Synchronous MV circuit-breaker with magnetic drive and electronic control

New synchronous circuit-breakers developed by ABB can be fully integrated in medium-voltage switchgear in order to provide synchronous functionality at the distribution level. Equipped with fully configurable software, such circuit-breakers offer flexible solutions that can be used in all types of network, eg to reduce switching transients. They extend the range of synchronous operation from capacitor bank switching to all distribution circuit-breaker applications, including the synchronous interruption of short-circuit currents. Advantages of the new breakers include high quality and reliability over their service life, reduced maintenance, improved availability and service continuity, as well as a potential cost-saving in the increasing number of applications in which power quality is important. By allowing networks to be simplified, they also help to reduce the overall power system costs.

In 1997 ABB introduced a new series of medium-voltage circuit-breakers with a magnetic drive instead of a spring-based operating mechanism [1]. This solution soon proved to be much more reliable than its predecessor. Following up on the success of the magnetic drive, ABB has now developed a new controlled switching technology which will allow the closing and opening operations to be synchronized with the power network.

Synchronous switching, also called ‘point on the wave’ switching, is a well-known concept [2,3], being used particularly in high-voltage applications to avoid or reduce switching transients and their power network disturbances.

The synchronous circuit-breaker has several important advantages over conventional switching equipment, eg:

- Transient stresses acting on network components are strongly reduced, enhancing reliability.
- The network exhibits a higher power quality.
- The electrical lifetime and performance of the circuit-breaker are improved.
- The network design can be simplified, thereby reducing the cost of the overall system.

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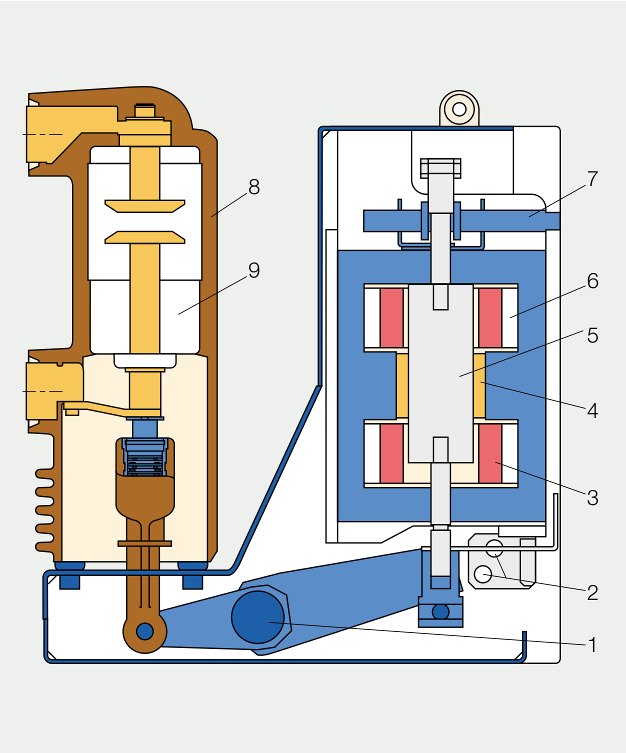
Electromechanical system

Manufacturers of synchronous circuit-breakers with a spring-based mechanism rely on the behaviour of the opening/closing operation being predictable. This means that the mechanism has to be designed with high excess energy and show minimal signs of wear and friction over its lifetime. It is also critical to keep the environmental influences under control. Extensive laboratory tests are therefore necessary, leading to algorithms that have to be implemented in an electronic controller.

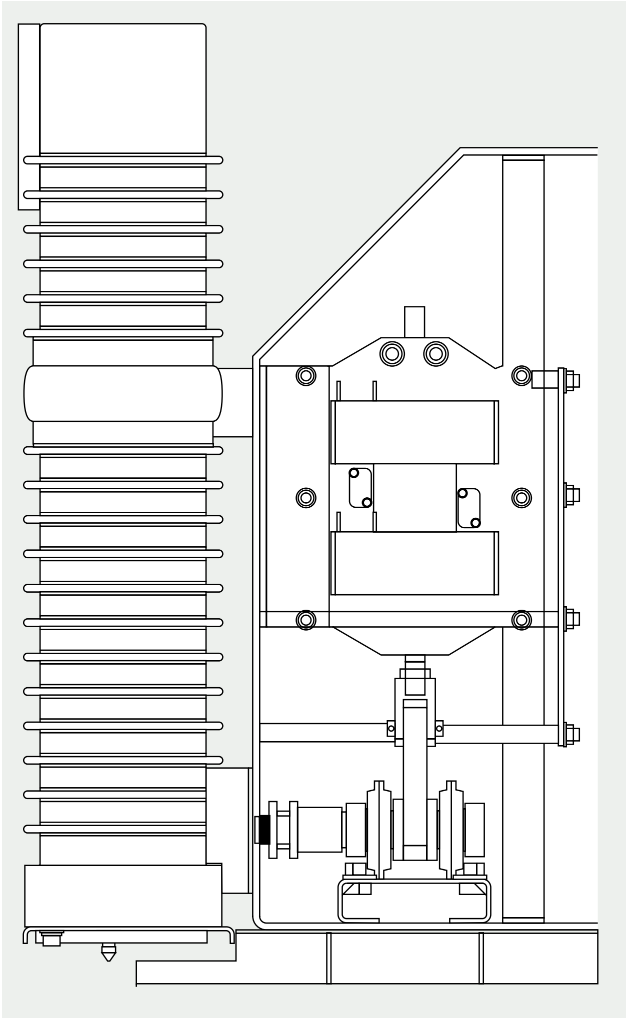
Not even all these features will ensure reliable behaviour, since the motion of the spring-based mechanism cannot be influenced after it has been released. A magnetic actuator, on the other hand, allows the adaptive algorithm to be implemented in a closed-loop control configuration. The motion can then be controlled and the influence of temperature, aging, etc, compensated for, guaranteeing that the operating time will remain stable in the long term.

Medium-voltage circuit-breakers nowadays usually consist of three mechanically connected poles and one drive. The drive can be a mechanical spring type or an electromagnetic actuator. Controlled switching for a very wide range of applications requires an individual drive for each pole. This is much easier to achieve with a magnetic actuator than with a mechanical drive. Furthermore, the repeatability of a magnetic drive is much better due to its smaller number of mechanical parts.



Section through the operating mechanism and pole compartment of a vacuum circuit-breaker **1**

1 *Lever shaft*
2 *Proximity sensors*
3 *Closing coil*
4 *Permanent magnets*
5 *Plunger*
6 *Opening coil*
7 *Emergency manual opening*
8 *Epoxy resin enclosure*
9 *Vacuum interrupter*



Section through the operating mechanism and pole compartment of an SF_6 gas-insulated circuit-breaker **2**

1 shows the simple mechanical construction of a vacuum circuit-breaker, in which the pole is connected to the actuator by a lever shaft. The SF_6 gas-insulated circuit-breaker shown in **2** has a similar mechanical structure, the actuator turning a shaft that leads into the SF_6 compartment of the pole. Inside the pole this rotational movement is transformed into a linear movement, which drives the moving contact. These principles are proven and well-established for non-synchronized breakers, which have one actuator driving all three poles in parallel.

The arrangement for individually driven poles is shown in **3** for the SF_6 circuit-breaker and in **4** for the vacuum circuit-breaker. Magnetic actuators allow a much simpler and more compact design than a mechanical drive. The SF_6 circuit-breaker is based on H Brea King poles manufactured by ABB SACE TMS, the vacuum circuit-breaker using VM1 poles. The vacuum interrupters of the VM1 poles, from ABB Calor Emag Mittelspannung GmbH in Germany, are embedded in epoxy resin to protect them against mechanical impact and pollution.

Synchronism with the network

A synchronous circuit-breaker (SCB) is a breaker which can carry out operations which are synchronized with network voltage or current signals, irrespective of when the starting signal is given and whether it is given manually or by remote control.

5 shows how a synchronous circuit-breaker should behave during a closing operation:

- The red line indicates the asynchronous closing signal sent to the circuit-breaker by the user or the control/protection systems.
- The green line shows the closing signal sent by the control electronics to the actuator, synchronized with the voltage signal or current signal.

- The brown line shows the closing instant when the voltage across the circuit-breaker is zero.

The task of the control electronics is to keep the operating time as constant as possible. To do this it must feature automatic adaptation as well as real-time closed loop control. Equipped with this capability, it will adhere to the specified tolerances even when there are changes in the ambient temperature, capacitor charge or any other relevant parameter. By automatically compensating for contact wear, the control electronics ensures that the contacts always open or close at the right instant.

Switching time tolerance

The basic function of the SCB is to perform switching operations with high reliability in a pre-defined time such that the expected reduction in transients is guaranteed, and to do this over its service life.

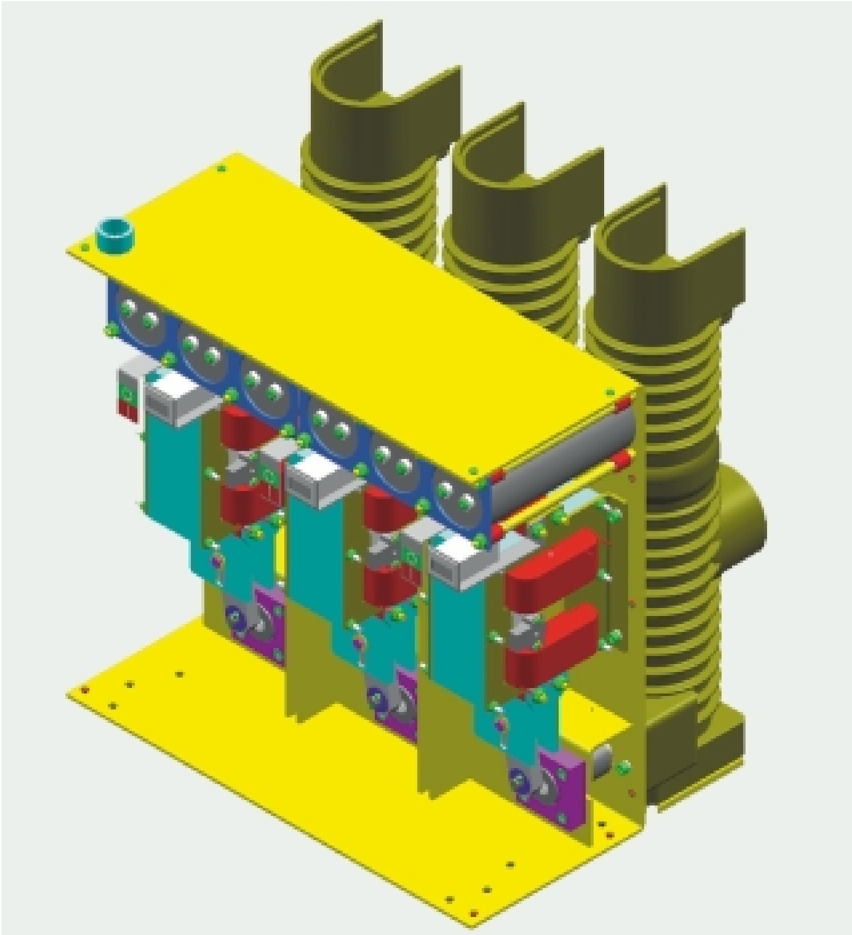
The switching time tolerance of the described SCB has the following maximum values:

± 1 ms for the closing operation
± 2 ms for the opening operation

Whereas the second value is mainly of importance (although not only) to the circuit-breaker manufacturer, the first value has a wider significance, being defined in the literature as the minimum value required for equal or better closing-transient behaviour than when the standard means for reducing such transients are used (*Table 1*) [4].

In order to guarantee these values over the complete lifetime of the circuit-breaker, the factory tests are carried out with a narrower tolerance range:

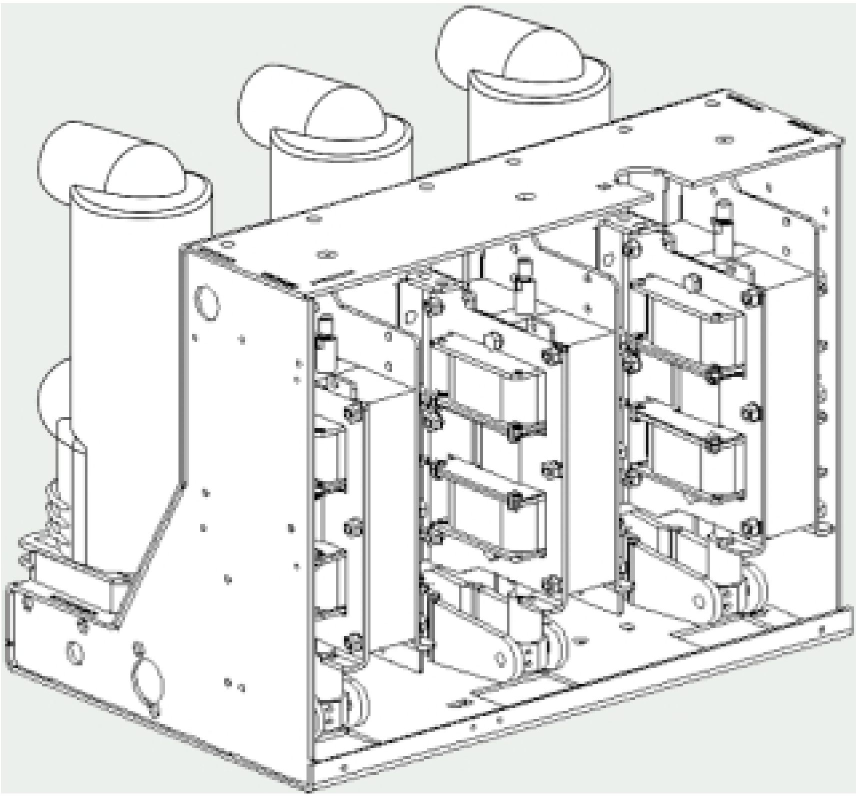
± 0.2 ms for the closing operation
± 1 ms for the opening operation



Arrangement of the actuators and poles of an SF_6 gas-insulated synchronous circuit-breaker **3**

Table 1
Comparison of methods used to reduce transients

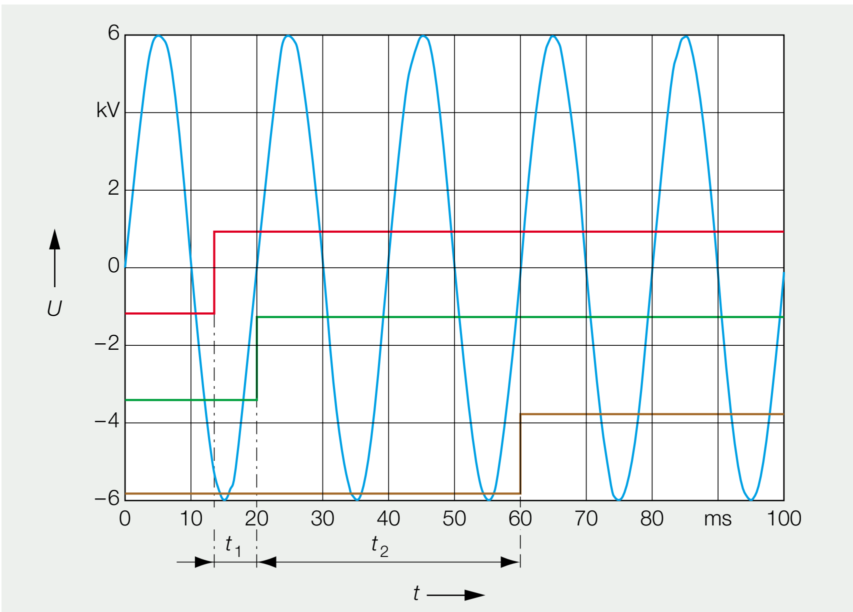
Transient control achieved with	Advantages	Disadvantages
Fixed inductor	Easy to employ Effective for reducing current	Losses & noise Life cost
Pre-insertion resistor	Inserted for short time prior to switching No losses	Complicated, low reliability
Pre-insertion inductor	Inserted for short time prior to switching No losses More effective than fixed inductor	Complicated, low reliability
Synchronous circuit-breaker (SCB)	Effective for reducing *I* and *U* during opening and closing operations Reduced breaker wear	Reliability and consistency problems with traditional SCB solution; problems overcome with new SCB



Arrangement of the actuators and poles of a vacuum synchronous circuit-breaker **4**

Typical closing operation with a synchronous circuit-breaker **5**

U	*Network voltage*	Red	*Asynchronous closing signal*
t	*Time*	Green	*Closing signal, synchronized with voltage or current signal*
t_1	*Synchronizing delay*		
t_2	*Operating time*	Brown	*Closing instant at zero*



Design of the synchronous circuit-breaker

6 shows the arrangement of the SCB control electronics. The signal processing and timing unit is the part of the SCB that handles the voltage and current signals. It receives the command to start the close/open operation and decides when the signal to open or close the following unit has to be given. The system controlling the pole operation checks that it is carried out within the given tolerance time range.

Control electronics hardware

7 shows details of the architecture of the control electronics. The signal processor and timing controller unit checks the power network currents and voltages and also manages the operation command. The control unit is interfaced with the magnetic actuators via the switching unit and the coil current sensors; it also controls the circuit-breaker poles by means of position sensor X.

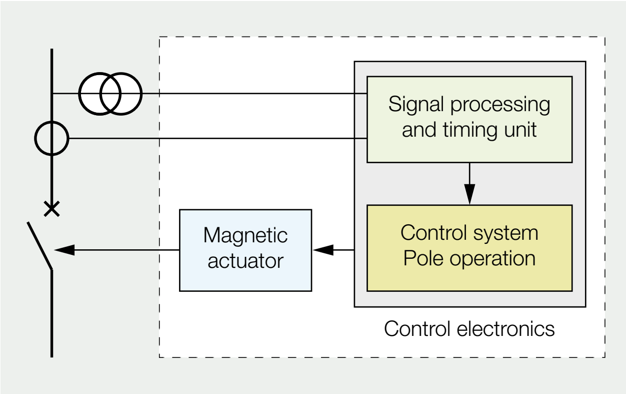
Control electronics software

The control electronics software can be divided into two main parts:

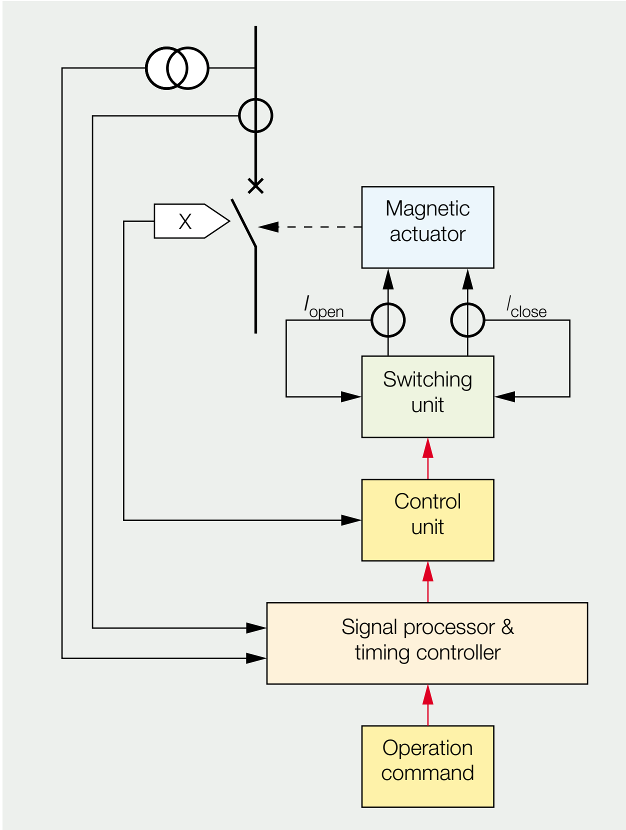
- The system software, which controls the interface with the hardware resources (digital signal processor core, 'on-chip' and external peripherals) and the time scheduling for the application software.
- The application software, which is responsible for the circuit-breaker position control, network quantities, zero-crossing calculation and man-machine interface.

Control unit functionality: application software

The main task of the control unit is to ensure that switching operations take place in the pre-assigned time.



Simple block diagram of the synchronous circuit-breaker control electronics **6**



Architecture of the synchronous circuit-breaker control electronics **7**

X *Position sensor*

Two phases are involved:

1) The current flows through the coil, charging the magnetic actuator, but the circuit-breaker pole does not yet move. This phase of the operation cannot be controlled directly by the software.
2) The pole starts to move and is 'guided' to make sure that the operation takes place at the correct time. This phase can be adapted within a certain range.

User-benefits of synchronous circuit-breakers

Advantages of reducing transients

Switching transients cause a variety of disturbances in distribution power systems. They range from poor power quality through untimely tripping of protection to unacceptable overvoltages, possibly causing severe damage and premature failure. While current transients are restricted to the switch location, transient overvoltages travel to remote locations, possibly affecting other users and propagating to different voltage levels.

Installing an SCB greatly reduces the stresses, overcurrent as well as overvoltage, that the network components experience during closing and opening operations under load. This has significant advantages, including higher power quality and increased system reliability.

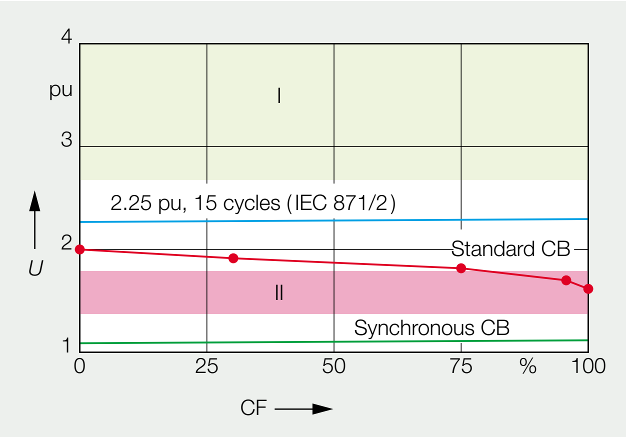
Network component stress is reduced

In the following, the effect of the reduced stress is evaluated for capacitor banks. Similar conclusions can be drawn for other components, eg insulation aging in cable and transformers, etc.

Capacitors are designed and manufactured to withstand the service rated conditions with a large margin. This capability is checked by type-testing in accordance with the requirements in IEC 871-2. According to this standard, switching overvoltage stresses have the highest influence on the aging of the capacitor dielectric and component failure modes. **8** shows the possible stresses experienced by capacitors as a consequence of switching operations with a standard circuit-breaker and with a synchronous circuit-breaker. It can be seen that the standard breaker generates overvoltages above the partial discharge inception voltage (PDIV), while the SCB limits the overvoltages to values below this level.

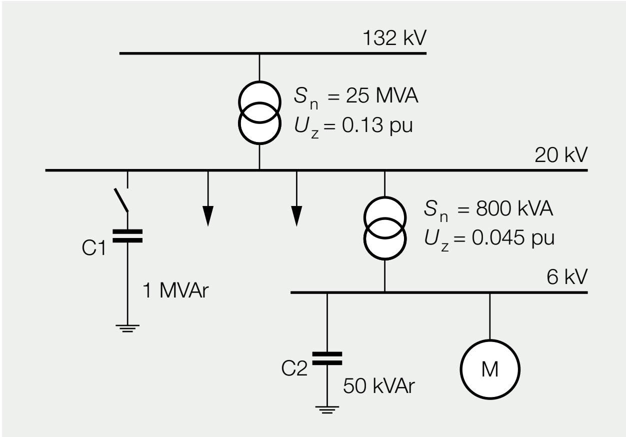
Voltage magnification phenomena or restrikes generate voltages in the area above the 2.6 pu stress level; this is much higher than the values used in endurance tests.

It is clear that limiting the closing transients to a value well below the PDIV for all the expected operating temperatures and



Voltage (U) versus cumulated frequency of overvoltages (CF) generated by standard and synchronous circuit-breakers 8

I Restrikes, magnifications
II Partial discharge inception voltage



Circuit diagram showing voltage magnification caused by transients generated by switching loads 9

C1 *Capacitor bank 1, switched*
C2 *Capacitor bank 2, exposed to voltage magnification*
M *Motor*
S_n *Apparent power*
U_z *Impedance voltage*

reducing the restrike probability to virtually zero will have a beneficial effect on the service life of the insulation. Such a solution totally removes the partial discharge failure mechanism and greatly reduces the electrical aging processes occurring during transients.

Voltage magnification

Transients generated by switching loads can cause resonances that lead to worse transients, called 'voltage magnification', in other sections of the network. This is especially the case with capacitor bank switching transients, which propagate to other voltage levels (MV or LV) when the natural frequencies of two coupled parts of the network are equal or similar, causing overvoltages of up to 4 pu at the remote bank location 9, 10.

When an SCB is used, the overvoltages caused by switching loads (especially capacitor banks) can be drastically reduced. The advantages of this are highly significant at the medium-voltage and low-voltage levels, where such overvoltages can easily lead to dielectric faults.

Circuit-breaker electric life enhancement

The electrical service life of a circuit-breaker depends mainly on the arcing energy the breaker is subjected to. This is because of the relationship between the electrical stress and the arcing energy that the interrupters have been exposed to, resulting in contact wear, dielectric stress, overtemperature and overpressure, gas wear, etc. Reducing the arcing energy by operating each phase independently and reducing the arcing time therefore lowers these forms of stress. The expected service life of the circuit-breaker is thus extended through an increase in its electrical life, minimizing the thermal requirements of the interrupter as well as the mechanical requirements of the drive actuator. In addition, synchronous opening of fault currents can increase the interrupting capacity of the circuit-breaker.

Taking the electrical endurance test in IEC 56 as reference, it can be said that the SCB allows a reduction in the electrical stress of at least 50 % for both vacuum and SF_6 interrupting technologies in the worst-case situation.

Considerable economic advantage can be derived from a reduction in circuit-breaker wear and therefore increased lifetime, particularly for applications in which rated current is interrupted very frequently and reconditioning or replacement of the breaker poles has to be scheduled on a yearly basis.

Restrike performance

Improvements made over the years to traditional circuit-breaker technology have greatly reduced the probability of restrikes. However, as the switching frequency can be high in industrial networks, the probability that overvoltages will occur cannot be neglected.

It also has to be said that restrikes sometimes occur in service despite the use of switching devices which are 'restrike free' as defined in the specifications. To take account of this the IEC 56 draft, which is currently under revision, introduces a new concept: 'As all circuit-breakers have a certain restrike probability in service, it is not possible to define a restrike-free circuit-breaker. It appears to be more logical to introduce the notion of a restrike performance in service.'

The basic nature of a restrike transient is identical to that of inrush transients, but, due to the increased magnitude, it may be damaging to power system equipment and make heavy demands on the switching device.

Synchronization enhances the 'restrike-free' capabilities of circuit-breakers by opening the poles independently long before the natural current zero occurs. Thus, although the total arcing time and energy are minimized, a certain arcing time is provided to ensure proper contact separation and the dielectric strength needed at the time of maximum TRV, essentially eliminating reignitions and restrikes as well as the associated overvoltages.

Reliability

The reduced stress experienced by the circuit-breaker during switching operations leads to higher reliability. Although breaker failures play only a minor role in the frequency of network failures, they typically have severe consequences because of the loss of selectivity.

The improved restrike performance translates into even lower circuit-breaker stress and a smaller risk of damage to the switching equipment and other network components.

The SCB therefore has an additional beneficial impact on the network and on the supply reliability and power quality.

Power quality

In today's competitive energy markets, power quality is becoming an important performance indicator. The increasing use of power electronics means that transients, once considered as acceptable minor variations, may give rise to unexpected failure modes, leading ultimately to a significant loss of industrial production.

Adjustable-speed drive tripping

Adjustable-speed drives (ASDs) are being used increasingly in industry to improve the efficiency and flexibility of motor applications.

The tripping of ASD overvoltage protection is often referred to as 'nuisance tripping', since it may occur day after day, often at the same time. The fact that capacitors connected to the MV busbar are operated at least daily means that nuisance tripping is also a potential cause of frequent standstills. Another problem is that ASDs often operate in critical process control environments, so nuisance tripping can be very disruptive and potentially costly. Even when very conservative failure rates are assumed, the total cost of tripping can easily be several times the cost of installing a synchronous circuit-breaker.

Reduction of transformer inrush current

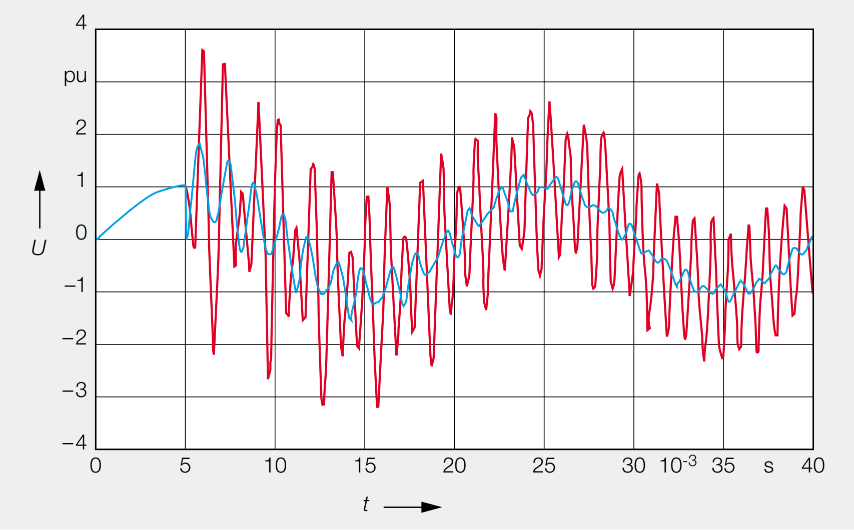
The use of an SCB can greatly reduce the inrush current when a transformer is energized, thus avoiding the statistical occurrence of protection tripping and other problems related to the heavy harmonic content of inrush currents.

Optimum closing strategies have been evaluated on the basis of the residual flux that needs to be considered when energizing a transformer. In such cases, it is necessary to know the residual flux after the last opening (the direction of the flux is especially important). A closing strategy that neglects the transformer residual flux will lead to anything but optimum conditions. However, even in this case, the worst conditions that can occur with conventional circuit-breakers can be avoided by using a synchronous circuit-breaker.

In the worst case, inrush currents are of the order of 8–15 times the transformer full-load current rating [2]. *Table 2* shows the reduction in inrush current obtained with controlled closing, the data being based on modelling of a specific transformer behaviour. A comparable current reduction is expected for other winding configurations and ratings.

Better protection and selectivity

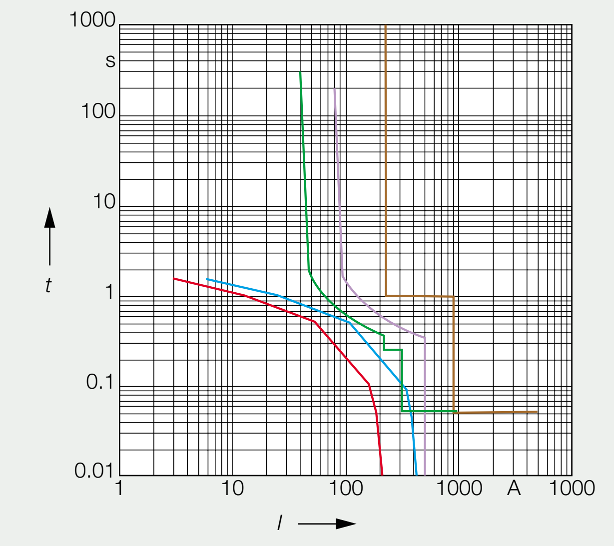
The reduction of transformer inrush currents to negligible values allows wider margins when selecting the protection relay curves and avoids unnecessary trips. Other benefits are that it allows concurrent energization of several transformers, together with small power generators, and eliminates a typical



Switching capacitor bank* C1 *causes a typical overvoltage of 1.8 pu at* C1 *(blue curve), and more than 3.5 pu at* C2 *(red curve) due to magnification. **10**

U *Voltage*

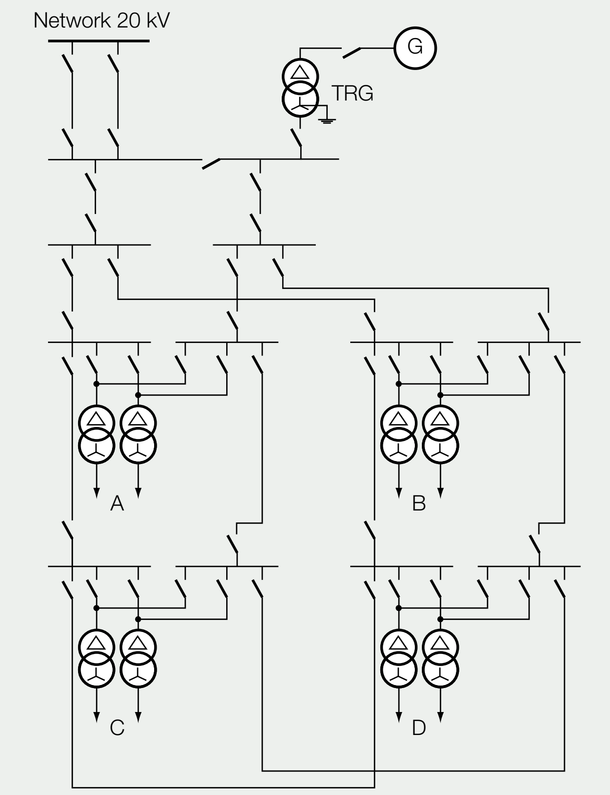
t *Time*



Time-current protection diagram in which two transformer inrush curves intersect with the circuit-breaker curve **11**

Red *Inrush current, one transformer*
Blue *Inrush current, two transformers*
Green *Breaker B*
Pink *Breaker A*
Brown *Utility protection curve*

I *Current*
t *Time*



Schematic of the energy network at Fiumicino (Rome) airport **12**

A, B, C, D *Transformers A, B, C, D*
G *Standby generator*
TRG *Generator transformer*

cause of fuse aging. This considerably improves power availability.

In a typical time-current diagram of protection coordination **11**, selectivity is ensured when the curves of the equipment on the load side are located below those of the equipment on the supply side. The limits are given in the upper part by the tripping curve of the equipment in the network on the load side of the plant, and in the lower part by the inrush curve of the transformers.

These often stringent limits result in a curve 'crush', preventing suitable tolerances from being applied to the thresholds and risking possible untimely tripping. This often prevents the concurrent energization of several transformers in parallel.

Example of concurrent energization made possible by SCBs

At Fiumicino (Rome) airport only one transformer can be energized at a time under emergency conditions **12**. This is because of the time interval that is needed until energization of the following transformer in order to avoid protection tripping of the generator. The result is a long and complex

Table 2
Reduction of transformer inrush currents (peak value) in pu when SCB is used

Case	Switching device	Inrush [pu]
Residual flux present; worst case	Circuit-breaker	up to 7.5
Residual flux present; closing strategy disregards value	SCB	up to 3.0
Residual flux present; optimal closing strategy	SCB	0.05

SCB *Synchronous circuit-breaker*

procedure for energizing the emergency loads after loss of the network supply. Use of synchronous circuit-breakers shifts the inrush to the left in the time-current protection diagram, allowing easier and more reliable protection coordination as well as concurrent energization of all the emergency loads. Significantly reduced downtime is the result.

Table 3
Available ratings in first step

SCB	Rated voltage	Rated current	Breaking current
SF_6	12 kV	630 / 1250 A	20-25-31.5 kA
	17.5 kV	630 / 1250 A	16-20-25 kA
	24 kV	630 / 1250 A	16-20-25 kA
Vacuum	12 kV	630 / 1250 A	20-25-31.5 kA
	17.5 kV	630 / 1250 A	16-20-25 kA
	24 kV	630 / 1250 A	16-20-25 kA

SCB *Synchronous circuit-breaker*

Methods of reducing switching transients

The most effective way to reduce switching overvoltages is to use appropriate switching equipment. The protection of sensitive equipment by means of surge arresters, chokes or higher insulating levels is expensive and not always effective. Alternative, traditional methods designed to avoid switching transients are compared in *Table 1*. A synchronous circuit-breaker offers a simpler, more cost-effective solution than, for example, fixed or pre-insertion inductors or pre-insertion resistors [5].

The SCB allows effective reduction of the current as well as the voltage transients. Both opening and closing synchronous operation can be handled by configuring the software of the control electronics to suit the circuit-breaker installation. The SCB is also much more flexible in load operation.

Summary

The described SCB is designed as a turnkey device for full integration in medium-voltage switchgear, thereby providing synchronous functionality at the distribution level. *Table 3* shows the ratings of the first SCBs scheduled to be launched.

ABB synchronous circuit-breakers are multi-purpose, flexible devices with fully configurable software. They extend the range of synchronous operation from capacitor bank switching to all distribution circuit-breaker applications, including the synchronous interruption of short-circuit currents.

The SCBs offer flexible solutions that can be used in all types of networks, eg isolated networks and compensated power systems with an extinguishing arc coil, a neutral connected to the ground by means of a resistor, and a strongly grounded neutral.

Synchronous circuit-breakers offer high quality and reliability over their expected service life. In addition, maintenance requirements are reduced, availability and service continuity are improved, and a cost-saving is possible in the increasing number of applications in which power quality is important.

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