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Medium-voltage switchgear

Switching of capacitors and filter circuits

Solutions for the high demands on switching technology

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Switching of capacitors and filter circuits

High demands on switching technology

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Abstract

High demands on switching technology

The use of renewable power producers and state-of-the-art consumers is increasing. This situation can significantly affect the quality of the power supply, because both alternative power sources as well as modern consumers influence the power quality with different types of harmonics.

Nonetheless, standards and consumers demand consistently high power quality. To ensure this, power factor correction equipment is increasingly being used. Power factor correction equipment consisting of capacitor banks and filter circuits must be reliably supplied and switched. This poses ever higher requirements on medium-voltage switching technology. Medium-voltage switchgear by Siemens with vacuum switching technology establishes the most favorable preconditions for satisfying these high requirements.

Content

Introduction

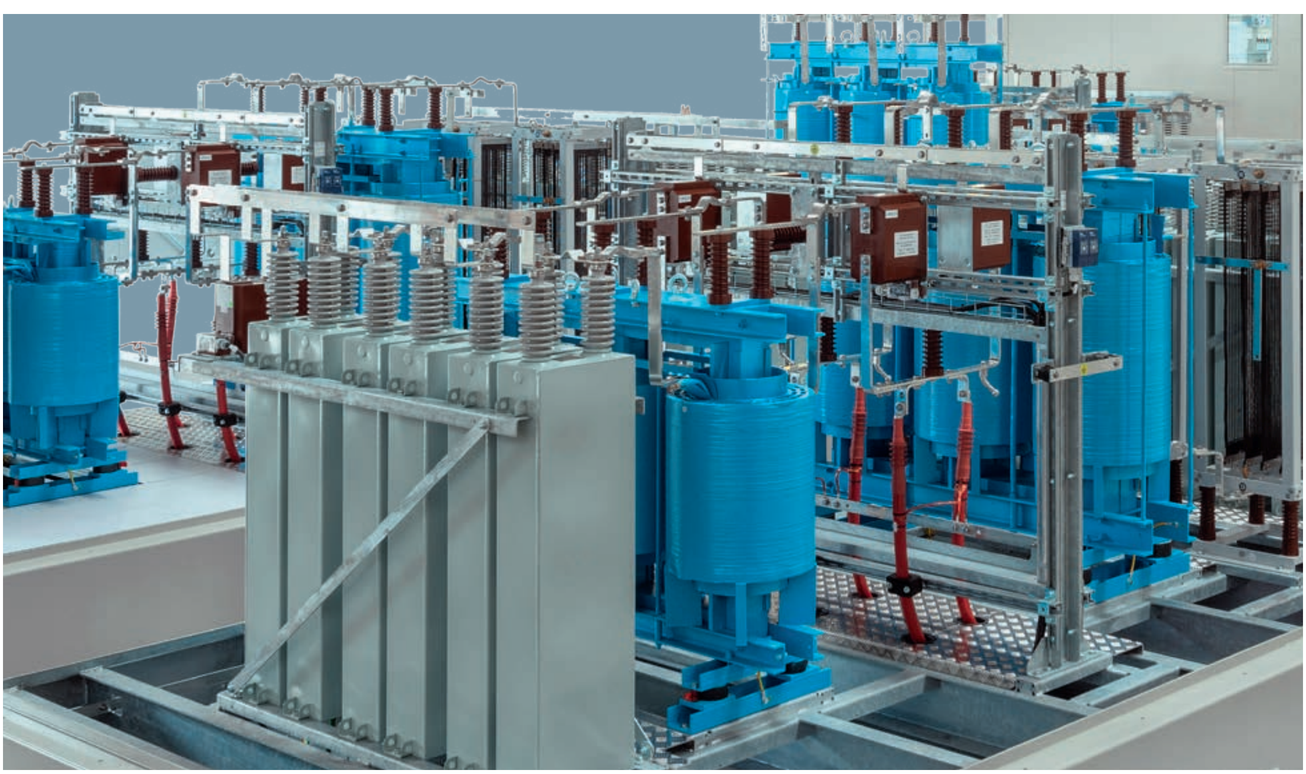
Switchgear in medium-voltage systems is responsible for reliably and safely distributing electrical energy. Circuit-breakers are among the most important elements of switchgear. They must be able to handle every load that arises and safely conduct and switch both inductive and capacitive currents as well as high short-circuit currents.

The demands that are placed on circuit-breakers arise from the demands placed on the power quality. These demands are defined both by the power producers and also by the consumers. The growing use of regenerative power producers, for example wind energy, has a not insignificant influence on quality. The same holds true for modern consumers: Voltage distortion from harmonics increases with the greater use of power electronics. On the other hand, the sensitivity of devices to current and voltage distortion increases to the degree that these devices produce harmonics.

Most systems are designed to operate efficiently with (nearly) sinusoidal voltage and current. This means that the quality of the power system is essential for all devices to operate reliably and efficiently. As a result, more and more power factor correction equipment, consisting of capacitors and coils, is being used to ensure the power quality promised to consumers.

Typical uses of power factor correction equipment are the generation of energy by wind turbines, converter-controlled motors used in industry, or power grids with a decentralized energy supply. In the meantime, power factor correction equipment is also being used for outputs smaller than 10 MW.

The consequence of the increased use of power factor correction equipment for smaller outputs is that circuit-breakers in medium-voltage switchgear are called upon to conduct and switch high capacitive currents ever more frequently. What this means and how the task should be handled is described below.



Switching of capacitors and filter circuits

Why are capacitor banks and filter circuits required?

Precise voltage and frequency tolerance specifications exist for electrical power systems and also exist regarding the level of potential harmonics. Industrial processes today frequently use automated systems and power electronics. Energy-saving devices with rectifiers are increasingly being used by household consumers. All these consumers influence the quality of the power supply, due to different types of harmonics. Harmonics are characterized by high frequencies. Not only do they “pollute” the power system, they also generate losses which in turn can lead to undesirable additional thermal loading of the devices and current conductors. The consequence of increased losses and temperature rise are larger conductor cross-sections and oversized switchgear. In order to counteract this trend, an attempt is made to compensate for such harmonics. Either coils or capacitors are used as compensation elements, or a combination of both is used.

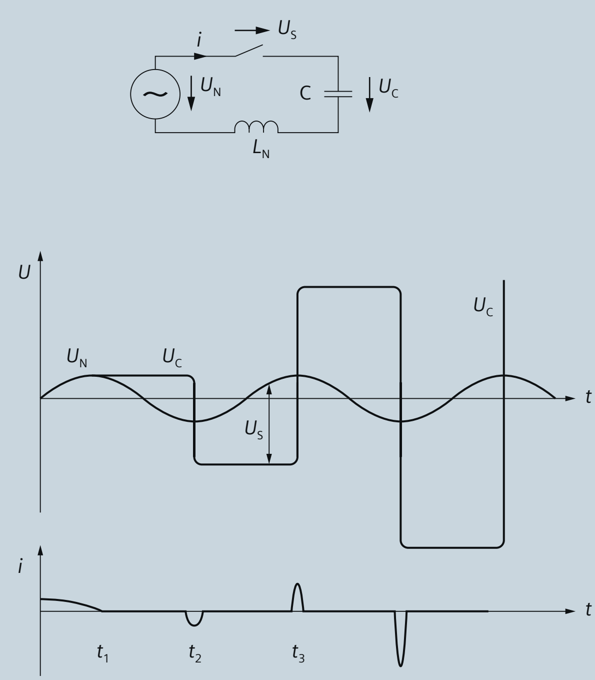
The circuit-breakers of medium-voltage switchgear must be able to switch both inductive and capacitive currents reliably. For today's circuit-breakers, switching inductive currents does not pose a particular challenge, whereas switching capacitive currents does. We will therefore only consider capacitive compensation below. An individual capacitor can be used, as can several capacitors connected in parallel. To prevent resonance, filter circuits consisting of capacitors and inductors connected in series are employed.

What are the stresses incurred when switching capacitors?

Switching capacitors off:

When a capacitor is switched off in current zero (time t_1), the capacitor remains charged at the peak value of the source voltage (U_C). The system voltage (U_N) continues in its sinusoidal change and reaches its opposite peak value after 10 ms. The recovery voltage (the difference between U_C and U_N) initially rises slowly; the stress in this case is not the rate-of-rise, but the absolute value of the voltage. If ignition occurs again within 5 ms of arc extinction, this is termed re-ignition. This type of re-ignition is not hazardous. If re-ignition occurs after a current-free pause of more than 5 ms, it is termed a restrike. If this occurs only after approximately 10 ms, it can cause high switching overvoltages.

A restrike causes the energy remaining in the capacitor to recharge; the voltage therefore theoretically jumps to a value corresponding to the capacitor voltage plus the momentary level of the system voltage (time t_2). However, this value is never reached in reality, due to the existing power system damping. If repeated recharging occurs (additional restrikes), the switching overvoltages can become so high that the system insulation is overstressed, resulting in arcing at the circuit-breaker or even at other switchgear components, or leading to the complete failure and destruction of the circuit-breaker.



U_N	System voltage
U_C	Capacitor voltage
U_S	Voltage across the circuit-breaker
i_C	Capacitor current
L_N	System inductance
C	Load capacitance
t_1	Time of interruption
t_2, t_3	Time of restrike occurrence

Restrikes during capacitive switching

Switchgear requirements:

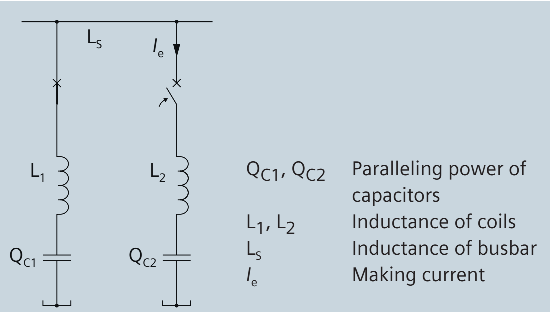
Safe control of the high recovery voltage so that restrikes and overvoltage do not occur.

Switching of capacitors and filter circuits

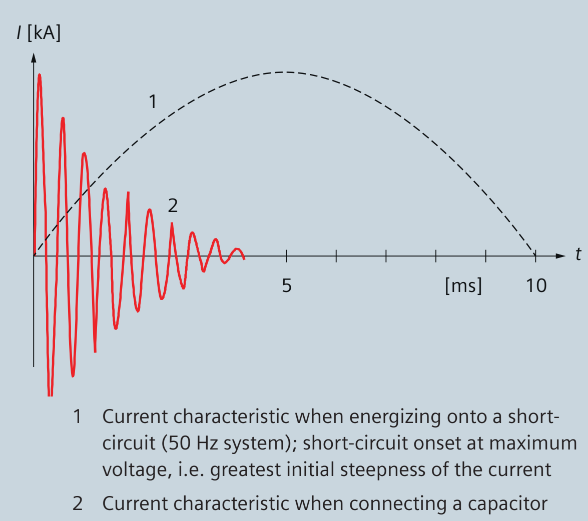
Capacitors connected in parallel:

If several capacitors are used in parallel for compensation and they are switched on and off separately, the permissible capacitive making current must be observed. If a capacitor is connected to a power system followed by another capacitor, very high peak making currents can arise depending on the capacitor size and the inductance of the switchgear.

When the switching contacts approach each other, pre-arcing arises across the open contact gap before the contacts experience galvanic contact. At this instant, a transient phenomenon arises between the power system and the capacitor. Making current values of up to several tens of kilo-amps can arise at frequencies up to several kilohertz. As pre-arcing occurs about 1 to 2 ms before galvanic contact is made, the entire compensation current (2) flows through the arc when the capacitors are switched on. By contrast, the instantaneous current value when energizing onto a (50 Hz) short-circuit (1) is significantly less. This means that, given equivalent current amplitude values, switching capacitors on is much harder than energizing onto a short-circuit.



Parallel connection of capacitors



Current when switching on capacitors

Switchgear requirements:

Safe control of very high making currents up to 20 kA at frequencies of several kilohertz.

To avoid an impermissible load onto the switching contacts, the limit values of the transient making current must be observed. The following making currents (peak values) are permissible for Siemens circuit-breakers:

- $I_e \leq 10$ kA for vacuum circuit-breakers without any knowledge of the damping time constant or frequency
- $I_e \leq 20$ kA for vacuum circuit-breakers with knowledge of the frequency up to a maximum of 4250 Hz

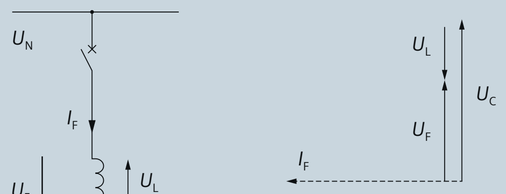
The limit for plate contacts is based on the tendency towards contact welding if the making current does not decay quickly enough in the pre-arcing time (1 to 2 ms) of the closing-on movement. If the making current is greater than the limit values specified, then agreement with the circuit-breaker manufacturer is required. If the amplitude quickly decays below the limit value, then greater starting values for the making current are permissible.

The 20 kA limit value for the parallel making current marks the rated making current recommended by the circuit-breaker standard for parallel capacitor banks, and can optionally be used as a rated value.

Filter circuits:

When switching off filter circuits or reactor-capacitor banks, the stress on the circuit-breaker arising from the recovery voltage is greater than just for capacitors. This is due to the properties associated with the series connection of coil and capacitor. When the same current flows through both elements, the voltage at the capacitor and coil is phase-shifted through 180°. The capacitor voltage U_C is thus greater than the system voltage by the amount of the coil voltage U_L. After switching off, the higher voltage U_C is present at the circuit-breaker, as the capacitor stores the electric charge. The capacitor voltage, and therefore also the stress on the circuit-breaker, depends on the filter circuit frequency. A circuit-breaker, with a higher rated voltage may be required.

Switching of capacitors and filter circuits



$$U_C = U_N \cdot \frac{\nu^2}{\nu^2 - 1} \quad \text{mit } \nu = \frac{F}{f_N}$$

U_N System voltage
U_L Coil voltage
U_C Capacitor voltage
U_F Voltage at filter circuit

F_F Filter frequency
f_N Power frequency
I_F Current through filter circuit

Voltages in filter circuits

Switchgear requirements:

Safe control of considerably higher recovery voltages in the filter circuit.

How is the suitability of switching devices for switching capacitor banks and filter circuits demonstrated?

The test requirements for switching capacitive currents are stated in IEC 62271-100 (High-voltage switchgear and control gear – Part 100: Alternating current circuit-breakers). According to this standard, tests are to be performed for the following applications among others:

- Switching off capacitor banks
- Switching on capacitor banks with connected capacitor banks (back-to-back)

An important criterion when switching off capacitive currents is the probability of restrike. It is divided into two classes:

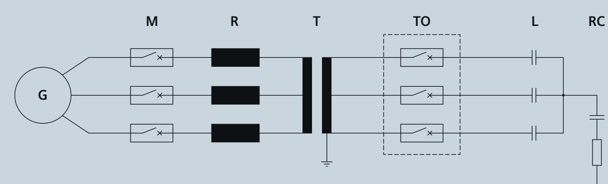
- Class C1:
  Low probability of restrike
- Class C2:
  Very low probability of restrike

The cited tests are generally performed on typical circuit-breakers, and also passed by those switching devices that are provided for such applications.

The IEC does not make any statements concerning the switching of filter circuits. For this reason, Siemens has specified its own test conditions, derived from practical experience:

When switching filter circuits, the maximum stress levels arise when the lowest center frequency is switched. This is why the characteristic values of the test object were tuned to the 2nd harmonic (n = 2; 120 Hz for a 60 Hz network)

The filter circuit was simulated with a capacitor bank on the load side of the test object. The reactor was on the supply side between the generator and transformer. This system establishes conditions that are comparable with switching a real filter circuit.



G Generator
M Making switch
R Reactor
T Transformer
TO Test object
L Load, here: capacitors
RC RC circuit

Circuit diagram for filter circuit testing

Which switching devices can be used for switching capacitor banks and filter circuits?

Switching of capacitors for compensation, in particular with several banks connected to the switchgear, is a more complex task not all switching devices are suitable for. The capacitive currents are greater in this context than with no-load lines and cables. In addition, the capacitors may be configured to be connected in parallel, depending on the setup. Switching devices for this application must be tested to see if they satisfy the requirements.

Siemens vacuum circuit-breakers are most suitable for this stress. Almost all circuit-breakers are approved for switching capacitor banks, as they have successfully passed tests of class C2 according to IEC 62271-100 for capacitive switching.

Switching of capacitors and filter circuits

For capacitors to switch off without restriking, no particles may cause the switching contacts to restrike after current zero. Suitable contact material and clean room production of extremely high quality mean that this effect can virtually be eliminated. The material of which the switching contact is made will influence the making capacity. Thus, contacts with a high percentage of chromium are more suitable, for example.

The operating voltage also influences the capacitive switching behavior. At low voltages, the dielectric stress between contacts is substantially less than is the case at high voltages. This means that, for really high recovery voltages, special measures are required on the vacuum interrupters and the circuit-breaker operating mechanism to switch without restriking.

The ability of a circuit-breaker to switch two or more capacitors in parallel basically depends on the capacitive making current, the frequency, and also on the contact material of the vacuum interrupter and operating mechanism. Any pre-arcing that occurs when the contacts close always causes the contact material to melt partially, and creates the risk of fusing the contacts in a closed position. This means that, after the capacitors are connected in parallel, the contacts must always be torn open with a certain amount of force. The force required for tearing open can be reduced by using a contact material which has a brittle component. For this reason, Siemens manufactures the contact material for these extreme requirements in its own factory.

Apart from the contact material, the operating mechanism of the switching device also has a great influence on the switching performance. To reduce the tendency towards welding, an adapted closing speed is required, which minimizes the bouncing or oscillation of the contact force as far as possible. To re-open slight bonding, which is impossible to avoid, the separation force during the opening operation needs to be strong enough. The interaction of all circuit-breaker components is of great importance, especially where the requirements are so high.

As described in the theoretical section, switching filter circuits is an even greater challenge than purely switching capacitors. Depending on the frequency of the filter circuit, the recovery voltage via the circuit-breaker contacts can increase by more than 30% in the worst case. It can then be seen how well the insulation coordination of the switching device has been implemented. Siemens has been able to accomplish this task up to operating voltages of 40.5 kV. Successful testing with recovery voltages of more than 100 kV shows that consistent elimination of effects, which negatively influence the dielectric strength, allows such high values to be controlled, even with only one vacuum interrupter. First of all, a precondition of this is the absolute purity of all components in the vacuum interrupters, an uninterrupted process chain in clean room conditions and, of course, specially selected contact material, which has also been manufactured under vacuum conditions.
An adjustment of the operating characteristics to these high requirements goes without saying.

Which medium-voltage switchgear is suitable?

As a general rule, all Siemens medium-voltage switchgear can be used to switch no-load cables and overhead lines. If capacitor banks are switched, then the circuit-breaker in air- or gas-insulated switchgear should be designed for higher stresses – in particular when connecting the capacitor banks in parallel. When switching filter circuits, the decision depends on the operating voltage of the network. Up to operating voltages of 24 kV, virtually any Siemens switchgear can be used; with small filter frequencies, e.g. 100 Hz corresponding to the 2nd harmonic, it may be necessary to select a switchgear of the next highest voltage rating.

Precisely this measure was used until now in the voltage range from 36 to 40.5 kV. At low filter frequencies, either two panels were connected in series or even a high-voltage circuit-breaker was used. This is now no longer necessary. With Siemens 8DA switchgear using newly developed vacuum interrupters, this measure is not required anymore. This means that less space is required and therefore less costs are incurred. This switchgear is particularly suited to switch capacitors and filter circuits safely at the medium-voltage level up to operating voltages of 40.5 kV. Thus, switchgear is now available which can also handle a high switching rate in such compensation tasks, i.e. up to 30,000 operating cycles.

Siemens has been able to accomplish this task with a single vacuum interrupter for voltages up to 40.5 kV.

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