage of the surge arrester must be at least equal to the highest operating voltage of the installation;

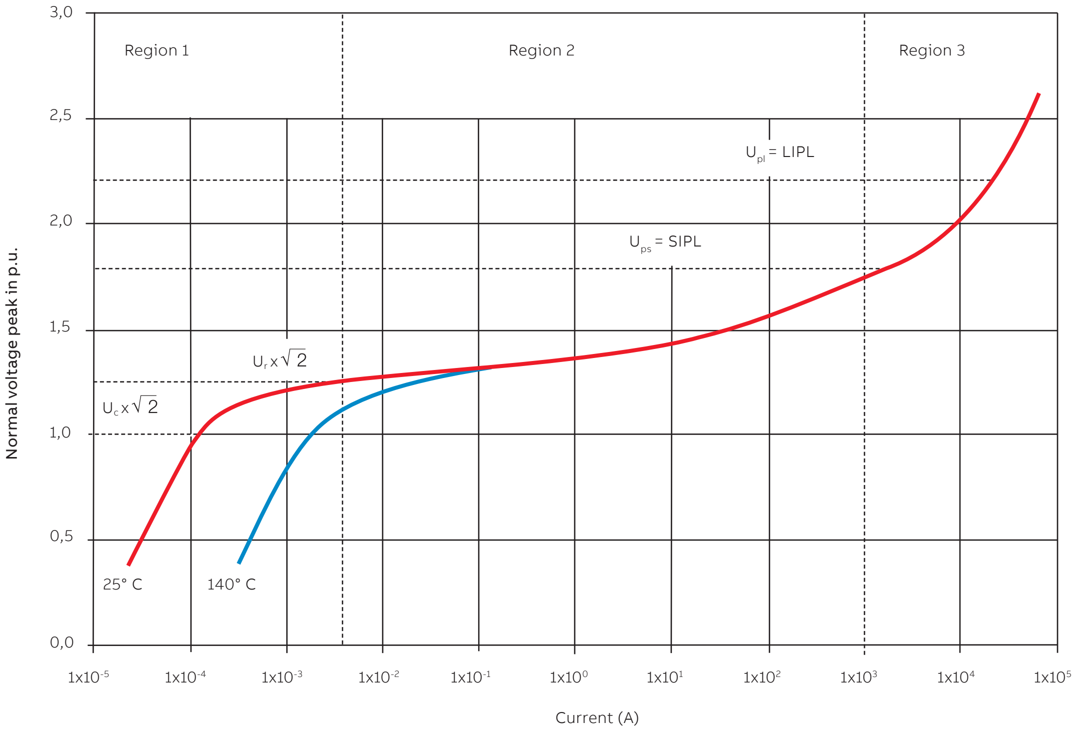


Fig. 19: reference curve according to Standard IEC 60099-5

- establish the rated voltage of the arrester with reference to the forecast overvoltage;
- estimate the magnitude and probability of the expected ligtning discharge currents 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 TRV value, 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 figure 19, where region 1 is the pre-breakdown zone 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. lightning). In addition, U_c is the continuous operating voltage, U_r the rated voltage, U_{pl} (or LIPL) is the maximum residual voltage at nominal discharge current for atmospheric discharge and U_{ps} (or SIPL) is the maximum residual level at the specified switching impulse current.
- the power absorbed determines the type of arrester with 200 to 1000 A peak currents for multiple re-ignitions, or those of 10 kA or more for lightning 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 as the apparatus that must be protected. In the example in figure 20 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.

2. Capacitor bank switching

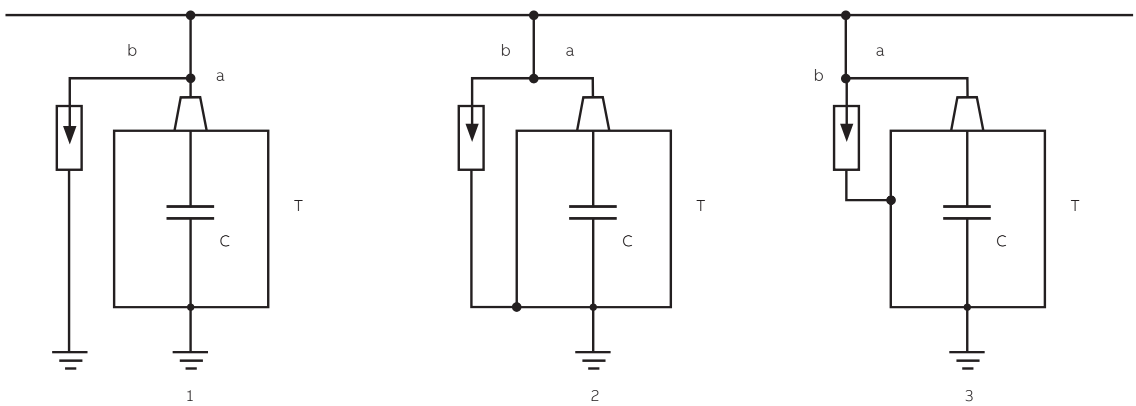


Fig. 20: position of a surge arrester to protect a transformer

The energy associated with re-striking due to capacitor bank switching must be assessed with the greatest care. Although rare, restriking can be a challeging task, especially for surge arresters installed near the capacitor banks. In actual fact, surge arresters installed even further away, including low voltage ones, can be affected in the case of multiple restriking events. The energy that affects the surge arrester depends on the capacitance of the capacitor bank owing to the charge stored in the bank itself. The effect of this is to increase overvoltage oscillation amplitude the instant restriking occurs. Annex G.2, standard IEEE Std C62.22-2009 “IEEE Guide for the Application of Metal-Oxide Surge Arresters for Alternating-Current Systems”, provides a method for calculating the energy dissipated by the surge arrester in this situation. Supposing that the transient overvoltage due to circuit-breaker restriking during the opening operation of a capacitor bank reaches 3 p.u. and that the discharge voltage of a typical surge arrester installed on the bank or in its immediate vicinity is about 2 p.u., the suggestion provided by the Standard is to estimate the energy discharged by a surge arrester as depending on the size of the capacitor bank, as described below:

Energy in surge arrester (kJ)
= 13.3 · MVAr per phase at 60 Hz
= 16.0 · MVAr per phase at 50 Hz

For example, considering the previously described 60 Hz system at U_s=13.8 kV with 6 MVAr three-phase capacitor bank, the result is:

Energy in surge arrester (kJ) = 13.3 · 6/3 = 26.6 kJ

thus, if the maximum continuous operating voltage U_c (according to IEC, MCOV or IEEE) that can be applied to the terminals of the surge arrester without impairing its characteristics in any way is:

$$U_c = 1{,}05 \cdot \frac{U_s}{\sqrt{3}} = 8{,}38\ kV$$

the result is:

$$\frac{26{,}6}{8{,}38} = 3{,}17\ kJ/kV$$

This means that there will be no problems from an energy aspect if an ABB MWD surge arrester is installed, since its energy has been tested in accordance with Standard IEC 60099-4 and is 5.5 kJ/kV.
Surge arresters can be installed in different positions depending on the switching device and limiting inductor. These positions are listed below:

a) on the supply side of the switching device;
b) on the supply side of the limiting inductor;
c) between the limiting inductor and capacitor;
d) at the ends of the limiting inductor.

The benefits and disadvantages of each installation, which must be preceded by research for the purpose of coordinating the insulation of the system, are outlined in the next table:

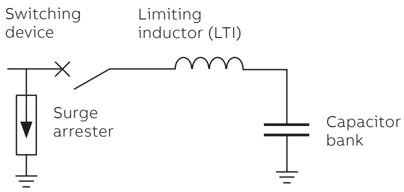
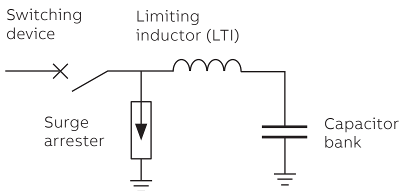
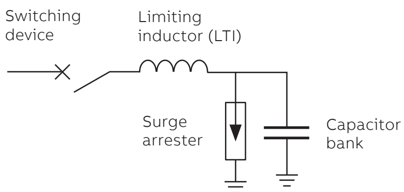
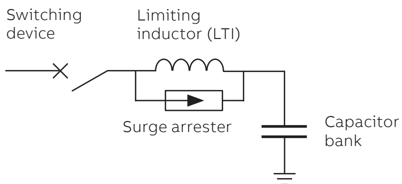
Position	Schema	Benefits	Disadvantages
a) On supply side of switching device		Protects switching device, when open, from lightning and switching; Protects limiting inductor from fast front surges (e.g. lightning).	Protects capacitor bank to a lesser because of voltage rise across inductor.
b) On supply side of limiting inductor		Protects limiting inductor from fast front surges.	Protects capacitor bank to a lesser extent because of voltage rise across inductor.
c) Between limiting inductor and capacitor		Optimum protection of the capacitor bank.	Protects limiting inductor from fast fronted surges (e.g. lightning) to a lesser extent. It surge arrester fails to ground, circuit-breaker may be subject to a higher TRV rate-of-rise.
d) At ends of limiting inductor		Protects inductor from lightning/switching surges. Can reduce TRV from inductor-limited faults. Surge arrester does not sense full line-to-ground voltage during normal operation.	Does not protect capacitor bank from lightning/switching surges A surge arrester fault short-circuits the limiting inductor.

Table 2: limiting inductor positions and relative benefits/disadvantages

The main disadvantage in using surge arresters is that they introduce a potential point of failure. If a fault occurs, the surge arrester starts conducting, thereby causing a short-circuit to earth, which can also affect other components in the installation. Check to make sure that surge arrester tripping is unable to cut out the inductor (thereby inhibiting its limiting effect) if the surge arrester has been installed for the purpose of protecting limiting inductors, as illustrated in configuration d) for example.

2. Capacitor bank switching

2.3.3 Synchronous switching systems
When it comes to reducing voltage and current transients, synchronous switching is now a reliable and economically valid alternative to the other traditional methods described previously.
There are various technical solutions. The first to be created consists of a circuit-breaker with three independent poles and a controller able to manage the closing and opening time of each pole depending on the phase angle of the voltage or current.
The precision required for opening or closing in a precise point of the sine wave is approx. ± 1ms to obtain overvoltages comparable to those of the pre-switch-in resistors, and ± 0.5 ms for negligible overvoltages. This means that the characteristics of the circuit-breaker must be able to guarantee switching stability in all operating and environmental conditions or, vice versa, that the controller must be able to calculate and offset all the variables that could influence the operation, such as ambient temperature, auxiliary voltage, idle times, etc. Bear in mind that certain compensations are dictated by foreseeable factors while others are based on log data and that they are therefore calculated on a statistical basis. In high voltage systems, some circuit-breakers are so dependent on idle time that it is the main cause for failure of a synchronous switching operation.
In addition, the circuit-breaker must have very high dielectric strength between the contacts so that there is no possibility of restriking during closing and until contact is made. At the same time, re-ignition during opening must also be impossible.
In accordance with Standards IEC 62271-302 (High-voltage switchgear and controlgear – Part 302: Alternating current circuit-breakers with intentionally non-simultaneous pole operation) or ANSI C37.04, the tests that this circuit-breaker must pass also include RDDS, or rate of decrease of dielectric strength and RDDS, or rate of rise of dielectric strength. The circuit-breaker must also pass the mechanical life tests in class M2 as well as correlation of the opening and closing times with idle time. According to CIGRE WG13.07, the sensors, controller and overall system should also be tested. The controller tests are both functional and as to hardware conformity. They are based on IEC 61000 and ANSI C37.90 concerning protection and control relays.
Regarding operation, the controller tests must include the pre-striking time (in the case of closing operations) or check the instant the contacts separate (opening operation) for each pole, with reference to the phase angle of the voltage.

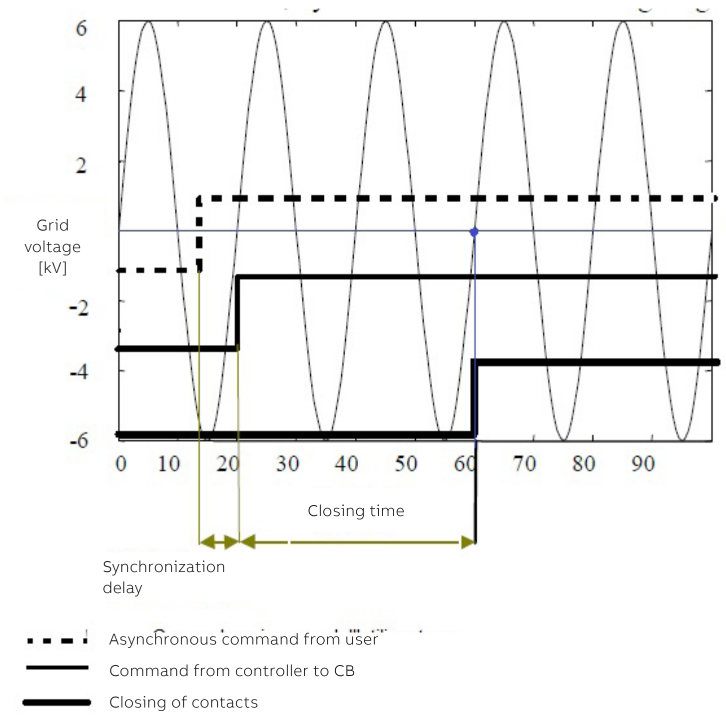


Fig. 21: synchronization of a circuit-breaker closing command

The closing command, which can arrive at any instant, must be sufficiently delayed to take account of the closing and pre-arc time, so as to close the contacts exactly at voltage zero.
As can be seen, sychronous interruption by means of a conventional circuit-breaker is very complicated and not absolutely free from voltage or current transients.

Static devices are another possible solution. The devices normally consist of thyristors connected in series in order to reach the rated voltage required. Each thyristor is installed in conjunction with a free-wheeling diode and RC filters, which protect both from transient overvoltage during operation.

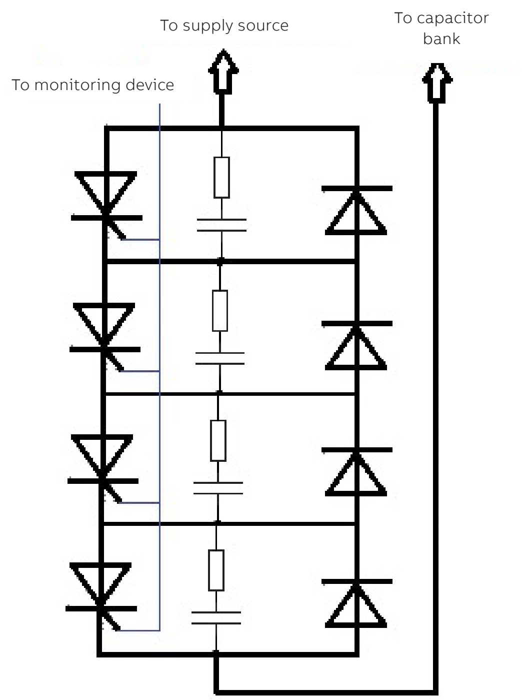


Fig. 22: static circuit-breaker circuit

These apparatuses can deal with an extremely high number of operations and function at a remarkably high switching speed. The electronic components ensure stability and accurate operating times, exceeding the limits described for conventional circuit-breakers. This makes these devices theoretically ideal for synchronous switching. However, they do pose the very well known problem for power electronics, of losses due to the internal resistance of the components. Cooling at continuous current is a serious problem, which has been resolved by using sometimes complex cooling systems, with solutions similar to those adopted for transformers with insulating oil, radiators and forced ventilation. This sort of cooling system obviously increases the size of the apparatus to a considerable degree and often makes it difficult to install. More importantly, devices with thyristors have difficulty in withstanding the overvoltages from the system and must be protected by surge arresters on the feeder, which must also be equipped with some sort of disconnector (fuse disconnector or plug-in circuit-breaker) to guarantee galvanic insulation.

Lastly, ABB proposes an innovative solution comprising a switch able to combine the advantages of conventional switch with those of the power electronics. The synchronous switch is the first switch to feature air-insulated diode technology and to be designed for switching capacitor banks in particular.
The basic principle is to resolve the problem of accurate identification of zero voltage or current, by connecting or disconnecting the diodes in advance of the main contacts so that the current begins to flow or is interrupted in a natural way. Thanks to this operating mode, the apparatus is able to ensure that overvoltages and overcurrents are absent, thanks to the absence of pre-ignitions and re-striking. As in all synchronous apparatuses, the operations are performed independently on all three poles. A controller receives the signals from the sensors and deals with the operations and diagnostic functions. Since the current flows by means of the switch contacts once the closing operation has terminated, the device does not need a dedicated cooling system. This makes it extremely compact. So much so, it can even be installed in a normal MV panel.
The main advantages of this device, which will be described in detail in the next chapter, are:
- improved grid reliability thanks to the sophisticated diagnostics system, which monitors the intrinsic operation of the device and reduces outages in the installation to the minimum;
- no impact on the installation components owing to transient overvoltage or overcurrent generated by capacitor switching;
- low environmental impact, since the switch is insulated with dried air, unlike other oil- or gas-insulated devices. Thanks to its small size, the device occupies less surface space (reduced footprint).

There are many, very interesting applications for this device. Its natural application 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.

2. Capacitor bank switching

2.4 The ABB DS1 synchronous capacitor switch

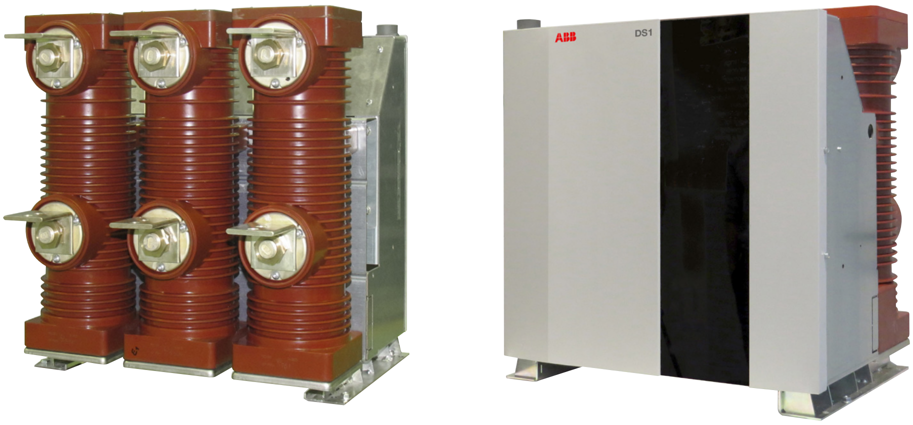


Fig. 23: ABB DS1 synchronous capacitor switch

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 capacitor banks in class C2. The tests for switching capacitive currents were 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. The tests performed on DS1 are listed in the table below.

Type tests	Standard	Level / Method
Temperature-rise tests	IEC 62271-103	630 A
Dielectric tests	IEC 62271-103 and IEC 61127-1	Rated voltage 17.5 kV Rated short-time withstand voltage at power frequency Common value 38 kV Across isolating distance 45 kV Rated lightning impulse withstand voltage Common value 95 kV Across isolating distance 110 kVp
Mechanical life tests	IEC 62271-103 specification requested by user	50,000 operations, well beyond class M2 requirements
Measurement of main circuit resistance	IEC 62271-103 specification requested by user	Additional test performed during temperature-rise and mechanical life tests
Tightness tests	IEC 62271-1	Test performed during mechanical life test Test performed with helium
Capacitive current switching	IEC 62271-100	Class C2 600 A, at 15.5 kV, 60 Hz 630 A, at 17.5 kV, 50 Hz
Short-time current withstand tests at peak current	IEC 62271-103	20 kA 0.5 Sec
Electromagnetic compatibility tests (EMC)	Immunity tests as required by IEC 62271-1	Immunity tests performed according to: IEC 61000-4-2, /-3, /-4, /-5, /-6, /-8, /-9, /-12, /-16, /-17, /-18, /-29
Tests at low and high temperature	IEC62271-103 specification requested by user	-15 °C -55 °C
Environmental test	IEC62271-103 specification requested by user	Test in hot damp environment according to IEC 60068-2-78: 40 °C, 93% Ur, for 2 years Test in hot damp environment according to IEC 60068-2-30: from 25 °C, to 55 °C, 2 cycles

Table 3: list of tests conducted on DS1

DS1 has been designed to combine high precision mechanics with power electronics. With reference to the figure below, the architecture of this device includes the following components:

- poles (6);
- electronic control unit (1);
- feeder module (2);
- actuating capacitor (3);
- servomotors (4).

The electronic control unit (1) is built into the device and pre-calibrated in the factory. It is formed by 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 operated independently, depending on the application required. The control unit also provides diagnostic functions.

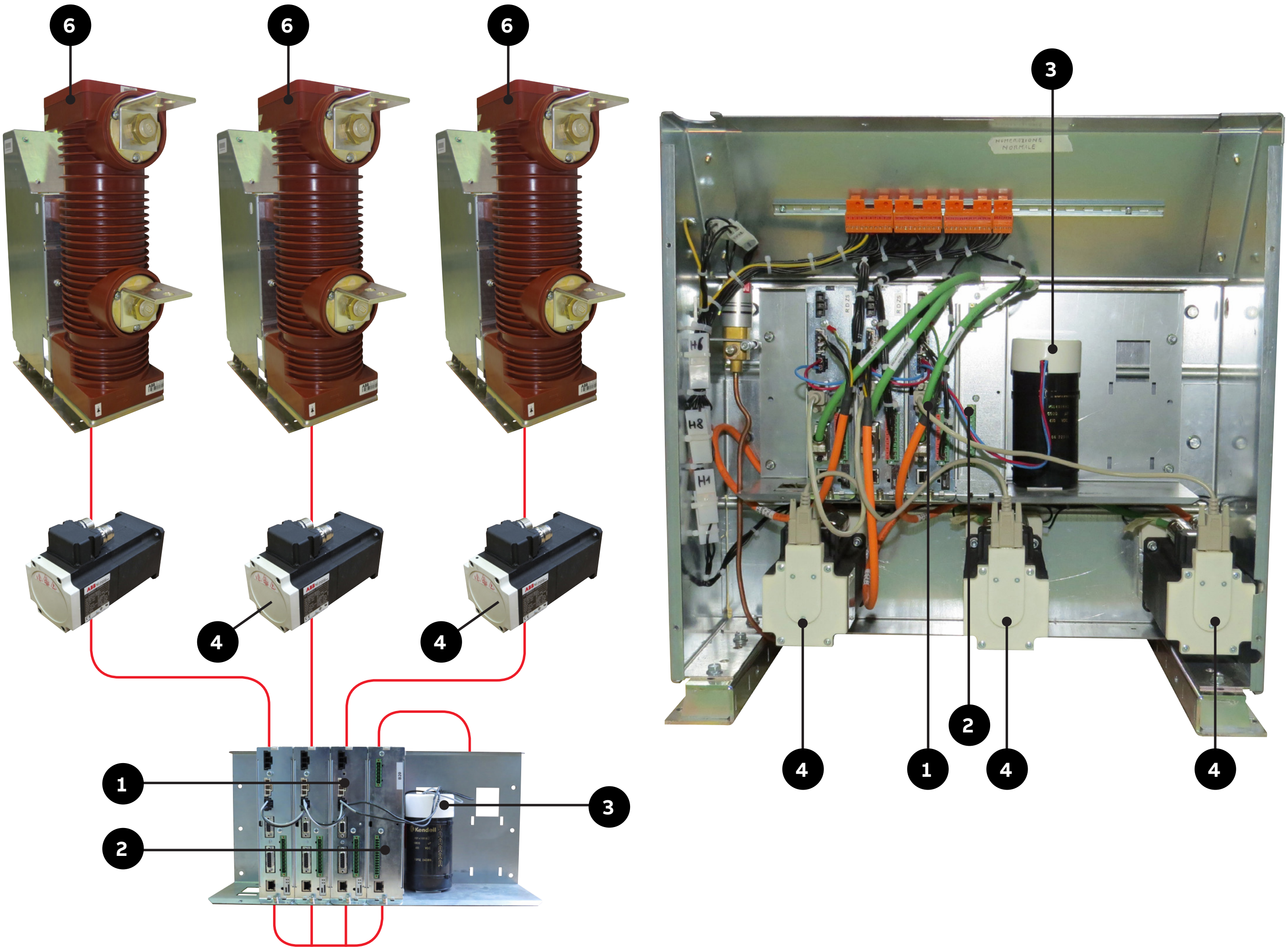


Fig. 24: main components of DS1

2. Capacitor bank switching

With reference to the next figure, 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.
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 26 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.
The energy dissipated in the arcing chamber is also reduced to the minimum, thereby allowing a large number of electrical operations to be performed.
Accurate control over the electrical and mechanical quantities was required in order to achieve this result.

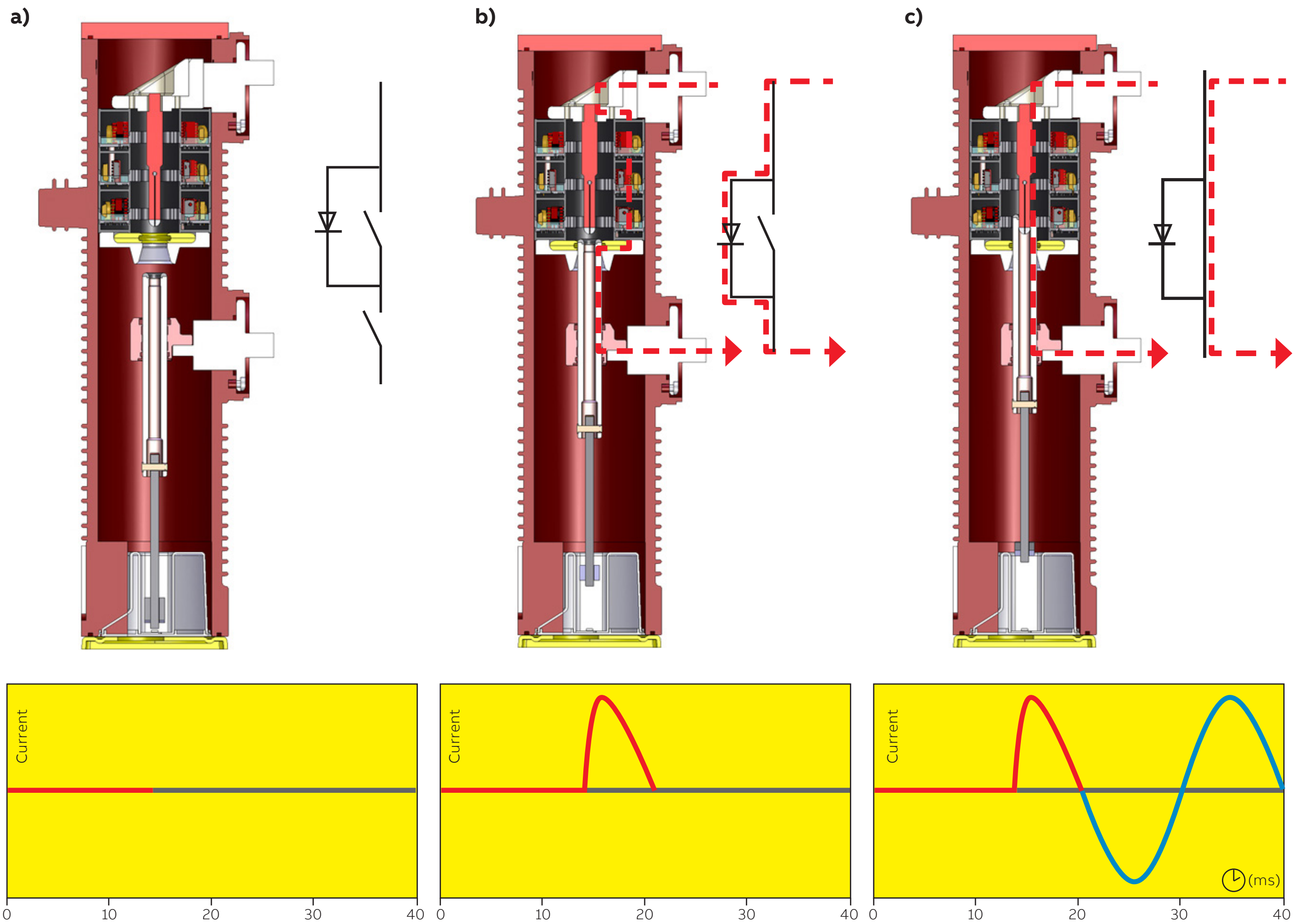


Fig. 25: closing command sequence

The diagnostic function provided by the control unit includes:

- continuous control of the synchronization signal; accuracy as to the presence of system voltage, frequency and harmonic distortion. The control unit regulates trip time for ±1.4 Hz frequency variations so as to ensure a high level of synchronization;
- 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 for the purpose of ensuring a maximum level of reliability for the operation;
- complete control of movements immediately after the operation has terminated, so as to check the position, speed and torque of the servomotors and inform the user about the way in which the operation had been performed;
- continuous monitoring of the servomotors by means of the state of the wiring and windings, so as to ensure complete functionality;
- regular inspection of the state of the capacitor by means of the voltage, so as to check that the capacitor is always loaded 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-monitoring functions.

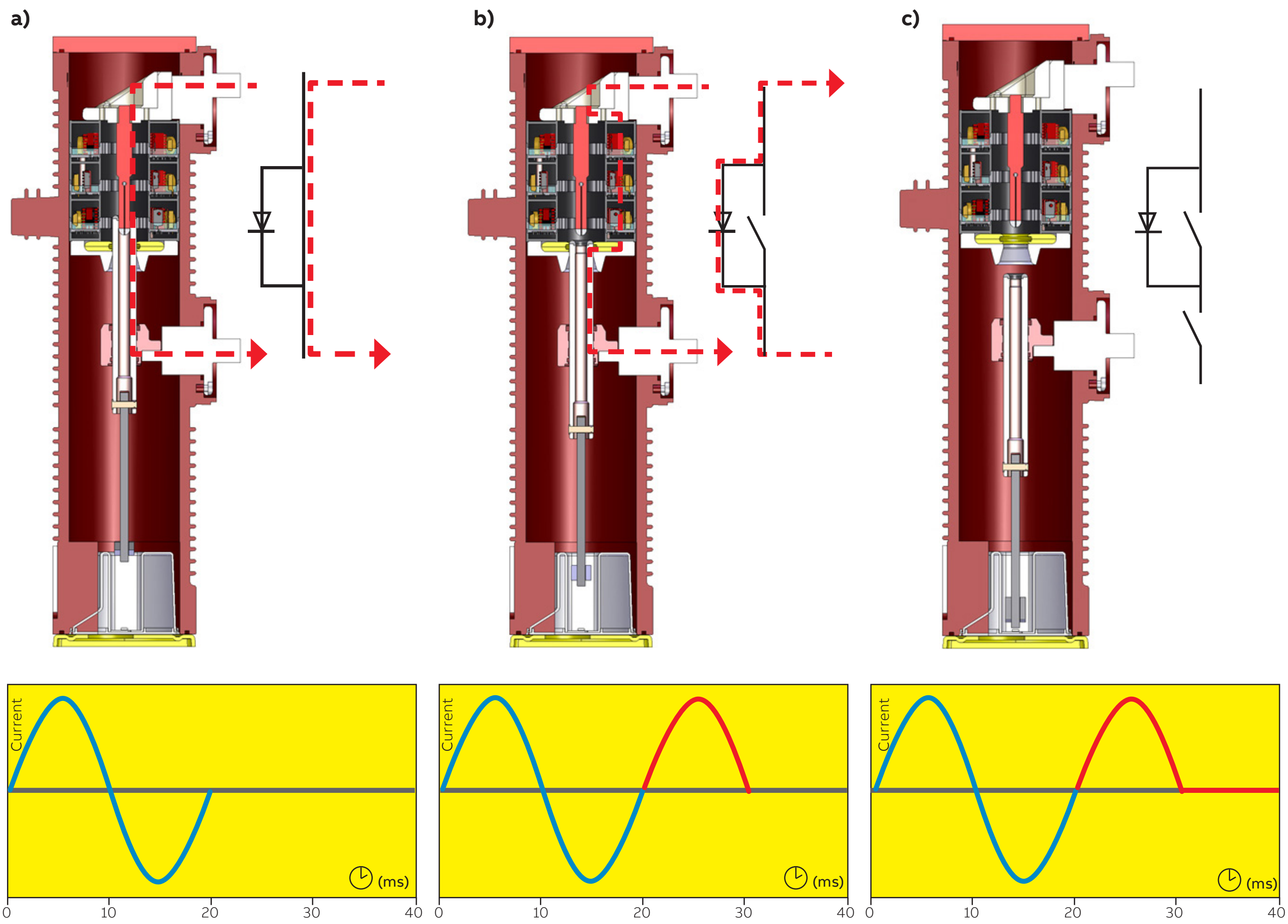


Fig. 26: opening command sequence

2. Capacitor bank switching

Further diagnostic functions concern the poles, e.g. monitoring of the internal pressure of the dried air by the pressure switch to ensure the insulation level is maintained, and monitoring of the apparatus operating mode.
The following are available at the DS1 terminal box:
- opening and closing command;
- interlock input;
- the open and closed state;
- the diagnostic output: ready and alarm (if the switch is unable to operate);
- the self-test output of the control unit.

There is a further function that allows switch reclosing to be inhibited until the capacitors have completely discharged. To achieve this, the closing command is inhibited for 5 minutes after opening and the not-ready signal is activated. This delay can be adjusted to suit different standards.
From the installation aspect, the most widely used solution is to install fuses on the load side and supply side of the switch so as to protect the capacitor bank if faults occur. A circuit-breaker is also positioned on the supply side of the capacitor banks to open the circuit if the fuses trip, in the case of unbalanced loads or, if it is the plug-in type, to isolate the line for maintenance. This function is performed by a feeder disconnector in the case of fixed circuit-breakers.

DS1 has been designed to support a sufficient short-time current to allow the fuses that protect the capacitor bank to trip. To prevent inappropriate closing, it can also be easily interlocked with the circuit-breaker on the supply side and with the feeder disconnector and earthing switch.
Regarding capacitive load switching, DS1 has been tested in accordance with Standard IEC 62271-100, which requires more stringent tests than IEEE 37.09a or IEC 62271-103.
In conclusion, synchronous capacitor switch DS1 offers the following advantages:
- it is eco-friendly, since it uses dried air for insulation;
- at its rated current value, it does not need cooling systems such as radiators or fans;
- limiting reactors for the inrush currents are not required since it eliminates the closing transients of the capacitor banks;
- surge arresters for protection against overvoltage are not required since, if supply-side circuit-breaker switches only in case of short-circuit, it eliminates the opening transients of the capacitor banks;
- it is extremely compact and interchangeable with MV circuit-breakers, thus easy to integrate into existing installations.

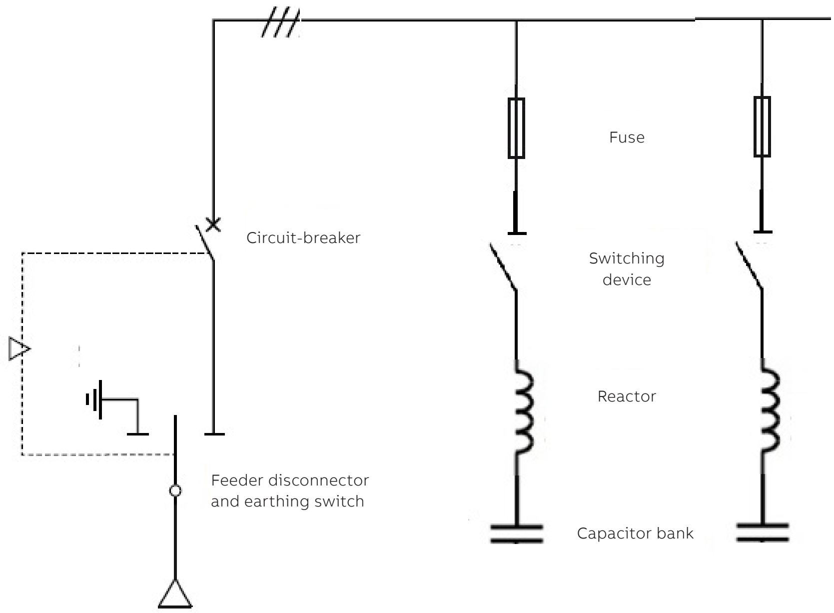


Fig. 27: example of a circuit for installation of capacitor banks

3. Comparison among different switching technologies for capacitor banks

As described in the previous chapter, there are various ways to reduce the value of the overvoltages generated when capacitor banks are switched-in and off. The various different solutions can be compared by using simulation software so as to check the maximum overvoltage generated during the switching operations and assess the efficacy of the solutions applied.
The following circuit can be used for this purpose, where Zs is the grid impedance and Zc the impedance of the connections:

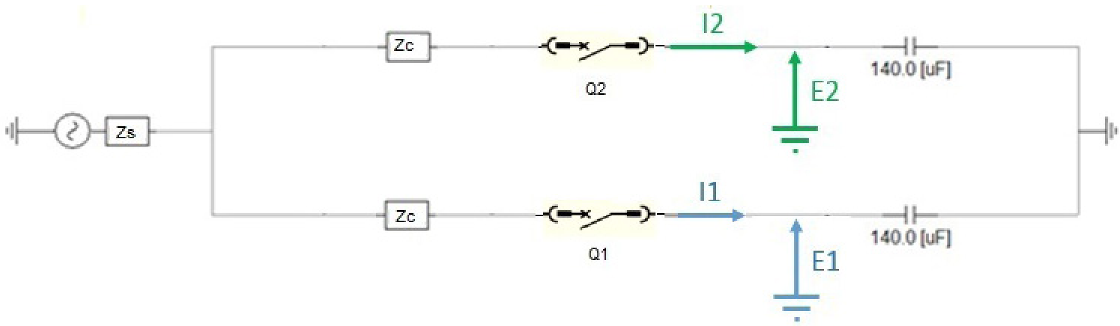


Fig. 28: simulation circuit without damping system

The operating voltage of the system is 6.9 kV at 60 Hz with 35 kA short-circuit current. The circuit consists of two 2.5 MVAr capacitor banks in parallel, amounting to 140 μF capacitance, switched by two separate switching devices.
If no voltage damping system is used, the overvoltage reaches its maximum value of 1.8 p.u. when the first capacitor is energized, while the inrush current reaches its maximum value when the second bank is energized back-to-back at 13.6 kA.

3. Comparison among different switching technologies for capacitor banks

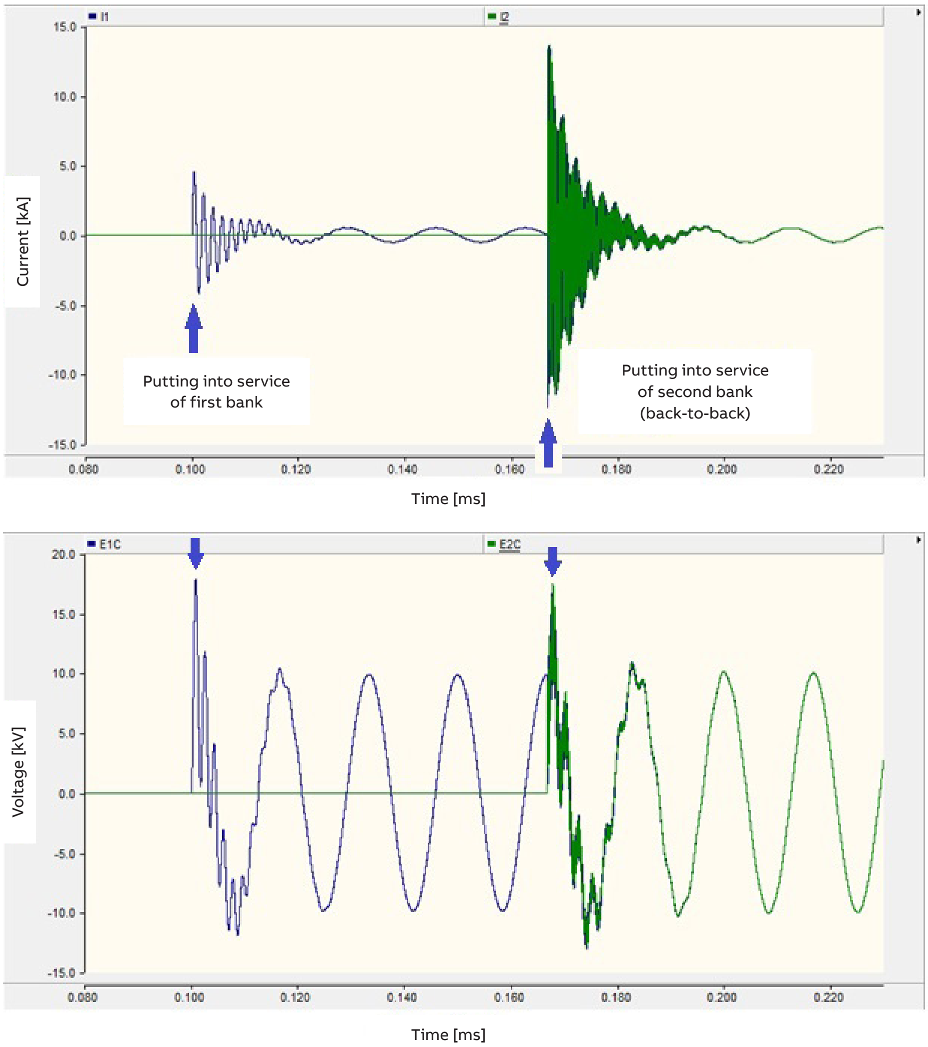


Fig. 29: voltage and current trend without damping devices

A limiting inductor can be included so as to reduce the inrush current. This also changes the resonance frequency. The inductance value must be chosen so as to avoid the third and fifth harmonic, i.e. normally a frequency of $f=4.5 \cdot f_0$ which, in this particular case, is $f=4.5 \cdot 60=270$ Hz. The value of the limiting inductor can therefore be calculated in the following way:

$$L = \frac{1}{(2\pi f)^2 \cdot C} = \frac{1}{(2\pi \cdot 270)^2 \cdot 140 \cdot 10^{-6}} = 2{,}5\ mH$$

Let us now include the inductor in the circuit:

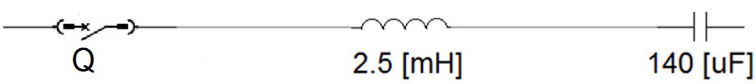


Fig. 30: simulation of circuit with limiting inductor

This is the result obtained:

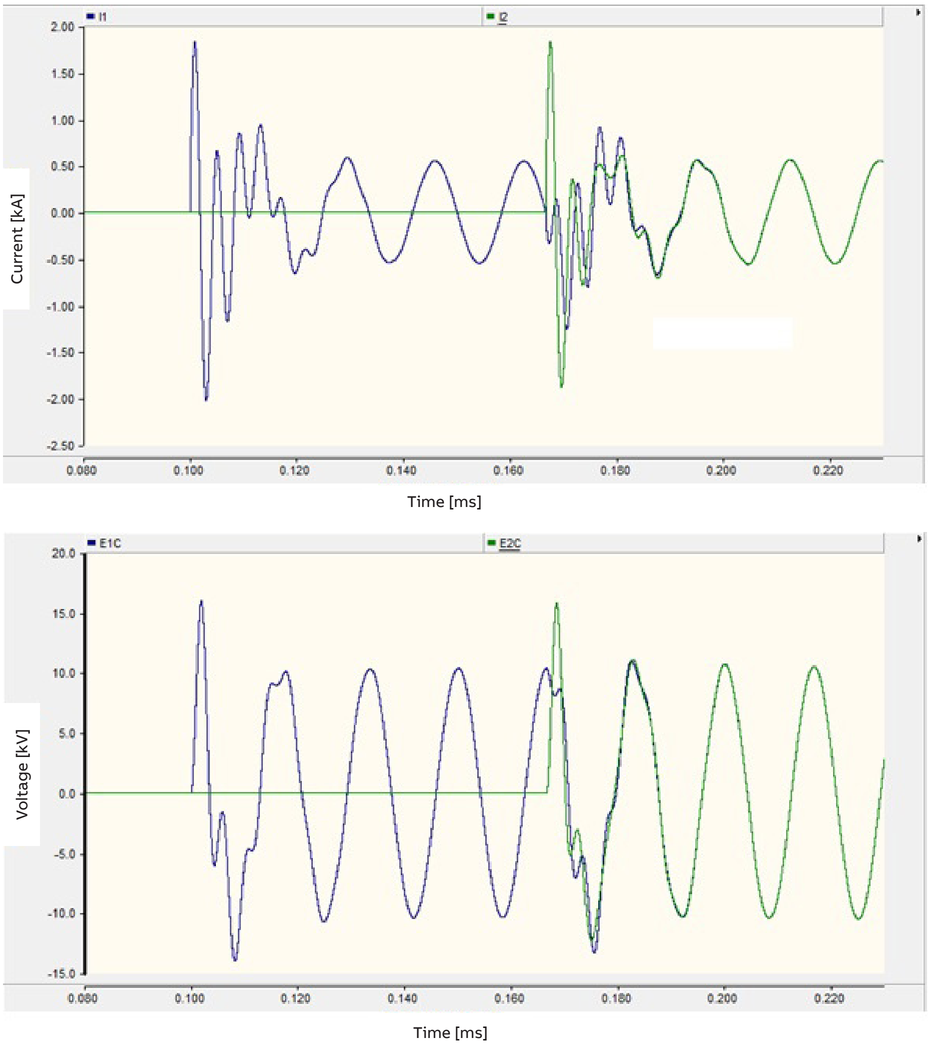


Fig. 31: voltage and current trend with limiting inductor

Note how there is a substantial reduction in inrush current, which has a peak value of approx. 2 kA, and a beneficial effect on the peak value of the overvoltage, which is 1.64 p.u.

We'll now examine the case where a pre-insertion resistor is included. Consider that a voltage transient will be generated the moment in which the resistor is short-circuited after a few milliseconds, to prevent unnecessary losses. Let's assume that a 6 Ohm resistor is included in the circuit:

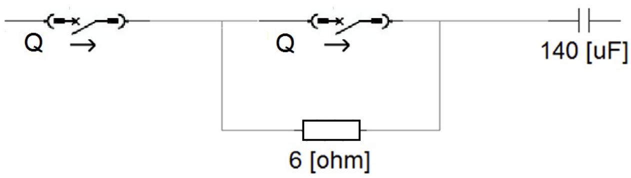


Fig. 32: simulation circuit with pre-insertion resistor

3. Comparison among different switching technologies for capacitor banks

The following result is obtained:

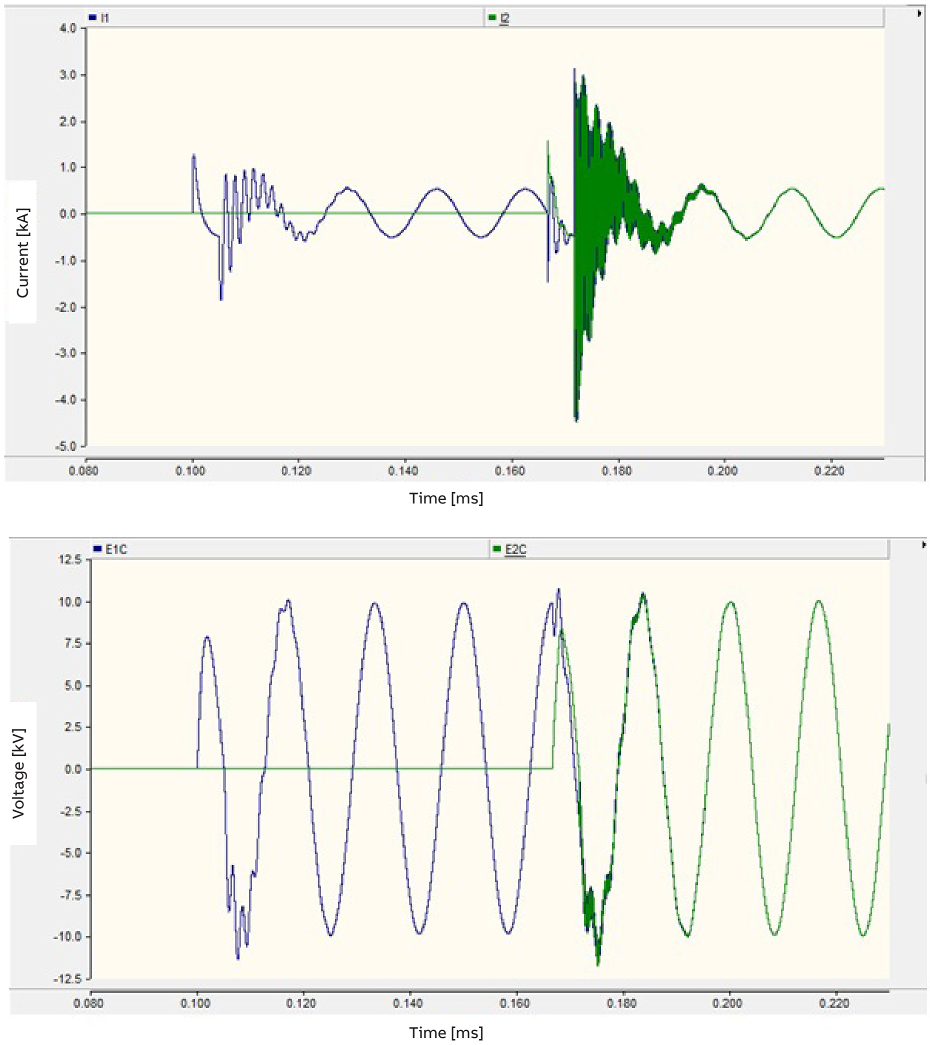


Fig. 33: voltage and current trend with pre-insertion resistor

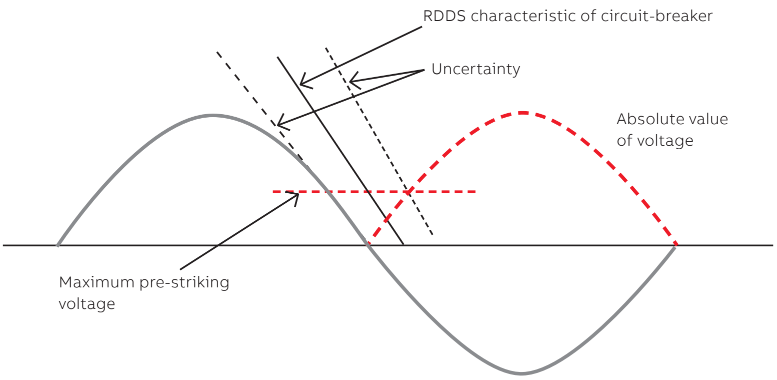


Fig. 34: uncertain closing of the contacts of a synchronous circuit-breaker

The graphs show that there has been a remarkable improvement in the inrush current value, which reduces to about 1.5 kA even though an additional 4.5 kA peak is caused when the resistor is disconnected. The overvoltage peak is also reduced to 1.8 p.u.

Now let's see how the circuit behaves if the switching device is a synchronized vacuum circuit-breaker. We'll consider 1-millisecond uncertainty in contact closing after current zero, normally delayed to avoid pre-striking phenomena. At 6.9 kV and 60 Hz, this equals a voltage value of 3.6 kV:

Here, a 60 µH limiting inductance is introduced so as to remedy the problem; thus the circuit becomes:

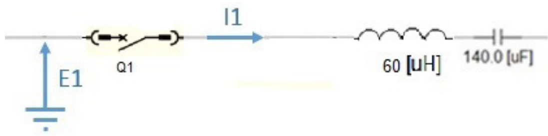


Fig. 35: simulation of circuit with synchronous circuit-breaker

Simulation is as follows:

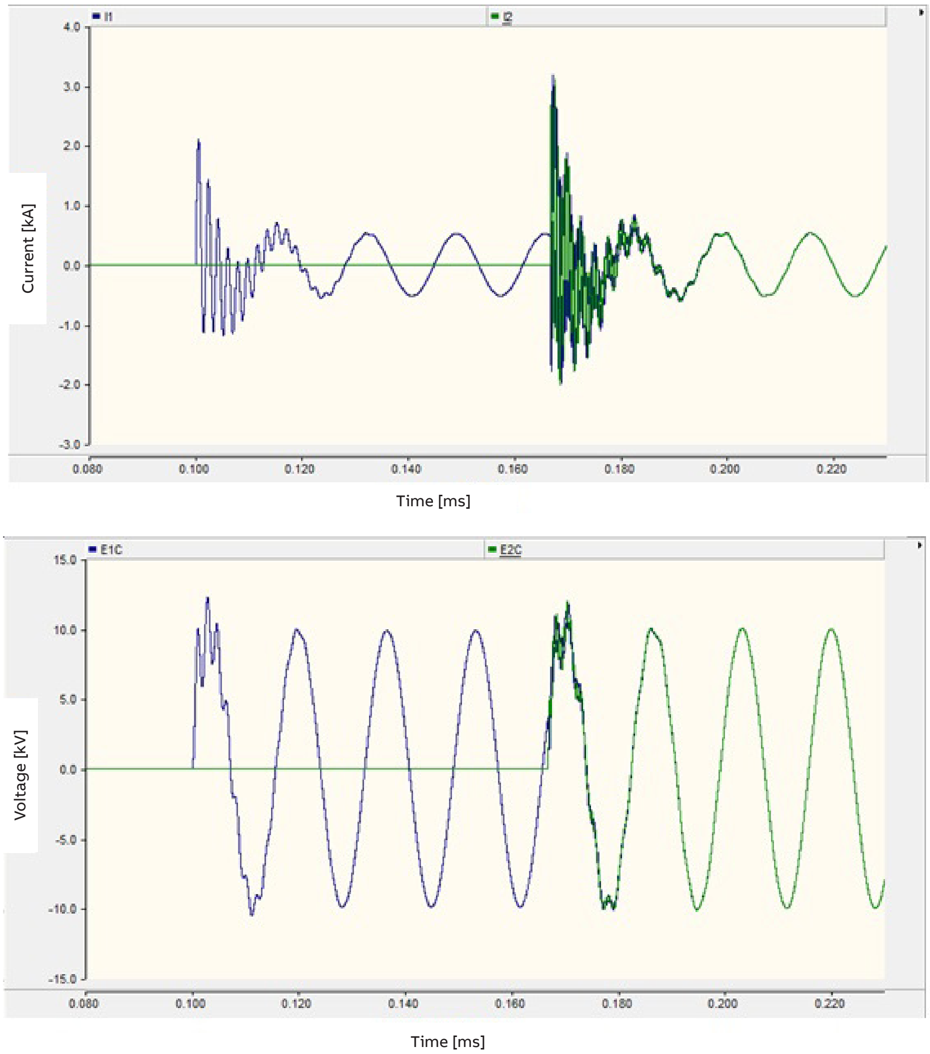


Fig. 36: voltage and current trend with synchronous circuit-breaker

3. Comparison among different switching technologies for capacitor banks

As can be seen, there is a reduction in the peak of inrush current, which is 3.2 kA, while the overvoltage peak is slightly higher than the previous case, i.e. 1.26 p.u.
Lastly, we'll check current and voltage behavior after DS1 has switched.

In this case, the improvement is drastic and better than the other methods. The inrush current drops to a peak of less than 1 kA with just 1.08 p.u. overvoltage.

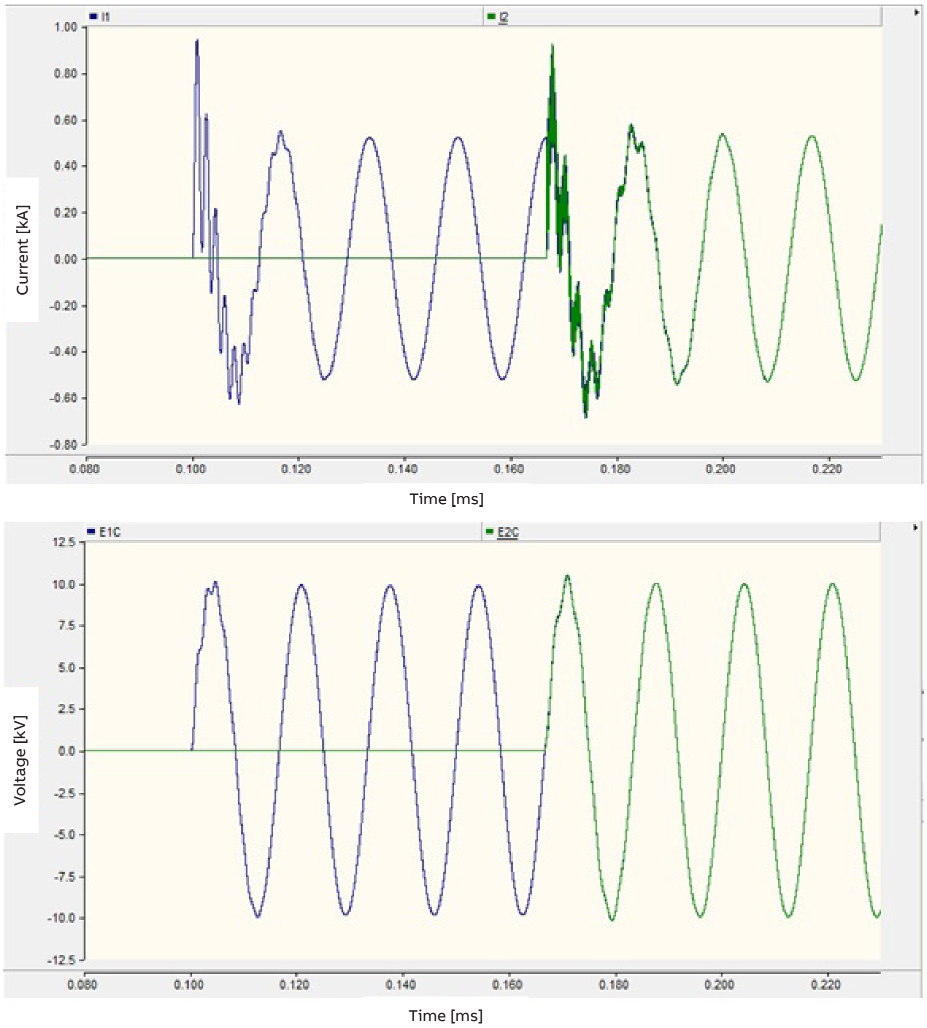


Fig.37: voltage and current trend with limiting DS1

The cases examined are outlined in the table below:

Simulated situation	Additional inductor	Maximum inrush current (peak kA)	Maximum overvoltage (peak p.u.)
No damping added	-	13.6	1.8
Limiting inductor	2.5 mH	2.0	1.64
Pre-insertion resistor	-	4.5	1.18
Synchronized circuit-breaker	60 µH	3.2	1.26
DS1 diode-based switch	-	1	1.08

Table 4: outline of the simulation results

In conclusion:

- diode-based capacitor switch DS1 offers the best solution as to reduction of both the inrush current and switching overvoltage.
- Inclusion of a limiting inductor also provides a good result when it comes to reducing the inrush current, but the overvoltages are still high. Additional losses and the size of the inductors must also be considered.
- Vice versa, pre-insertion resistors reduce switching overvoltage but do not provide a good result as to reduction of inrush current.
- Lastly, the synchronized circuit-breaker is a good solution, but the inrush current and overvoltage are higher than those obtained by using the DS1 diode-based capacitor switch.

4. Impact of overvoltage on the components of an electrical installation

Even though they are very brief, overvoltages due to transient phenomena can have significant impact and shorten the electrical life of the electrical components in an electrical installation if they occur frequently. The factors that affect the life of the components to the greatest degree are the inrush currents and overvoltages deriving from capacitor switching-in transients and the probability of prestrikes and restrikes in the respective switching devices [2] [3] [4].
Repeated overvoltages can trigger off partial discharge which, as is known, cause the insulation in electrical devices to age and progressively deteriorate until it actually tears and leads to failure.

4.1 Impact of overvoltage on capacitors: theory

Over the years, capacitor manufacturing has undergone numerous modifications for the purpose of improving the ability to withstand stress. At the present time, the capacitors used for power factor correction have polypropylene as a dielectric material. The edges of the aluminum foil are bent and the fluid used for impregnation has better resistance to electrical stress. The overall result is higher stress resistance (nowadays approximately 60 Vrms/µm), a lower dissipation factor (approx. 10^{-4} at 50 Hz) and higher power (> 300 kVAr) [1] [13].
Despite these improvements, capacitors still remain sensitive to the transients to which they are subjected during their lifetime and which make them less reliable. More precisely, partial discharge cannot be avoided despite the higher inception voltage values and lower absorption rate of the gases of the insulating fluids used in modern capacitors [5] [6]. If the phenomenon begins, it triggers off a slow but relentless deterioration process that particularly affects the edges of the polypropylene insulating film [5] [8].
Even in correctly impregnated capacitors, there can still be partial discharge in the gas bubbles that form in the impregnating fluid where electrical stress is greater, always owing to transient switching overvoltage [7].
The impact of overvoltage on the life of capacitors is testified by certain statistical surveys conducted on a significant sample group of 8,736 capacitors installed in 153 substations over a period of 10 years, between 1980 and 1990, which showed a failure rate of almost 6%, the majority of which due to insulation problems [9].
541 faulty capacitors were analyzed and the causes were identified and classified for 536 as can be seen in the next table [9], which gives data for four different manufacturers. They were all 150 kVA single-phase capacitors installed in 4.8 kV distribution systems.

Manufacturer	**N°**	**Main insulation**		**Oil leaks**		**Insulators**	
	unit	unit	%	unit	%	unit	%
A	325	306	94.15	10	3.08	9	2.77
B	150	137	91.33	11	7.33	2	1.34
C	38	36	94.74	1	2.63	1	2.63
D	23	17	73.91	5	21.74	1	4.35
Total	536	496	92.54	27	5.04	13	2.42

Table 5: classification of the nature of faults

The main fault was clearly the main insulation breakdown (92.5%), which could have been due to internal problems deriving from the manufacturing process, general problems concerning quality or external causes (such as switching overvoltage) due to the operating conditions.
Faults due to insulation can depend on problems concerning quality during the manufacturers' production processes or on external causes deriving from the operating conditions (such as switching overvoltage), especially when the capacitors are switched by apparatus affected by prestriking or restriking phenomena. The majority of capacitors are subjected to switching overvoltage at least once a day. The statistics also show the impact of switching frequency on failure percentage. The next table illustrates this effect by comparing the failure percentage of capacitors that are permanently in service and those switched at least once a day [9]:

Operating conditions	**Switch-in at least once a day**	**Always in service**	**Total**
Total banks	2450	462	2912
Faulty banks	293	37	330
Failure %	12	8	11.3

Table 6: statistical analysis on the basis of switching-in frequency

In addition, it turns out that the faults are statistically concentrated in the individual banks, since all the capacitors belonging to the bank are simultaneously affected by the same overvoltage [9]:

Manufacturer	**Total number of failures**		**Number of failures for**			
			2 failures, same bank		3 failures, same bank	
	Banks	Unit	Banks	Unit	Banks	Unit
A	215	325	48	96	32	96
B	103	150	41	82	4	12
C	26	38	8	16	2	6
D	21	23	3	6	0	0
Others	2	5	0	0	0	0
Total	365	541	100	200	38	114

Table 7: statistical analysis on the basis of fault location

4. Impact of overvoltage on the components of an electrical installation

Meaning that 37% of the faulty units belong to the category of two failures per bank and 21% of the faulty units to the category of three faults per bank.
Tripping of the internal fuses that protect the capacitors allows faults in the individual units to be eliminated and the bank to continue to function, but does not solve the problem in general.

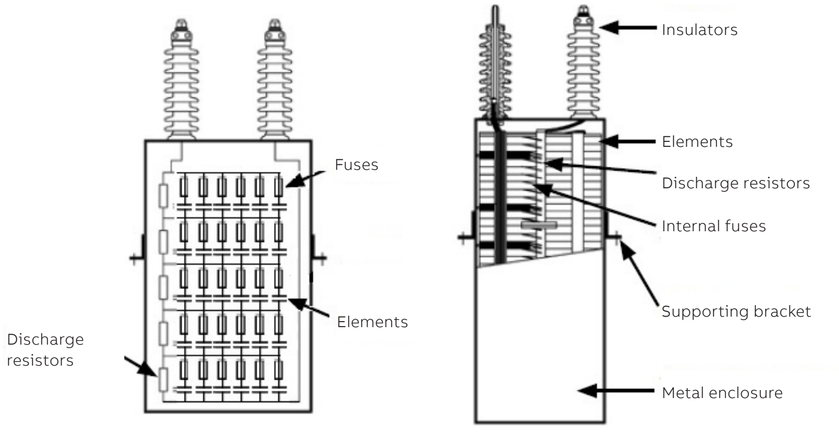


Fig. 38: internal structure of a capacitor

As illustrated previously, one of the phenomena that negatively and sometimes significantly influences the electrical life of capacitors is partial discharge. This phenomenon consists of electrical discharge in a portion of the dielectric between two conductors. This discharge is due to electrical stress concentrated inside or on the surface of the dielectric itself. The discharge is normally of the pulsed type and lasts around 1 µs. Internal partial discharge forms in solid dielectrics owing to cavities, called vacuoles, in the dielectric containing gas that forms or is already present at the origin owing to a poor quality production process, or during service owing to mechanical, thermal or electrical stress. Partial discharge can also appear in fluid insulating media owing to the formation of gaseous bubbles due to thermal or electrical stress.

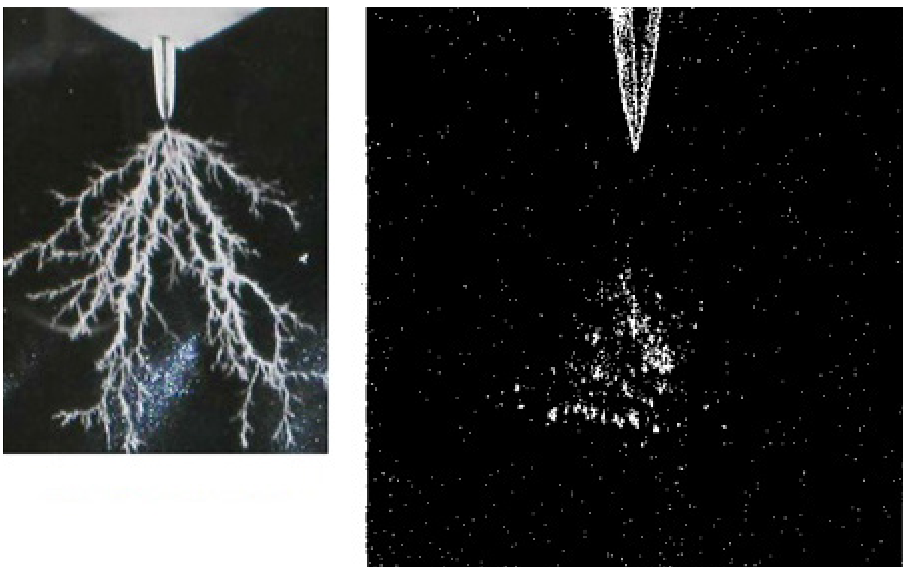


Fig. 39: effect of partial discharge on solid and liquid insulating media [20] [21]

In any case, partial discharges lead to slow and progressive deterioration of the dielectric, which is irreversible in the case of solid dielectric and which can finally lead to a discharge that destroys it.
With respect to the surrounding dielectric, vacuoles are characterized by a lower dielectric constant ε and by a higher electric field, thus discharge can easily generate inside it. The physical state of the vacuole changes and successive discharges can occur at lower voltage values and progressively deteriorate the material.
Once initiated, partial discharge can also continue at lower voltage values than the inception voltage (called PDIV) and the extinction voltage (called PDEV) becomes 10 to 30% lower than the inception voltage. Partial discharge is at low power. It deteriorates the dielectric slowly and neither affects nor is it measurable during the insulation tests of devices.
In modern capacitors with polypropylene film, vacuoles are not present initially thanks to the quality of the production process. They can form successively throughout the years of service owing to overvoltage. Gaseous formations can also occur in areas of higher electrical stress, typically at the edges of the aluminum conductive foil, even when the dielectric impregnating product has also been chosen to minimize the partial discharges themselves.

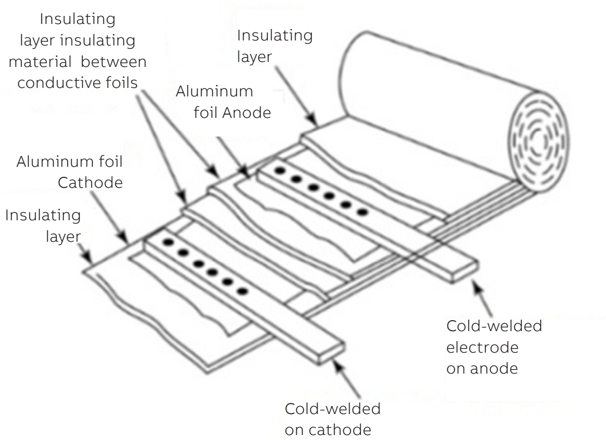


Fig. 40: internal structure of a capacitor element

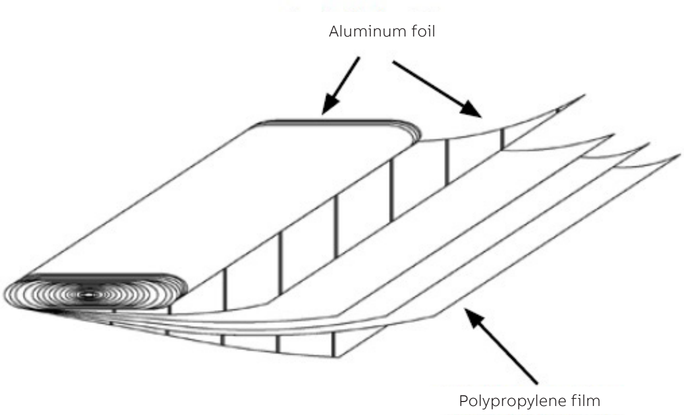


Fig. 41: internal layers of an element

Normally, the most critical situation is due to the switching-in transient, since the switching overvoltages are followed by a period of operation and therefore allow partial discharges to come into play.
The PDEV value is extremely important since partial discharge ceases below that value and the impregnating insulating fluid can re-establish itself.
The edge of the conductive foil is one of the most critical points since the magnetic field is stronger and it is here that partial discharge concentrates more frequently.

4. Impact of overvoltage on the components of an electrical installation

In short, overvoltage can trigger off partial discharge in capacitors which, in the long run, can irreversibly deteriorate the materials and in extreme cases, with a certain probability, cause the capacitor to fail.
It is not easy to establish by how much the lifetime of a capacitor is reduced when it is subjected to repeated switching overvoltage. However, certain assessments can be made by changing the probabilistic method used to determine this reduction in electric cables subjected to transient overvoltage [10].
By applying the inverse power lifetime model, frequently used in research into the ageing of materials subjected to mechanical and electrical stress, life expectancy L, or failure time, can be determined with respect to a larger electric field E in the following way [10]:

$$L = L_H \cdot \left(\frac{E}{E_H}\right)^{-n} \qquad (1)$$

Where L_H is the reference life due to the sole electric field E_H, and n is the voltage endurance coefficient (VEC), which can be obtained from the accelerated ageing tests to which the capacitors are subjected. Note that for E, E_H and L_H constants, the lifetime of the materials increases as the VEC value increases.
The case of a capacitor with n=11.5 is illustrated in the graph below by way of example:

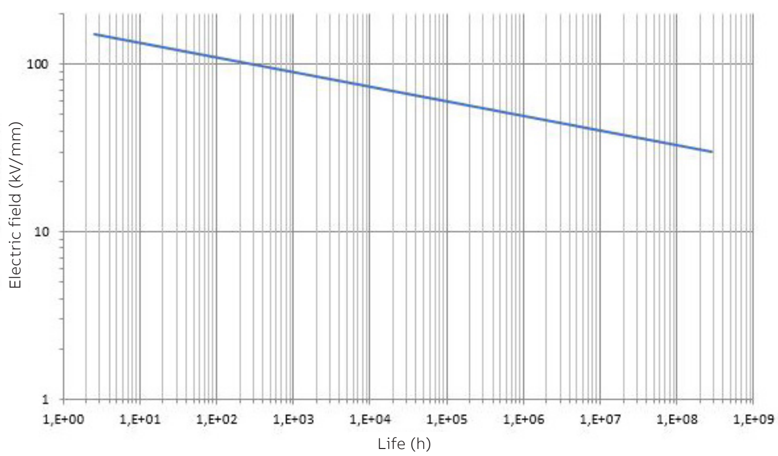


Fig. 42: graph of the inverse power model for a capacitor

The considerable reduction in lifetime, due to the constant electric field applied, is evident. The electric field is actually the most accelerating factor in the ageing of power capacitors, especially if it is sufficient to trigger off the partial discharge phenomenon.
The method is not directly applicable in the case of transient overvoltages, since the overvoltages are only applied for a short time. However, one can assume that the overvoltages are subjected to a constant alternating voltage, that they are all of the same amplitude and that they repeat with a constant frequency. Using these simplified suppositions, we can apply the following formula, called Miner's rule [10] [11], according to which a failure occurs when:

$$\frac{t_{ac}}{L(V_{ac})} + \frac{t_p}{L(V_p)} = 1 \qquad (2)$$

where t_{ac} and t_p are the application times of A.C. voltage V_{ac} and the transient overvoltage peak V_p, $L(V_{ac})$ and $L(V_p)$ represent the admissible lifetime at V_{ac} and at V_p, this latter calculated using the inverse power model. In short, every t_i/L_i represents damage caused by the i-th overvoltage and failure occurs when the sum of all ratios equals 1.
If we now use α_i to indicate the fraction of time during which
the known overvoltage is applied, calculated as the ratio between time t_i and total lifetime L_{tot}, estimated considering the superimposing effect, thus $\alpha_i = \frac{t_i}{L_{tot}}$, we can write that:

$$t_{ac} = \alpha_{ac} \cdot L_{tot} \quad \text{and} \quad t_p = \alpha_p \cdot L_{tot}$$

and then rewrite the Miner's rule as:

$$\frac{\alpha_{ac} \cdot L_{tot}}{L(V_{ac})} + \frac{\alpha_p \cdot L_{tot}}{L(V_p)} = 1 \qquad (3)$$

from which L_{tot} is obtained:

$$L_{tot} = \frac{1}{\frac{\alpha_{ac}}{L(V_{ac})} + \frac{\alpha_p}{L(V_p)}} \qquad (4)$$

However, the formula is only applicable to transient overvoltage with constant value V_p. Overvoltages of different amplitudes require a probabilistic approach. Leaving A.C. constant voltage aside for the moment, the effective lifetime can be considered as the sum of N intervals t_{pi}, each with V_{pi} voltage peak value. We can then suppose
that each $\alpha_{pi} = \frac{t_{pi}}{L}$ is proportional to the density of the probability that V_{pi} equals V_p:

$$\alpha_{pi} = \frac{t_{pi}}{L} = f(V_{pi}) \cdot \Delta V_p \qquad (5)$$

Thus, for the sole transient overvoltage part, the result in accordance with Miner's cumulative damage rule [11] is:

$$\sum_{i=1}^{N} \frac{t_{pi}}{L(V_{pi})} = 1 \qquad (6)$$

Substituting t_{pi} in the last formula gives:

$$\sum_{i=1}^{N} \frac{f(V_{pi}) \cdot \Delta V_p}{L(V_{pi})} = \frac{1}{L} \qquad (7)$$

and, calculating L by infinitesimal intervals:

$$L = \frac{1}{\int_0^\infty \frac{f(V_p) \cdot dV_p}{L(V_p)}} \qquad (8)$$

The upper limit of the integral is infinite in the aforementioned equation since it corresponds to the probability of having a failure equal to 1. For practical purposes one can consider, for V_p, an upper limit of $V_{p\text{-lim}}$, such that the contribution to the equation provided by the integration between $V_{p\text{-lim}}$ and the infinite is negligible. An acceptable limit is 99.9% of the probability density function, which we'll call $V_{p99.9\%}$.

Now, assuming that a voltage pulse with amplitude V_p applied for an interval of $dt(V_p)$ and probability density $f(V_p)$ obtains lifetime $L(V_p)$ and that A.C. voltage is constantly applied throughout the total lifetime of the insulation L_{tot} (thus $t_{ac}=L_{tot}$), using equations (4) and (8) the result is:

$$L_{tot} = \frac{1}{\frac{1}{L(V_{ac})} + \int_0^\infty \frac{f(V_p) \cdot dV_p}{L(V_p)}} \qquad (9)$$

Returning to the inverse power model for calculating the lifetime of the insulation of the capacitors and also taking account of overvoltage, we can write [10]:

$$L = L_{Hp} \cdot \left(\frac{E}{E_{Hp}}\right)^{-n_p} \frac{f_0}{f} \qquad (10)$$

where E_{Hp} is the dielectric strength in kV/mm (measured by means of the rising-voltage test), L_{Hp} is the failure time in hours following application of E_{Hp}, f is the frequency with which the overvoltage event occurs and f_0 is the frequency of occurrence for AC voltage.
Lastly, the total lifetime model can be rewritten by substituting, in (9), equations (10) with $L(V_p)$ and (1) with $L(V_{ac})$:

$$L_{tot} = \frac{1}{\frac{1}{t_{ac}}\left(\frac{E_{ac}}{E_{Hac}}\right)^{n_{ac}} + \frac{f}{f_0}\int_0^{E_{p,99\%}} \frac{1}{t_p}\left(\frac{E_p}{E_{Hp}}\right)^{n_p} f(E_p) dE_p} \qquad (11)$$

Values E_{ac}, E_{Hac}, E_p and E_{Hp} are all peak-peak values since this value is known to be the most important factor for electric ageing. If an overvoltage is able to trigger off partial discharge in a capacitor, this effect must be considered in the model by means of a significant reduction of the VEC of the lifetime model, i.e. of parameter n_p. Given the geometry of the capacitor, the maximum electric field E_{ac} and the probability density of the electric field due to overvoltage $f(E_p)$ can be calculated starting from the known values of voltage V_{ac} and $f(V_p)$.

4. Impact of overvoltage on the components of an electrical installation

The time-to-failure of the insulating material, or its lifetime, follows a stochastic law. Different failure times are observed in identical capacitors subjected to the same stress owing to the different consistency of the insulating materials, different production processes employed, imperfect quality control, environmental conditions, etc. Failure time can therefore be associated with a failure probability by means of an appropriate probability distribution function. Assuming that lifetime distribution for electrical insulations subjected to electrical stress can be represented by the two parameters of a Weibull distribution, the cumulative distribution function that provides failure probability at time t is therefore [10]:

$$F(t) = 1 - e^{-\left(\frac{t}{\alpha_t(E)}\right)^{\beta_t}} \qquad (12)$$

Where t is the failure time, β_t is the shape parameter and α_t is the scale parameter, which represents the time-to-failure for F(t)=63.2% and depends on electric field E.
This equation (12) can be used to obtain the expression of the probabilistic lifetime model which, for a certain probability, provides the time-to-failure at electric field E:

$$t = [-ln(1-F)]^{\frac{1}{\beta_t}} \cdot \alpha_t(E) \qquad (13)$$

Parameters β_t and α_t can be estimated by performing an accelerated lifetime test at different stress values E_j, with j=1,…,m (≥3). n_i samples are tested for each E_j to obtain time-to-failure t_{Fi}. Assuming that the time-to-failure complies with Weibull distribution, parameters β_t and α_t are estimated for each sample using the linear regression method or the maximum probability estimation method [10]. Laboratory tests show a modest variation in β_t as the level of electric stress varies. This value can therefore be considered as a constant. On the contrary, α_t has been found to vary significantly depending on the electric field applied. Since, by definition, α_t represents time-to-failure at 63.2% probability, one can expect a notable diminution of α_t as the electric field increases, in accordance with the inverse power model. The relation between α_t and electric field E can therefore be written in the following way:

$$\alpha(E) = \alpha_{tH}\left(\frac{E}{E_H}\right)^{-n} \qquad (14)$$

Where E_H is the maximum E_j and α_{tH} is the 63.2-th percentile of time-to-failure below E_H.

If we now consider the overvoltages, we can replace α_t in the equation (12) with the complete lifetime model (11), thereby obtaining the following function of the probability distribution model:

$$F(t) = 1 - e^{-\left[t\cdot\left(\frac{1}{t_{ac}}\left(\frac{E_{ac}}{E_{Hac}}\right)^{n_{ac}} + \frac{f}{f_0}\int_0^{E_{p,99\%}} \frac{1}{t_p}\left(\frac{E_p}{E_{Hp}}\right)^{n_p} f(E_p)\,dE_p\right)\right]^{\beta_t}} \qquad (15)$$

Vice versa, reliability, i.e. the probability that failure will not occur within a certain time t, becomes:

$$R(t) = e^{-\left(\frac{t}{\alpha_t}\right)^{\beta_t}} = 1 - F(t) \qquad (16)$$

Thus, reliability for the capacitors becomes:

$$R(t) = e^{-\left[t\cdot\left(\frac{1}{t_{ac}}\left(\frac{E_{ac}}{E_{Hac}}\right)^{n_{ac}} + \frac{f}{f_0}\int_0^{E_{p,99\%}} \frac{1}{t_p}\left(\frac{E_p}{E_{Hp}}\right)^{n_p} f(E_p)\,dE_p\right)\right]^{\beta_t}} \qquad (17)$$

4.2 Impact of overvoltage on capacitors: calculation example

After having developed the theory, the reliability of the capacitors can be calculated by means of the following parameters [19]:

tac≈tp [h]	E_{Hac} [kV/mm] (peak-peak)	E_{Hp} [kV/mm] (peak-peak)	n_{ac}	n_p	β_t	f_0 [Hz]	Rated voltage of capacitor elements [kV]	Thickness of dielectric [µm]
0,0004	500·2·√2	840·2·√2	11.5	5.5	0.7	50	1.5	15 + 15

Table 8: Numerical values chosen for the capacitor reliability calculation

The thickness of the dielectric was chosen by considering the rated voltage of the elements so as to obtain the typical A.C. electric field of a power capacitor (50 kV/mm), as considered in literature [6] [13].

Dielectric strength E_{Hac} was chosen considering that values up to 600 kV/mm are declared for the new biaxially oriented polypropylene film (BOPP) [15]. However, values between 200 kV/mm and 300 kV/mm are indicated for less recent film [13]. In this case, the high-range value was chosen to highlight the impact of overvoltages on useful life even when the capacitors have been manufacturered according to the best technology.

Regarding E_{Hp}, dielectric strength measured by means of the rising-voltage test is always higher than E_{Hac}. Consequently, in accordance with literature, multiplication factor 1.7 was considered in this case [13].

The value of n_{ac} was chosen by considering the case of a capacitor similar to the one discussed in literature [14]. Note that the value chosen for n_p is lower than that of n_{ac} since it is assumed that transient overvoltages trigger off partial discharges, responsible for accelerated ageing.

The value of β_t is similar to the one used for the cables, since one assumes that the ageing phenomenon is similar from the stochastic point of view.

4. Impact of overvoltage on the components of an electrical installation

The installation illustrated in fig. 43 will be considered by way of example. Two capacitor banks are connected to an MV busbar in the back-to-back configuration for power factor correction. In addition, another capacitor bank is connected to the LV riser of the transformer. The main data are:

MV rated voltage [kV]	MV capacitor bank [MVAr]	LV rated voltage [kV]	LV capacitor bank [kVAr]
10	2 x 1,38	0,4	140

Regarding the overvoltages due to switching-in capacitors, we will consider those due to switching-in capacitors since, as capacitors remain energized after switch-in, these overvoltages are the most damaging from the partial discharge aspect. We will also assume that closing occurs with uniform probability in any point of the voltage cycle and that therefore, the closing stage covers all the switch-in angles with equal probability. Using this basis, a probability distribution f(Ep) can be calculated for the switching overvoltages which, as one would expect, is between 1 and 3 p.u. for the installation in question, i.e. at voltage between 8.16 kV and 24.49 kV.

We will now consider two frequencies: the first refers to capacitors switched-in four times a day ($f=4.64 \cdot 10^{-5}$ Hz) while the second refers to ten switch-in operations a day ($f=1.16 \cdot 10^{-4}$ Hz). Using the formula (17), we can plot the curves of fig. 44, where the green vertical line represents the typical 30-year project life cycle [19].

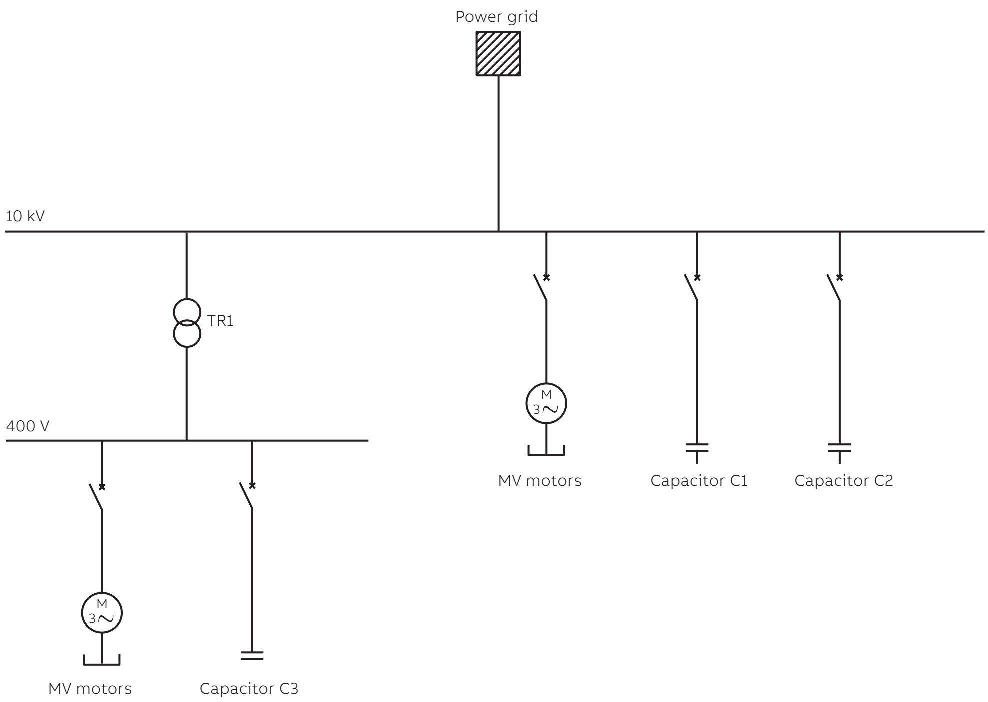


Figure 43: single-line diagram of the installation described in the example

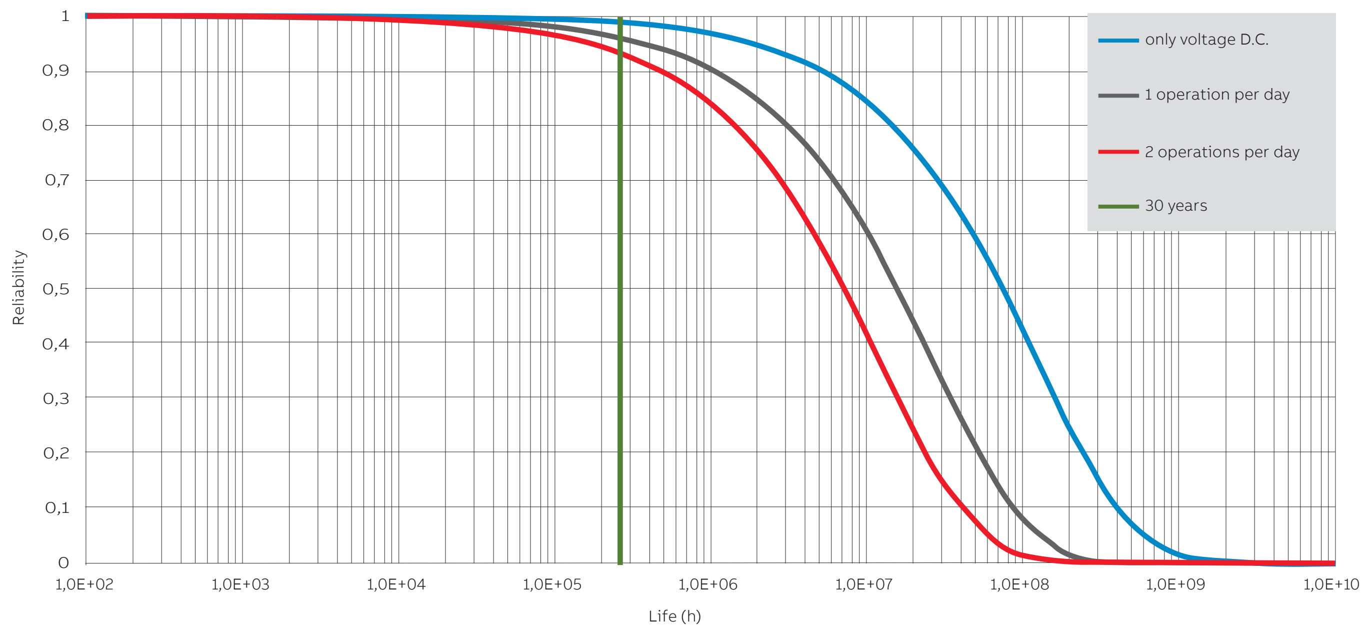


Figure 44: reliability trend of an MV capacitor element

Using the 30-year life cycle as a reference, it is much more practical to calculate reliability on the basis of the number of switch-ins, as can be seen in figure 45.

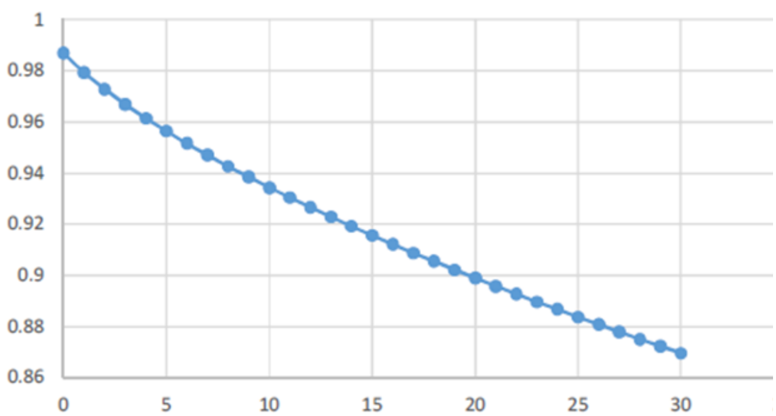


Figure 45: reliability after 30 years on the basis of the number of switches

The vertical line in the graph represents the thirty years lifetime normally required when capacitors are designed. In the absence of overvoltages, reliability is 99% at thirty years (blue curve).

Reliability diminishes in the presence of overvoltages. At a frequency of four switches a day, reliability drops to about 96% (black curve) and to 93% at a frequency of ten switches a day (red curve). The value gets worse if switching occurs more frequently. This could occur when motors are started by switching-in capacitors in parallel. Lastly, consider the trend of the partial discharge phenomenon is progressive and not constant, and that this can impair reliability to an even greater extent.

As can be seen from the way the curves slope, compared to the condition without overvoltages, deterioration of reliability after thirty years becomes extremely marked.

Bear in mind that the result described is the outcome of a theoretical study by researchers and specialists and that it should therefore be considered in qualitative terms for the purpose of demonstrating how the reliability of capacitors depends on the phenomenon of overvoltages due to switching of the capacitors themselves.

4. Impact of overvoltage on the components of an electrical installation

4.3 The protection system associated with the capacitor bank

The impact of the failure of a single capacitor depends on the construction characteristics of the bank. Some capacitor banks are protected by external fuses while others are protected by internal fuses.
Capacitor banks without internal fuses consist of a set of groups of elementary single capacitors connected in parallel.
Failure of one element will short-circuit the group associated with that unit. This leads to an increase in the current that crosses the bank and an increase in the voltage on the elements of the remaining groups. In this sort of construction, it is normally necessary to replace the affected bank as soon as the first failure is detected.
Vice versa, when the capacitors have internal fuses, all the elementary capacitors have a fuse in series. Thus the faulty element is excluded without compromising the others in the group to which it belongs.

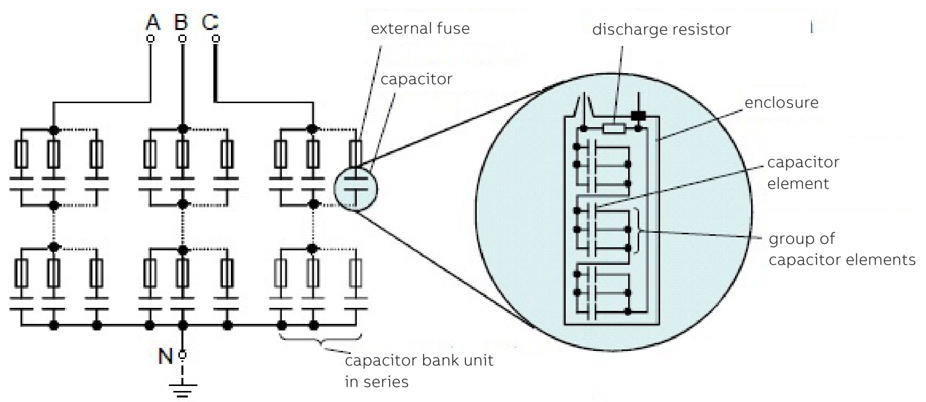


Fig. 46: capacitor banks with external fuses

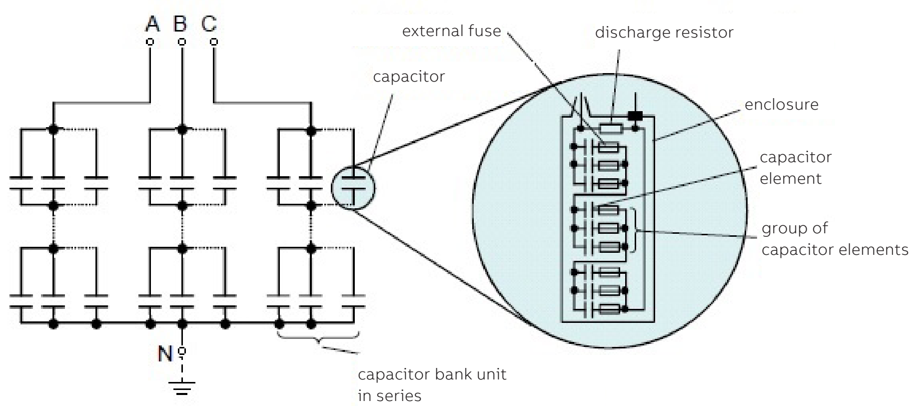


Fig. 47: capacitor banks with internal fuses

The bank can remain in service with reduced reactive power so long as the voltage on the remaining capacitors does not exceed the tolerance margin of +10% of the rated voltage envisaged by the manufacturer. Obviously, the more elementary capacitors form the bank, the lower will be the impact, in percentage terms, on both the diminution of reactive power and on the increase in the voltage on the remaining capacitors.
The following formula gives the overvoltage V_{pu} on the remaining capacitors in the group in relation to the number n of faulty capacitors:

$$V_{pu} = \frac{S \cdot P}{S \cdot (P - n) + n}$$

where S is the number of groups in series, each consisting of P capacitors in parallel. E.g.: consider a bank formed by 5 groups of 10 capacitors in parallel. When the first element fails there will be:

$$V_{pu} = \frac{5 \cdot 10}{5 \cdot (10 - 1) + 1} = 1{,}087$$

or 8.7% of overvoltage, thus the bank need not be disconnected. When the second failure occurs there will be:

$$V_{pu} = \frac{5 \cdot 10}{5 \cdot (10 - 2) + 2} = 1{,}19$$

or 19% of overvoltage. It is therefore advisable to disconnect the bank having exceeded 110% of the rated voltage.

The protection system associated with the capacitor bank must comply with the following criteria:
- the increase in the rated voltage of the bank caused by loss of each individual capacitor must not exceed 10%. The alarm of the protection function must trip as soon as one or more elements fail before 10% overvoltage is reached.
- the protection function must disconnect the bank when the overvoltage in any of the units exceeds 10% of the rated value.

This avoids serious damage and allows the bank to be replaced in good time.

One of the functions used for protecting the capacitors is protection against phase unbalance. This protection is based on the quantity or on the variation of the current or voltage due to an unbalanced neutral, which is the result of a certain number of elementary capacitors or units having failed and which can be calculated on the basis of the bank configuration and rating plate data.
In the very common case in which the capacitor banks are managed with an isolated neutral, the layout for protecting a single bank is as follows:

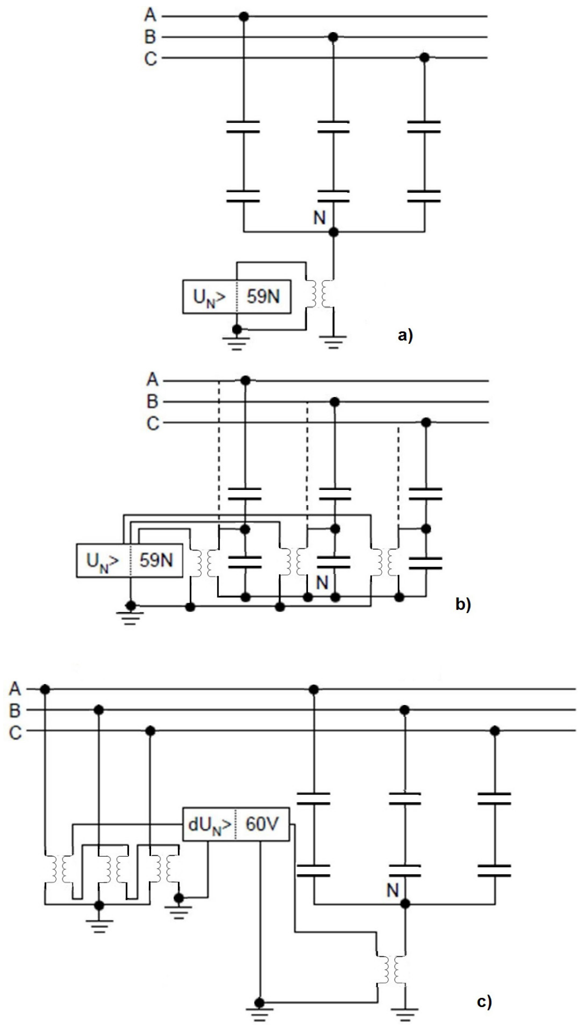


Fig. 48: protection layout for a single bank with isolated neutral

4. Impact of overvoltage on the components of an electrical installation

The simplest way to detect unbalance in this case, is to measure the voltage on the neutral or zero sequence. In normal conditions, the voltage is obviously zero, while any variation on one of the phases causes a variation in the neutral current or zero sequence. Figure 48 a) illustrates the method, which consists in measuring the voltage between the capacitor neutral and earth using a VT or resistive divider and an overvoltage protection function. This method is very simple, but its disadvantage is that it also measures grid unbalance and the natural unbalance of the bank.
A second method, shown in figure 48 b), consists in using three VT and calculating the zero sequence voltage from the phase-neutral voltages. Lastly, figure 48 c) illustrates a solution for eliminating both grid unbalance and that of the bank. Grid unbalance is eliminated by measuring the zero sequence residual voltage, by connecting the secondaries of the broken-delta VT, or by calculating it numerically from the phase-earth voltages. The natural unbalance of the bank can be calculated by means of a compensation function included in all modern protections.
The protection layouts for two capacitor banks are illustrated in figure 49.
In this situation, it is very simple to obtain compensated unbalance protection since the zero sequence component of the system affects the two banks in the same way, while a faulty elementary capacitor seems like an unbalance between neutrals. The first diagram shows a current transformer connected between the two neutrals and an overcurrent protection function. The second diagram uses a voltage transformer and an overvoltage protection function. The effect of voltage unbalance in the system is eliminated in both cases but not that of natural bank unbalance due to the tolerances involving the presence of currents or voltages between the neutrals, even in the absence of faults.
Consequently, a natural unbalance compensating function must be adopted if a very sensitive protection is required.
The error due to natural unbalance may make the protection insensitive or, vice versa, cause untimely trips. It is advisable to perform compensation by means of the relative protection function if the error nears 50% of the required alarm threshold.
A so-called H configuration is often used in large capacitor banks, with a current transformer connected between the connections between banks, as shown in figure 50.

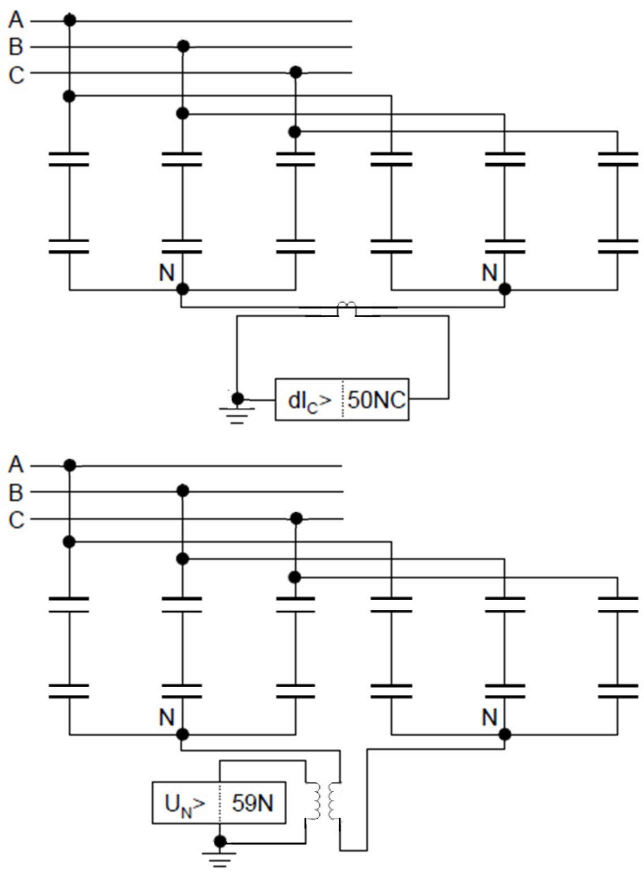


Fig. 49: protection layout for two banks with isolated neutral

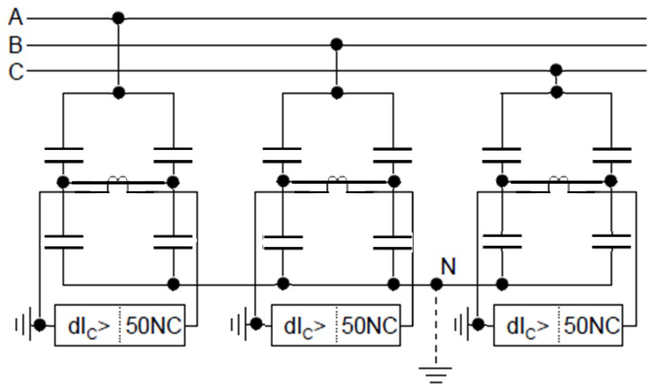


Fig. 50: protection layout for H-connected bank

No current flows in the absence of faulty elements, otherwise a current begins to flow through the current transformers. The advantage of this configuration is its insensitivity to grid unbalance, but natural unbalance causes a current to flow between the branches. This means that here again, a natural unbalance compensating function must be used so as to obtain a very fast and sensitive unbalance protection. This is why this configuration is so widely used for large capacitor banks.
Overload protection is also used for capacitor banks. If the capacitors are subject to overvoltages for long periods, e.g. owing to a high harmonic content, this can cause the current that flows around the bank to increase and stress the individual elements. Since capacitors are particularly sensitive to overvoltage, it is advisable to measure the voltage peak. However, it is also possible to use an overload protection based on filtered current measurement, which is certainly more economical (figure 51).
There must obviously also be a protection against short-circuits between the phases and towards neutral and earth. In this case, an overcurrent protection with two thresholds is normally employed, in which the higher threshold is used for short-circuits between the terminals of the banks and circuit-breaker while the lower threshold is used for faults between banks, where greater sensitivity is required. In order to avoid untimely trips, the overcurrent thresholds must take account of the inrush currents. Typically, the minimum value of the first trip threshold for banks with isolated neutral must be 125% of the rated phase current, while the value of the upper threshold must be higher than the transient inrush current in any case, e.g. from three to four times the rated current of the bank. Whether it is directional or not, in the case of an earth fault in systems with isolated neutral, the protection must be as sensitive as possible. If the earth fault occurs inside the bank, this will also cause an unbalance. Thus the unbalance protection is also a back-up protection for the earth fault protection.
The unbalance protection may not be sensitive enough to trip when certain faults occur inside large capacitor banks, e.g. faults between racks in certain H configurations. In this case, it may be necessary to add a back-up protection, i.e. an negative sequence overcurrent protection.
A further protection function must be included to prevent the banks from reconnecting immediately after a disconnection, i.e. before the discharge time has terminated, thus in medium voltage within 5 minutes ((ANSI/NFPA 70) or within 10 minutes (IEC 60871-1). This is normally achieved by using an appropriately delayed undervoltage or minimum current function to prevent the circuit-breaker or switch from reclosing before the discharge has terminated. If a specific apparatus has been installed to switch the bank in addition to the circuit-breaker (such as DS1), this function must be performed on the load side of the switching apparatus. DS1 inhibits reclosing after the bank has opened for an adjustable time so as to account for the discharge time (5 min by default).

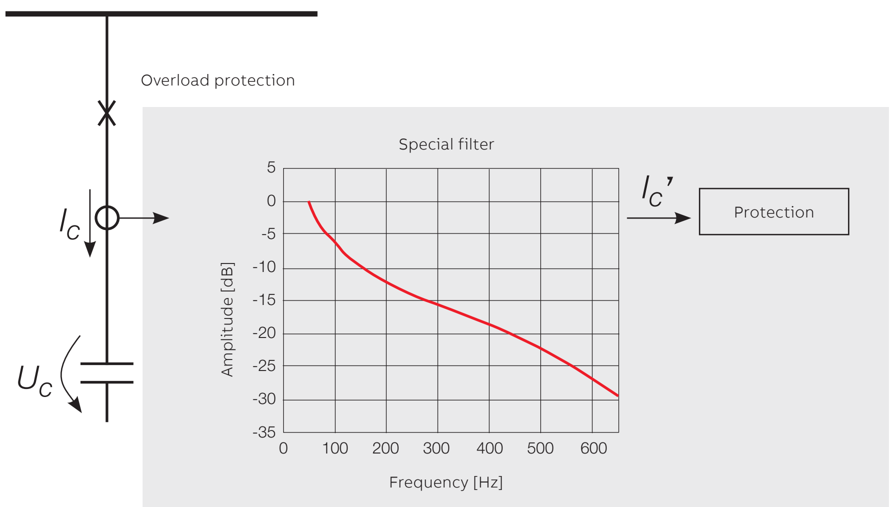


Fig. 51: protection configuration 51c

4. Impact of overvoltage on the components of an electrical installation

Lastly, it is also advisable to install an overvoltage protection function to prevent the banks from being subjected to abnormal overvoltage long enough for them to be damaged. When the banks open, the overvoltage in their vicinity is also limited, thereby reducing the stress to which the other components of the installation are subjected. The voltage is normally measured from the busbar on the supply side of the circuit-breaker. The function must be coordinated with that of the overcurrent and can therefore also act as a back-up protection.

For example, let's examine a protection system with a REV615 type relay in a large H-connected capacitor bank.

Fig. 52: REV615 relay

With reference to the example illustrated in figure 53, the protection functions implemented in REV615 are:
- for short-circuits and overcurrent (50, 51);
- for unbalance (51NC);
- for overload based on the current (51C);
- negative sequence overcurrent protection (51Q);
- for earth faults (51N, 50N)
- undervoltage, overvoltage and residual voltage so as to monitor the power supply grid (59, 27, 59N)

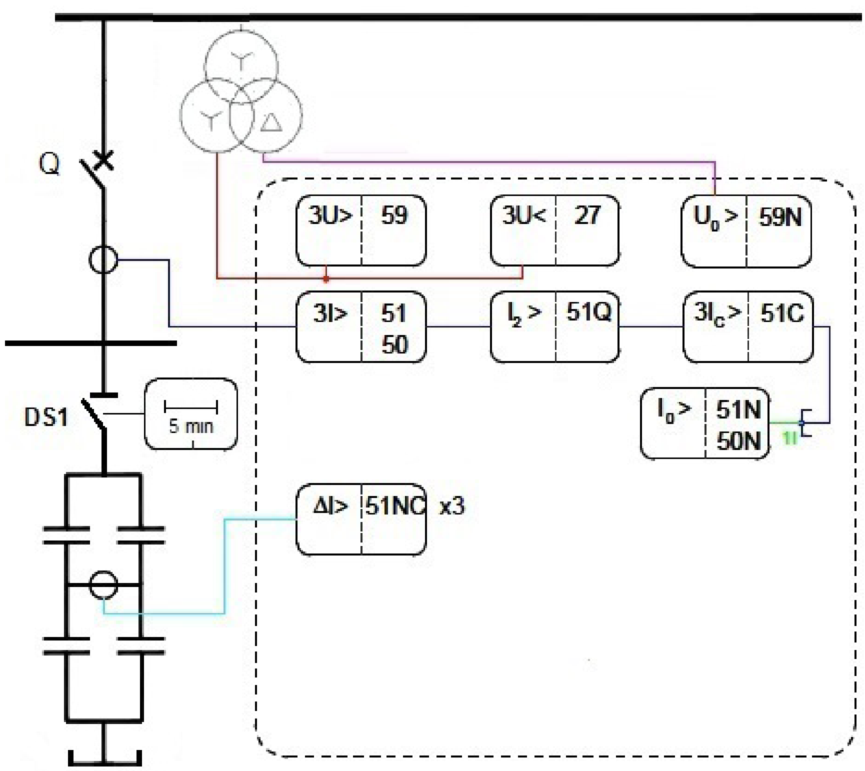


Fig. 53: schematic diagram of the capacitor protection functions

Generally speaking, it is advisable for switching to be performed by dedicated capacitor switching devices, such as DS1, following the TRV and capacitive corrents that appear during the break. Circuit-breakers are suitable for interrupting short-circuit current but they are often in difficulty when switching capacitors. When it comes to operating logic, the proposed solution is as follows (figure 54). The opening commands have been divided between the circuit-breaker and capacitor switch, depending on the protection function involved. Function 51Q was divided so as to have the low threshold connected to the DS1 operating mechanism and the high threshold to that of the circuit-breaker. Obviously, the logic will have to be validated case by case, depending on the installation concerned.

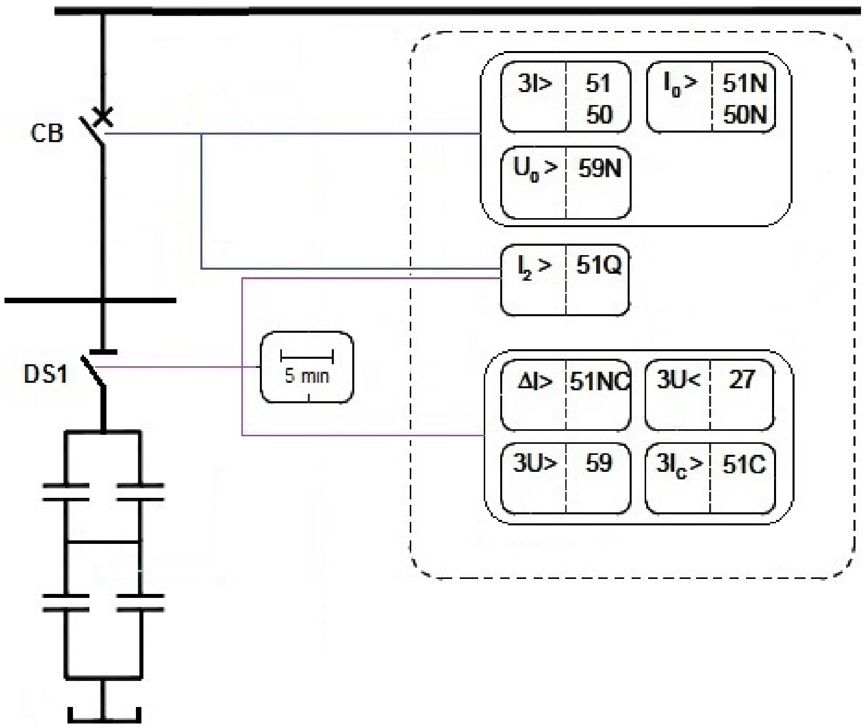


Fig. 54: example of the division of opening commands between CB and DS1

4. Impact of overvoltage on the components of an electrical installation

4.4 Impact of capacitor switch-in transients on the other components in an electrical system

Capacitors are frequently used in industrial installations for power factor correction in the presence of large motors that operate with a power factor at full load starting from 0.60. Certain precautions must be taken when sizing these capacitors, especially to prevent overvoltage due to self-energizing of motors disconnected from the network and still turning, when the capacitors are permanently connected to them. The presence of capacitors also prolongs residual voltage damping after opening, thereby increasing the risk of restarting during this transitory period, during which the actual motors and other equipment could sustain damage.

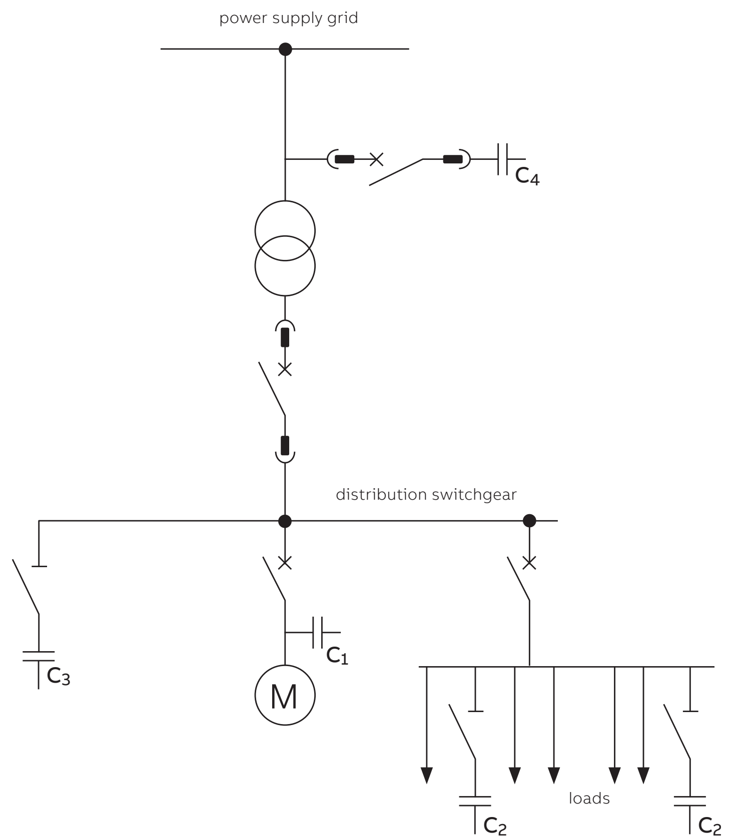


Fig. 55: example of a circuit with several power factor correction points

In the case of low voltage motors, the standards (e.g. IEEE 141-1993) recommend the maximum capacitor size (C1 in figure 55) coupled to a certain motor if permanent connection is required. If a larger size capacitor is required, provide for separate switching (C3 in figure 55) by means of a dedicated switching device. Irrespective of whether medium voltage or low voltage is used, this latter configuration still poses the problem of overvoltage caused by capacitor switching, since the consequent transient overvoltages or multiple zero crossings can cause the protections of the variable speed starting systems of the motors to trip. In certain types of drive with the first conversion stage formed by simple rectifier diodes, the overvoltage that reaches the terminals comes from the DC connection (figure 56).

To protect the capacitor and the electronic components of the inverter stage, the DC connection of the drive is normally protected against overvoltage. This protection functions by disconnecting the drive when the overvoltage exceeds a certain threshold, generally little more than 110% of the rated DC voltage.
This situation may get worse in the case of medium voltage capacitor switching (C4 in figure 55) when other low voltage capacitors are present (C1, C2, C3 in figure 55), thus on the load side of the MV/LV transformer. So-called secondary resonance may occur in this case, where overvoltage caused by medium voltage capacitor switching may cause much higher overvoltage in the low voltage secondary circuit if the resonance frequency of the capacitors is near to the natural resonance of the switched medium voltage capacitor. In this case, the initial MV overvoltage creates LV overvoltage as in the relation:

$$f_c = f_m \cdot \sqrt{\frac{L_m \cdot C_m}{L_s \cdot C_s}}$$

Where f_c is the oscillation frequency that couples with frequency f_m of switching oscillation, L_s and C_s are inductance and capacitance in the secondary circuit, L_m and C_m are inductance and capacitance in the MV circuit. The lower the f_c/f_m ratio, the greater the amplitude of the consequent LV transient, which can even reach 5 p.u.

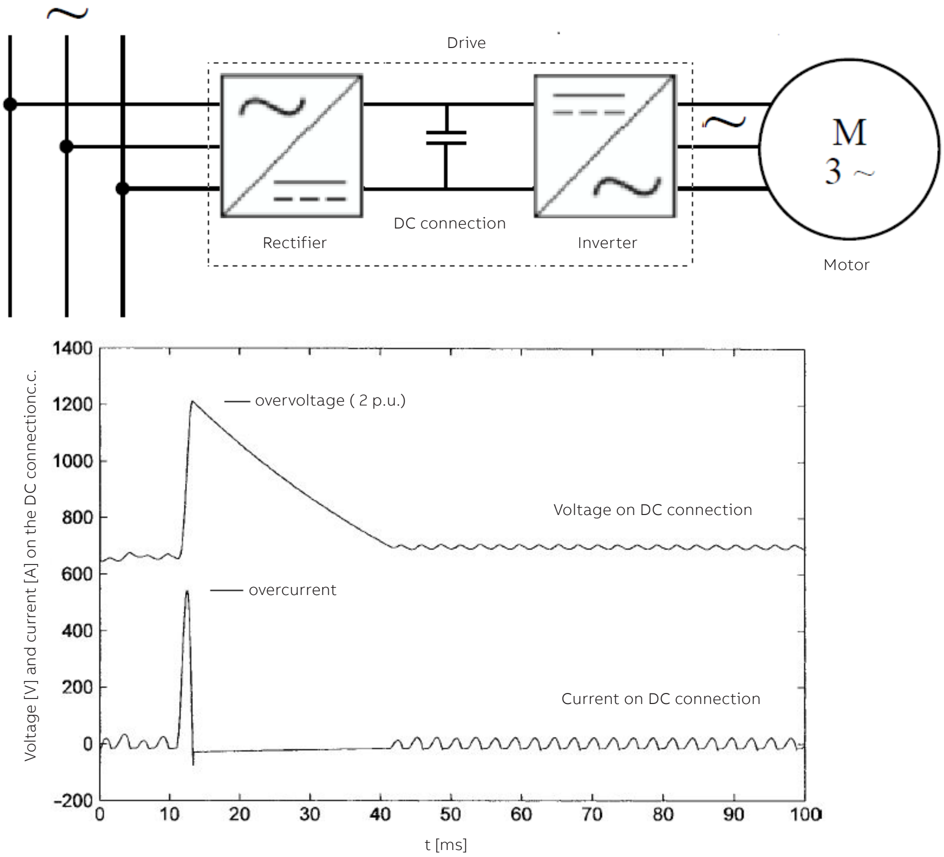


Fig. 56: diagram of a motor driver and example of the effect on the DC connection of a capacitor switching operation

The next figure illustrates the low voltage transient overvoltage caused by switching a 6 MVAr, 13.8 V capacitor bank in the presence of a 200 kVAr, 480 V capacitor on the load side of a 2 MVA transformer.

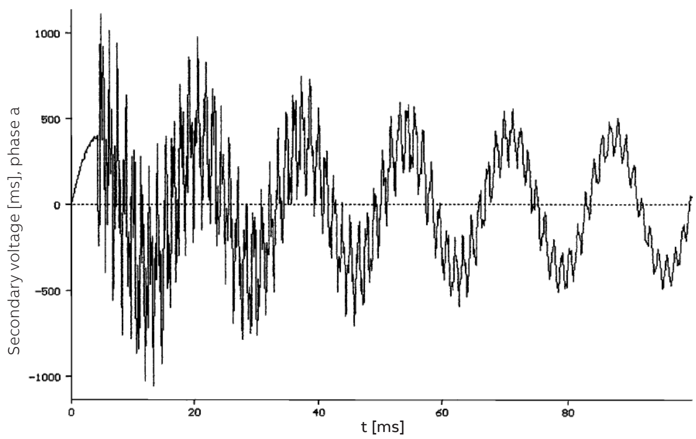


Fig. 57: LV transient overvoltage due to MV switching

4. Impact of overvoltage on the components of an electrical installation

These overvoltages can therefore cause faults and trip the protection relays and fuses on the low voltage side as well as tripping the motor drive protections.

Since the motor must obviously remain in service and production downtimes must be avoided, chokes are installed in series with each drive. Typical values range from 3 to 5% of the drive power expressed in kVA and are sufficient to reduce the overvoltage on the DC bus to below tripping level. Although it is simple, this solution clearly requires a large number of reactances to be installed in relation to the number of motors in the installation.
Once again, the alternative solution is to eliminate the switching overvoltages of MV capacitors by using a synchronous capacitor switch. In the previous example, where a DS1 was used to eliminate the switching overvoltage, one can assume that f_m is nil and that therefore, the secondary oscillation frequency is also nil.
No-load or low-load switching-in of transformers performed in presence of power-factor correction capacitor represents another sort of installation where the presence of capacitors can generate overvoltages. In such conditions, it is not rare for the capacitors themselves to fail or for fuses installed on the transformer primary to trip in an untimely way.

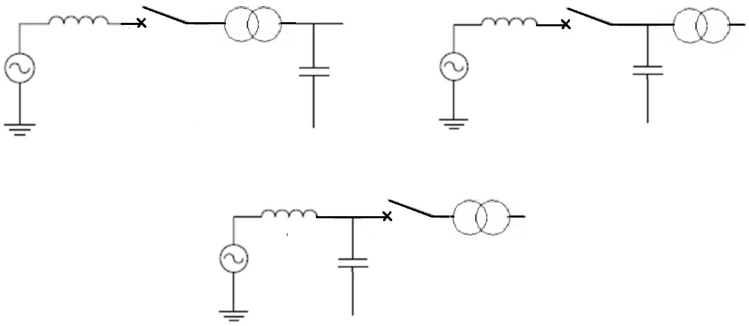


Fig. 58: possible positions of the power-factor correction capacitor with respect to the transformer

This phenomenon can be amplified by resonance phenomena even when the capacitors are not switched-in together with the transformer. This is because the no-load switching-in current of the transformers has a certain harmonic content. One of the harmonics, typically of the lower order, may resonate with the capacitors, causing prolonged overvoltage with a high harmonic content that may last for many cycles.

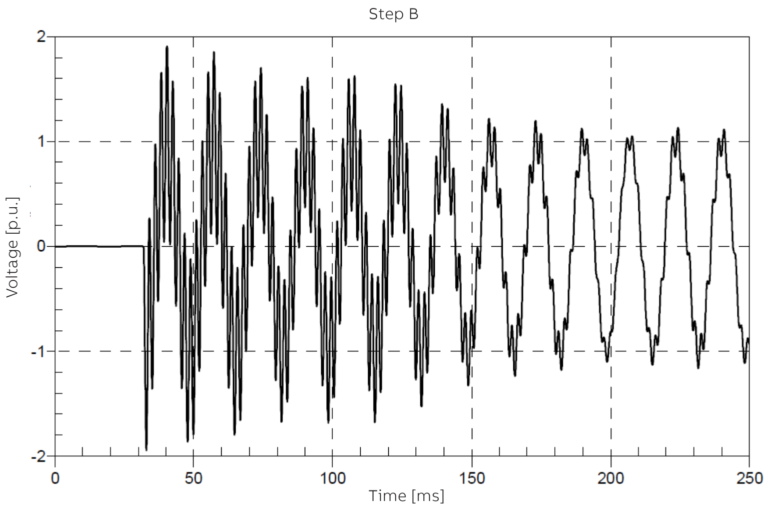


Fig. 59: resonance in the case of no-load switching-in of a transformer

Although these overvoltages do not normally reach high values, it is still inadvisable to switch capacitors and transformers together. Switching them in separately, with the capacitors at a later stage, is the best solution. However, the generation of overvoltages when they are switched-in is still a problem, thus the really best solution is to switch the capacitors with suitable apparatus, such as the DS1 synchronous capacitor switch.

5. Economic benefits obtained by using the diode-based synchronous capacitor switch

Fig. 60: Power factor correction system in ABB ABBACUS switchgear

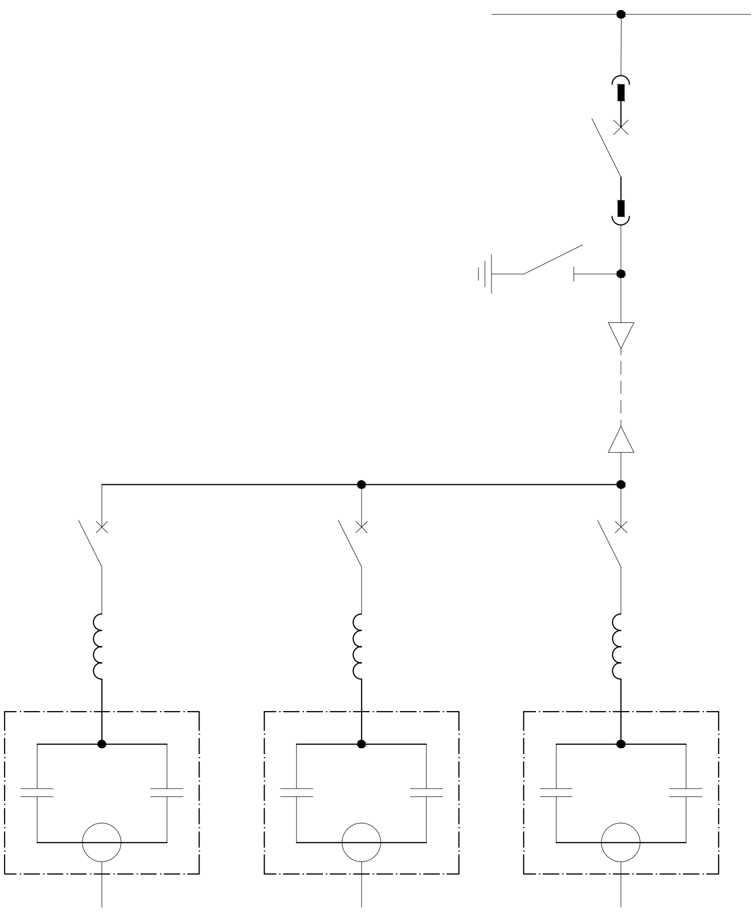


Fig. 61: example of a circuit diagram with power-factor correction capacitor banks

Based on the explanations given in the previous chapters, let us now consider a medium voltage industrial system with a centralized power factor correction system by way of example:

The power-factor correction system consists of three three-phase capacitor banks, each controlled by its own switching device.
We will assume that each bank is switched-in four times a day.
Two different solutions will now be compared in which the capacitor banks are switched by a conventional device in the first case and by a DS1 in the second case
.

5. Economic benefits obtained by using the diode-based synchronous capacitor switch

We'll consider that the cost of the banks equals C_{con} for both configurations.
In the first case, with reference to chapter 4, capacitor reliability is calculated on the basis of the black curve of figure 44, which refers to four switches a day. In these conditions, reliability is 98% after ten years or, vice versa, failure probability is 2%. In a capacitor bank formed, for example, by 4 groups in series of 12 capacitors, this is the equivalent of having 1 failed capacitor (figure 62) and to therefore being in a critical situation since the voltage on the single capacity already with two failures is:

$$V_{pu} = \frac{S \cdot P}{S \cdot (P - n) + n} = \frac{4 \cdot 12}{4 \cdot (12 - 2) + 2} = 1{,}14$$

thus higher than the limit value, which is 10% more than the rated voltage.

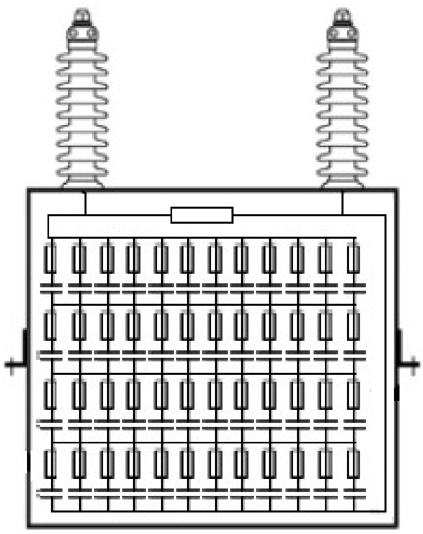


Fig. 62: capacitor with 4 groups in series of 12 elements in parallel

Statistically speaking, the number of failures in this example should not be such as to require the banks to be placed. However, since one element is no longer usable, the situation should be closely monitored.
When this cost is annualized, the result is:

$$C_{con1} = 0$$

The cost of replacing the circuit-breaker must also be considered. In the first case, the normal life of a circuit-breaker is 10,000 operations. At the rate of 1460 operations a year, the apparatus will have to be replaced every 10000/1460=6.9 years. Supposing that the circuit-breaker replacement cost is C_{CB}, the result is:

$$C_{sost1} = \frac{C_{CB}}{6{,}9}$$

When it comes to maintenance costs and supposing that maintenance must be performed after every 2,000 operations, it is due every 2000/1460=1.37 years. Supposing that the cost equals C_{man} per maintenance operation, the result will be:

$$C_{man1} = \frac{C_{man}}{1{,}37}$$

Since, in the first case, a limiting inductor has been used as a method for reducing transients, this will generate losses equal to $P=R \cdot I^2$, which must be multiplied by the overall switching-in time of the respective capacitor banks. To assess the order of magnitude of costs due to losses, a 60 µH limiting inductor with 2 kW losses at rated current can be considered by way of example.

Assuming that the capacitor banks function for 8 hours a day and considering a cost per time-slot B = 0.13 €/kWh, the yearly losses per three-phase bank will be:

$C_{pe1} = 2 \cdot 8 \cdot 365 \cdot 0.13 \cdot 3 = 2278$ €/anno

Another problem in the first case concerns tripping of the protections in the variable frequency starters that control the motors in industrial installations or, at any rate, untimely trips of the protection relay or fuses as a consequence of overvoltage. In the first case, this involves an additional cost for possible loss of production C_{pp1}.
The total annual cost in the case of the circuit-breaker will therefore be:

$C_{totcb1} = C_{sost1} + C_{man1} + C_{pe1} + C_{pp1}$

Fig. 63: DS1 synchronous capacitor switch

Now let us attempt to analyze the costs in the second case, i.e. using a DS1.
In the absence of overvoltages, the failure probability for switching overvoltage becomes negligible, thus C_{con2}=0
When it comes to replacement costs, the normal life of a DS1 is 50,000 operations. At the rate of 1460 operations a year, the apparatus will have to be replaced every 50000/1460=34 years. Thus C_{sost2}=0 since the design life of a capacitor bank themselves is 30 years.
As to maintenance costs, DS1 is maintenance-free so maintenance costs can be considered nil:

$C_{man2} = 0$

Since limiting inductors are not required, the cost of the relative losses is nil, thus:

$C_{pe2} = 0$

Lastly, since there are no overvoltages, the cost of loss of production due to tripped protections will also be nil:

$C_{pp2} = 0$

The total annual cost in the case of DS1 will therefore be:

$C_{totDS1} = 0$

It is therefore evident that $C_{totCB} >> C_{totDS1}$, thus with significant savings if the DS1 solution is used.
Obviously, this analysis is purely qualitative and can vary, depending on the type of installation in question.

6. Conclusions

Frequent switching of capacitors for power-factor correction in MV power grids can generate switching overvoltages and overcurrents able to progressively deteriorate the state of the components in the actual installation. Certain statistical studies have shown that these same capacitors may be affected by this deterioration process over time, with progressive loss of life until complete breakdown occurs in the bank. Although there are tried-and-tested techniques that allow these transients to be reduced, they are unable to fully resolve the problem.
On the other hand, the new and innovative diode-based capacitor switch technology provides an efficient solution to the problem by reducing both inrush currents and switching overvoltages to negligible levels.
The main economic benefit provided by this solution is obviously due to the lower level of stress to which the electrical installation is subjected and, thus, by the ensuing enhanced continuity of service and lower maintenance and replacement costs.

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1VCP000629-Rev A - en - 2018.05 - (Technical Application Manual No. 23 Medium voltage synchronous capacitor switching) (gs)