10 High-voltage apparatus

10.1 Definitions and electrical parameters for switchgear

Disconnectors are mechanical switching devices which provide an isolating distance in the open position. They are capable to open or close a circuit if either a negligible current is switched or if there is no significant change in voltage between the terminals of the poles. Currents can be carried for specified times under normal operating conditions and under abnormal conditions (e.g. short circuit). Currents of negligible quantity have values $\leqq$ 0.5 A; examples are capacitive charging currents for bushings, busbars, connections, very short lengths of cable and currents of voltage transformers.

Isolating distances are gaps of specified dielectric strength in gases or liquids in the open current paths of switching devices. They must comply with special conditions for the protection of personnel and installations and their existence must be clearly perceptible when the switching device is open.

Switches are mechanical switching devices, which not only make, carry and interrupt currents under normal conditions in the network but also must carry for a specific time and possibly make currents under specified abnormal conditions in the network (e.g. short circuit).

Switch disconnectors are switches which satisfy the requirements for an isolating distance specified for a disconnector in their open position.

Circuit-breakers are mechanical switching devices able to make, carry and interrupt currents occurring in the circuit under normal conditions, and can make, carry for a specified time and break currents occurring in the circuit (e.g. short circuit) under specified abnormal conditions.

Earthing switches are mechanical switching devices for earthing and short-circuiting circuits. They are capable of carrying currents for a specified time under abnormal conditions (e.g. short circuit). They are not required to carry normal operating currents. Earthing switches for transmission networks may also be required to make, carry and break induced currents (capacitive and inductive) under normal circuit conditions. Earthing switches with short circuit making capability shall be able to make the short-circuit current.

Fuses are switching devices that open the circuits in which they are installed by the melting of one or more parts specified and designed for the purpose of breaking the current when it exceeds a given value for a sufficiently long period.

Auxiliary switches must be rated for a continuous current of at least 10 A and be capable to break the current of the control circuits. The manufacturer must provide details. In the absence of such information, they must be capable of breaking at least 2 A at 220 V d.c. at a minimum circuit time constant of 20 ms. The terminals and wiring in auxiliary circuits must be designed for at least 10 A continuous current. The auxiliary switches that are actuated in connection with the main contacts must be directly actuated in both directions.

Electrical characteristics

(Peak) making current: peak value of the first major loop of the current in one pole of a switching device during the transient period following the initiation of current during a making operation.

Peak current: peak value of the first major loop of current during the transient period following initiation.

Breaking current: current in one pole of a switching device at the instant of initiation of an arc during a breaking process.

Breaking capacity: value of the prospective breaking current that a circuit-breaker or load switch can break at a given voltage under prescribed conditions for application and performance; e.g. overhead line (charging current) breaking capacity.

Short-line fault: short circuit on an overhead line at a short but not negligible distance from the terminals of the circuit-breaker.

Out of phase (making or breaking) capacity: making or breaking capacity for which the specified conditions for use and behaviour include the loss or the lack of synchronism between the parts of an electrical system on either side of the circuit-breaker.

Applied voltage: voltage between the terminals of a circuit-breaker pole immediately before making the current.

Recovery voltage: voltage occurring between the terminals of a circuit-breaker pole after interruption of the current.

Opening time: interval of time between application of the auxiliary power to the opening release of a switching device and the separation of the contacts in all three poles.

Closing time: interval of time between application of the auxiliary power to the closing circuit of a switching device and the contact touch in all poles.

Break time: interval of time between the beginning of the opening time of a switching device and the end of the arcing time.

Make time: interval of time between application of the auxiliary power to the closing cuircuit of a switching device and the instant in which the current begins to flow in the main circuit.

Rated value: value of a characteristic quantity used to define the operating conditions for which a switching device is designed and built and which must be verified by the manufacturer.

Rated normal current: the current that the main circuit of a switching device can continuously carry under specified conditions for use and behaviour. See below for standardized values.

Rated short-time withstand current: current that a switching device in closed position can carry during a specified short time under prescribed conditions for use and behaviour. See below for standardized values.

Rated voltage: upper limit of the highest voltage of the network for which a switching device is rated. See below for standardized values.

Additional rated values:
rated withstand current,
rated making current,
rated short-circuit breaking capacity etc.

Standard value: rated value based on official specifications to be used for designing a device.

Standardized rated voltages: 3.6; 7.2; 12; 17.5; 24; 36; 52; 72.5; 100; 123; 145; 170; 245; 300; 362; 420; 550; 800 kV.

Standardized rated normal currents: 200; 250; 400; 500; 630; 800; 1000; 1250; 1600; 2000; 2500; 3150; 4000; 5000; 6300 A.

Standardized rated short-time currents: 6.3; 8; 10; 12,5; 16; 20; 25; 31,5; 40; 50; 63; 80; 100 kA.

Rated insulation level: standardized combination of the rated values for the lightning impulse withstand voltage, the switching impulse withstand voltage (if applicable) and the short-time power frequency withstand voltage assigned to a rated voltage. As standardized insulation level, only combinations of values from one and the same line of Table 10-1 are valid.

Rated short-duration power frequency withstand voltage: rms value of the sinusoidal a.c. voltage at operating frequency that the insulation of a device must withstand under the specified test conditions for 1 minute.

Rated lightning impulse withstand voltage: peak value of the standard voltage surge 1.2/50 µs that the insulation of a device must withstand.

Rated switching impulse withstand voltage: peak value of the unipolar standard voltage surge 250/2500 µs which the insulation of a device with a rated voltage of 300 kV and above must withstand.

Note:

For disconnectors and specific (asynchronous) circuit-breakers for rated voltages of 300 kV and above, the isolating distances or breaker gaps are tested with combined voltage so that the power frequency test voltage (Table 10-1, peak values in parentheses) is applied at one terminal and the counterpolar test surge voltage (lightning or switching) occurs in the time range of the maximum voltage at the other terminal. The test with combined voltage was originally known as the bias test.

Table 10-1

Standardized rated insulation level for disconnectors, switches, circuit-breakers and earthing switches according to DIN EN 60 694 (VDE 0670 Part 1000)

Rated voltage kV (rms value)	Rated short-duration power frequency withstand voltage kV (rms value)		Rated lightning impulse withstand voltage kV (peak value)	
	Phase to earth, between the phases and across the open breaker gap	Across the isolating distance	Phase to earth, between the phases and across of the open breaker gap	Across the isolating distance
1	*2*	*3*	*4*	*5*
3.6	10	12	20 40	23 46
7.2	20	23	40 60	46 70
12	28	32	60 75	70 85
17.5	38	45	75 95	85 110
24	50	60	95 125	110 145
36	70	80	145 170	165 195
52	95	110	250	290
72.5	140	160	325	375
100	150 185	175 210	380 450	440 520
123	185 230	210 265	450 550	520 630
145	230 275	265 315	550 650	630 750
170	275 325	315 375	650 750	750 860
245	360 395 460	415 460 530	850 950 1 050	950 1 050 1 200

(continued)

Table *10-1 (continued)*

Rated voltage kV (rms value)	Rated short-duration power frequency withstand voltage kV (rms value)		Rated lightning impulse withstand voltage kV (peak value)		Rated switching impulse withstand voltage kV (peak value)		
	Phase to earth and between the phases	Across the open breaker gap and/or isolating distance	Phase to earth and between the phases	Across the open breaker gap and/or isolating distance	Phase to earth and across the open breaker gap	Between the phases	Across the isolating distance
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
300	380	435	950	950 (+ 170)	750	1 125	700 (+ 245)
			1 050	1 050 (+ 170)	850	1 275	
362	450	520	1 050	1 050 (+ 205)	850	1 275	800 (+ 295)
			1 175	1 175 (+ 205)	950	1 425	
420	520	610	1 300	1 300 (+ 240)	950	1 425	900 (+ 345)
			1 425	1 425 (+ 240)	1 050	1 575	
550	620	800	1 425	1 425 (+ 315)	1 050	1 680	900 (+ 450)
			1 550	1 550 (+ 315)	1 175	1 760	
800	830	1 150	1 800	1 800 (+ 455)	1 300	2 210	1 100 (+ 650)
			2 100	2 100 (+ 455)	1 425	2 420	

The values in parentheses are the peak values of the a.c. voltage applied to the opposite terminal.

10.2 Disconnectors and earthing switches

Disconnectors are used for galvanic isolation of networks or sections of switchgear installations. As an independent air-insulated device, they form a visible isolating distance in their open position. They are suitable for switching small currents (< 0.5 A) or also larger currents if the voltage does not change significantly between the contacts of a disconnector pole during switching (commutation currents).

Disconnectors can carry currents under operating conditions continuously and under abnormal conditions, such as short circuit, for a specified time (1s, 3s).

More than 10 different designs are in use around the world. The most important are rotary disconnectors, two-column vertical break disconnectors and single-column disconnectors.

Earthing switches are used for earthing and short-circuiting deenergized station components. Earthing switches can withstand currents during a specified time (1s, 3s) under abnormal conditions, such as a short circuit, but they are not required to carry continuous operating currents.

In general, earthing switches are combined with the adjacent disconnectors to form one unit. However, earthing switches can also be installed separately.

The applicable standard for disconnectors is DIN EN 60 129 (VDE 0670 Part 2). IEC 61128 is specifically applicable for switching commutation currents with disconnectors.

DIN EN 60 129 (VDE 0670 Part 2) is also applicable for earthing switches. In addition, DIN EN 61 129 (VDE 0670 Part 212) shall be considered with reference to switching induced currents.

Selection of the disconnector design is primarily guided by the layout of the installation (structural design), see Section 11.3.3. The ABB disconnector range can cover virtually all important layout variations in the ranges 72.5 to 800 kV, (rated voltage), 1250 to 4000 A (rated current) and 63 to 160 kA (rated peak withstand current).

10.2.1 Rotary disconnectors

Two-column rotary disconnectors SGF

This disconnector type is used by ABB for rated voltages of 72.5 to 420 kV (in individual cases also for 525 kV), preferably in smaller installations and also in larger switchgear installations as incoming feeder or sectionalizing disconnector. An earthing switch can be installed on both sides.

As shown in Fig. 10-1, the two rotating bases are mounted on a sectional steel frame and connected by a braced tie-rod. The insulators (post insulators) are fixed to the rotating bases and carry the swivel heads with the arms and the high-voltage contacts. Both arms swivel 90 degrees with their insulators during the switching movement.Two-column rotary disconnectors in their open position form a horizontal isolating distance. The rotary bases are weather protected and have maintenance-free ball bearings. The rotary bases are fastened on stay bolts, which allow precise adjustment of the contact system after the lines have been rigged and also compensate the insulator tolerances.

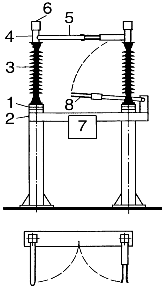


Fig. 10-1

Two-column rotary disconnector type SGF 123 kV, 1 Rotating base, 2 Frame, 3 Post insulator, 4 Rotating head, 5 Contact arm, 6 High-voltage terminal, 7 Mechanism, 8 Earthing switch

The swivel arms are an aluminium-welded construction with non-corroding contact joints, thereby eliminating any long-term changes in resistance. Disconnectors ≥ 170 kV have an interlocking mechanism (pawl and pin). This prevents the contacts from opening at high short-circuit currents. The current in the maintenance-free swivel heads, which are protected against external influences, is transferred via contact fingers arranged in a tulip shape around two contact pins, or for operating currents > 2500 A via tapered roller contacts. The high-voltage contacts can be rotated 360 degrees, allowing the tube or wire runs to be connected in any direction. The contact system has separately sprung contact fingers with no exposed springs.

The disconnectors and earthing switches have an operating mechanism with dead-centre interlocking. This prevents its position from being changed by extreme external influences, such as short circuits, earthquake or high winds. Disconnectors and earthing switches have separate mechanisms. For rated voltages of up to 300 kV, a three-pole disconnector or earthing switch group is generally actuated with one mechanism each. The individual poles of one group are mechanically linked by a connecting rod. The torque is transferred by the mechanism to a rotating base and rotates it by 90 degrees. The tie-rod rotates the second rotating base simultaneously. The contacts make both a rotary and a sliding movement when opening and closing the disconnector. This easily breaks heavy icing. The torque of the earthing switch is transferred to the shaft of the earthing switch. On closing, the arm of the earthing switch swivels upwards and meets the earthing contact attached to the swivel arm.

Three-column rotary disconnectors TDA

These ABB disconnectors are primarily used outside Europe with a side-by-side configuration of the three poles of a group. In comparison to two-column rotary disconnectors, they allow smaller pole spacings and higher mechanical terminal loads.

The two outer insulators are fixed to the base frame and carry the contact system (Fig. 10-2). The middle insulator is fastened to a rotating base and carries the one-piece arm, which rotates approximately 60 degrees during a switching operation and engages the contact systems on the outer insulators. The earthing contacts of the earthing switches, which can be mounted on either side, are located at the fixed contact system.

The three-column rotary disconnectors have the same components as the two-column rotary disconnectors described above. The same information applies for contact arm, swivel bases, contact system and interlocking mechanism, centre-point interlock, earthing switch and mechanical connection of the poles.

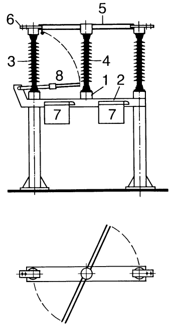


Fig.10-2

Three-column rotary disconnector type TDA, 145 kV, 1 Swivel base, 2 Frame, 3 Post insulator, 4 Rotating insulator, 5 Contact arm, 6 High-voltage terminal, 7 Mechanisms, 8 Earthing switch

10.2.2 Single-column (pantograph) disconnector TFB

In installations for higher voltages (≥ 170 kV) and multiple busbars, the single-column disconnector (also referred to as pantograph or vertical-reach disconnector) shown in Fig. 10-3 requires less space than other disconnector designs. For this reason and because of the clear station layout, it is used in many switchgear installations. The switch status is clearly visible with the vertical isolating distance.

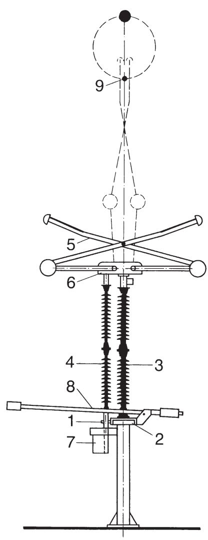


Fig.10-3

Single-column disconnector type TFB 245 kV, 1 Rotating bearing, 2 Frame, 3 Post insulator, 4 Rotating insulator, 5 Pantograph, 6 Gearbox, 7 Mechanism, 8 Earthing switch, 9 Fixed contact

The base of the disconnector is the frame, which holds the post insulator carrying the head piece with the pantograph and the gearbox. The actuating force is transferred through the rotating insulator to the gearbox. The suspended contact is mounted on the busbar situated above the disconnector. On closing, it is gripped between the pantograph arms. During the closing movement, the pantograph arms swivel through a wide range and are therefore capable of carrying the fixed contact even under extreme position changes caused by weather conditions. The feeder line is connected to the high-voltage terminal of the gearbox. In general, the single-column disconnector allows higher mechanical terminal loads than the two-column rotary disconnector.

The frame with the rotary bearing for the rotating insulator is fastened to the support with four stay bolts. They allow the disconnector to be accurately adjusted relative to the suspended contact.

The pantograph is a welded aluminium construction. It is fixed to the gearbox with the pantograph shaft by pins, preventing the pantograph unit from moving during the entire lifetime. This also ensures long-term high contact pressure between the contacts of the pantograph and the fixed contact. A contact force of 700 to 1500 N (depending on the pantograph design) not only ensures secure current transfer but also breaks heavy icing. Tapered roller contacts transfer current from the gearbox to the lower pantograph arms and make the connection from the lower to the upper pantograph arm.

The contact bars on the top of the pantographs and the fixed contact are silver-coated copper, for heavy duty or special cases they have a fine silver inlay. This results in low contact erosion, good current transfer and long service intervals.

Disconnectors for high short-circuit currents have a damping device between the arm joints. In the event of a short circuit, it prevents any reduction in the contact pressure and damps the oscillations of the pantograph caused by the short-circuit current.

The single-column disconnectors have a centre-point interlock in the gearbox and therefore cannot change their position spontaneously. It retains the switch position in any case, even if the rotating insulator breaks or if the disconnector is subjected to extreme vibrations caused by earthquakes or short-circuit forces. Anti-corona fittings on the ends of the arms act as a stop for the suspended contact if it moves in a vertical direction. Even under high tensile forces, it is securely held in the contact zone in the event of a short circuit.

Special designs of single-support disconnectors have been used in installations for high-voltage direct current transmission (HDVC) for many years.

A rotary-linear earthing switch (Section 10.2.4) can be installed on every disconnector pole.

In general, single-column disconnectors and the associated earthing switches are actuated by one mechanism each per pole.

Suspended contact for commutating current switching with single-column disconnector (bus-transfer current switching)

When switching between busbars without current interruption in outdoor switchgear installations, commutation currents occur during the switching operation and cause increased contact erosion on the contact bars of the disconnector and on the suspended contact. The height of the currents depends on the distance of the switching location from the power supply and the type of switchover, i.e. whether between busbars or switch bays, with the latter causing the higher stress. The commutation voltage can be calculated.

Commutation processes occur both on closing and opening. Closing causes bouncing between the contact bars and the suspended contact, which causes only slight arcing and a low degree of contact erosion. However, opening causes arcing between the opening contact bars that continues until the inverse voltage for quenching the arc has been generated. Because of the slow start of the movement of the contact bars, this process lasts for several cycles and causes significant stress on the disconnector contacts. Heavy-duty 420-kV outdoor switchgear installations can have commutation voltages up to 300 V and commutation currents to approximately 1500 A.

The ABB-developed commutation suspended contact for single-column disconnectors has two independently operating enclosed auxiliary switching systems. This ensures proper function in every case, regardless of which of the two contact bars on the pantographs is first to touch or last to leave the suspended contact. The most important components are illustrated in Figs. 10-4 and 10-5. The auxiliary switching system built into an anti-corona hood consists of a spring contact – connected to the auxiliary contact bar by a toggle lever – and a deion arc-quenching device. The spring contact is opened and closed independently of the switching speed at a defined position of the auxiliary contact bar.

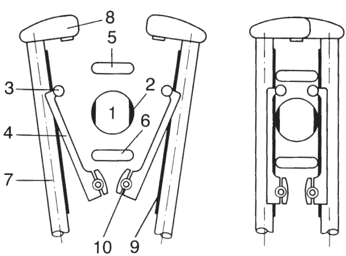


Fig.10-4

Commutating suspended contact, operating principle of guide strips,
1 Main contact support, 2 Main contact bar, 3 Auxiliary contact bar, 4 Toggle lever, 5 Upper guide strip, 6 Lower guide strip, 7 Pantograph arm, 8 Catch device, 9 Pantograph contact bar, 10 Insulated pivot with reset spring

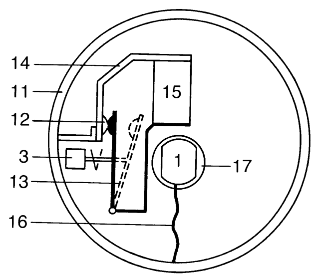


Fig.10-5

Commutating suspended contact, schematic diagram of auxiliary switching chamber,
1 Main contact support, 3 Auxiliary contact bar, 11 Anti-corona hood, 12 Fixed contact, 13 Spring contact, 14 Arc-deflecting baffle, 15 Deion arc-quenching plates, 16 Flexible connection for equipotential bonding, 17 Rotary bearing

Because the arc only lasts for about 25 ms on average during opening, the contact erosion on the spring contact system remains slight and the current is safely interrupted before the pantograph contact bar separates. Separating the main and auxiliary contact systems keeps the latter completely free from the effects of forces resulting from a short circuit. Short-circuit testing has confirmed a peak withstand current strength of 200 kA. Each switching system can take at least 350 switching cycles at commutation currents up to 1600 A and commutation voltages up to 330 V.

Installing commutation suspended contacts provides the system operator with flexibility and reliability of operation. Older installations can be upgraded by replacing the suspended contacts. Installations with switchgear from other manufacturers can also be retrofitted with ABB commuting suspended contacts.

10.2.3 Two-column vertical break disconnectors

This type of disconnector is preferred for higher voltages (≥ 170 kV) as a feeder or branch disconnector (at 1 1/2 circuit-breaker structure, Section 11.3.3). It differs from two-column rotary disconnectors by smaller phase spacings (with side-by-side configuration) and higher mechanical terminal loads. In its open state, there is a horizontal isolating distance with the contact arm open upwards.

As shown in Fig. 10-6, the two post insulators are mounted on a frame. The gearbox with contact arm and high-voltage terminal and the fixed contact with high-voltage terminal are mounted on them. The rotating insulator fastened to the rotary bearing transfers the actuating force to the gearbox, which transmits the force into a torque for opening the contact arm.

Each side of the disconnector can be fitted with an earthing switch (Section 10.2.4) depending on the requirements. The associated earthing contacts are installed on the gearbox or on the fixed contact.

For rated voltages of up to 245 kV one mechanism per three-phase disconnector or earthing switch group is sufficient, at higher nominal voltages one mechanism per pole is generally used.

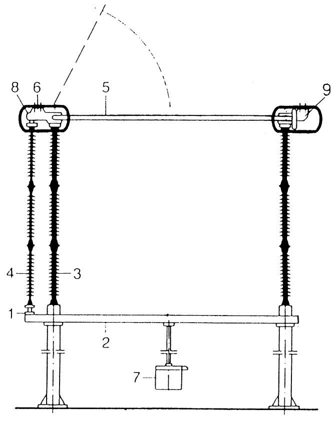


Fig.10-6

Vertical break 525 kV,
1 Rotary bearing, 2 Frame, 3 Post insulator, 4 Rotating insulator,
5 Contact arm, 6 High-voltage terminal, 7 Mechanism, 8 Gearbox,
9 Fixed contact

As with the other disconnector types, the post insulators are also fixed to stay bolts, which enable precise adjustment of the contact arm and equalization of the insulator tolerances after the lines have been fastened.

The contact arm of the vertical break disconnectors is also a welded aluminium design. The contacts are silver-coated copper. The current in the gearbox is carried by tapered roller contacts.

A tie-rod transmits the actuating force from the mechanism to the contact arm with rotary bearings, rotating insulator and gearbox. This tie-rod, like the tie-rods in the gearbox, passes though the centre point shortly before reaching the end position,ensuring that the centre-point is interlocked against spontaneous changes of position under extreme external conditions. At high voltages and high short-circuit currents, or when ice loads have to be broken, a rotary movement of the contact arm around the longitudinal axis (approx. 25°) after reaching the "On" position provides a higher contact pressure, an additional interlock or frees the contacts from ice.

10.2.4 Single-column earthing switches

In outdoor switchgear installations, earthing switches are required not only directly adjacent to the disconnectors but also at other positions in the installation, e.g. for earthing individual busbar sections. Single-column earthing switches are used for this purpose, and they can be simultaneously used as supports for tubular busbars.

The components of the earthing switches are the same for mounting on disconnectors or separate single-column configuration. The only exceptions are the frame and support for the earthing contact.

The insulator is supported by a base frame with the operating mechanism (Fig. 10-7). It supports the contact holder with the earthing contact.

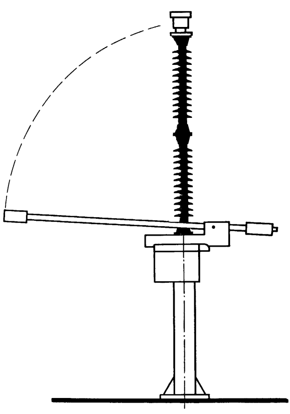


Fig.10-7

Single-column earthing *switch, type TEB, 420 kV*

Two designs are available for the different requirements: a) Vertical-reach earthing switches for low rated voltages and rated currents, b) rotary-linear earthing switches for higher rated voltages and currents. They differ in the design of the earthing mechanism and hence in the switching movement of the contact arm.

On the vertical-reach earthing switch, the contact arm swivels on the shaft and only rotates around a switching angle of about 90 degrees. In the closed position, the earthing contact is situated between the contact fingers and these are against a spring stop. On the other hand, the rotary-linear earthing switch has a more complex mechanism. The contact arm first executes a rotary movement similar to that of the vertical-reach earthing switch and towards the end of the rotary movement moves on a straight line into the earthing contact. The contact blade on the contact arm is fixed in the earthing contact so the connection can withstand even high peak currents.

10.2.5 Operating mechanisms for disconnectors and earthing switches

Disconnectors are almost entirely actuated by motor-driven operating mechanisms, but manual mechanisms are also used for earthing switches. The operating mechanism is either mounted directly on the base frame of the disconnector or earthing switch or placed at operator level (1.20 m above ground level). Motor-operated mechanisms may also have an emergency manual actuator in case of failure of auxiliary power or for adjustments.

The operating mechanism housing has the position indicator switches for showing the switching position and for control and interlocking, and the motor-operated mechanisms also have contactors, etc. for controlling the actuators. The controllers are designed so that only one switching impulse is necessary to start the mechanism. They shut down automatically when the end position is reached. In the event of an emergency manual operation, the control circuit of the motor-operated mechanism is interrupted by a safety contact, making a simultaneous actuation from the control room impossible. The motor-operated mechanisms can also be fitted with pushbuttons for local control.

The mechanisms of the disconnectors and earthing switches can be interlocked relative to each other and to the associated circuit-breakers to prevent maloperation. Motor-operated mechanisms have an indicator switch contact for the relevant device incorporated into the control circuit of the mechanism. Manual and motor-operated mechanisms can also be fitted with a locking solenoid, which prevents manual switching when there is no power and also breaks the control circuit of the motor mechanism with a separate auxiliary contact. Mechanical interlocking between disconnectors and earthing switches is also possible with directly mounted earthing switches.

The mechanical actuation energy is transmitted from the motor to the actuation shaft by a spindle gear, which has an increased torque on closing and opening the main contact point to break ice loads.

Disconnectors and earthing switches have an operating mechanism with centre-point interlocking, which prevents any spontaneous changes of position under extreme external influences, such as short circuits, earthquakes or hurricanes.

Future generations of mechanisms will be motor-operated mechanisms with semiconductor controls and electronic indication of switch position.

10.3 Switch disconnectors

High-voltage switch disconnectors are switching devices that make, carry and break operating currents and also carry and in part also make short-circuit currents. In their open position, they also form an isolating distance.

The relevant standards are the following:

– DIN EN 60 265-1 (VDE 0670 Part 301) for rated voltages of 1 kV to 52 kV
– DIN EN 60 265-2 (VDE 0670 Part 302) for rated voltages of 52 kV and above

  Note: the standards also cover switches, i.e. devices whose open switching gap does not meet the special requirements of an isolating distance. In practice, equipment of this type is no longer used in central Europe.

The two above standards classify the switch disconnectors into the following by their usage:

– general-purpose switch disconnectors,
– switch disconnectors for limited applications and
– switch disconnectors for special applications.

General-purpose switch disconnectors must be capable of making and breaking the load current for which their current path is designed (rated current) and of carrying and making (at the same level) short-circuit currents for a specified time (1s, 3s). These devices have a very wide application. They are encountered with rated voltages of 12 kV, 24 kV and 36 kV in varying designs, primarily for operating currents to 630 A, but also for 1250 A (Section 8.1.2). Switch disconnectors with this versatility are found in the area of transmission voltages only as integrated devices in SF_6-insulated switchgears.

Switch disconnectors are available for special applications in the area of air-insulated switchgear technology in the range up to 245 kV. They are capable of carrying high operating currents (up to 2000 A) and short-circuit currents, but can only make and break much lower currents.

These devices are used as follows:

– Transformer switches for smaller power supplies in the distribution network for switching magnetizing currents and commutation currents (e.g. 100 A at up to 2.5 kV voltage difference) when changing transformers or the power supply,
– Line switches at one end of an overhead line
– Busbar section switches
– Switches for short cable length (I_c < 3A).

While the switch disconnector is the most common switching device in many distribution networks, it is much less common in transmission networks, in spite of its much lower costs compared to circuit-breakers.

10.4 Circuit-breakers

10.4.1 Function, selection

High-voltage circuit-breakers are mechanical switching devices capable of making, carrying continuously and breaking electrical currents, both under normal circuit conditions and, for a limited period, abnormal circuit conditions, such as in the event of a short circuit. Circuit-breakers are used for switching overhead lines, cable feeders, transformers, reactor coils and capacitors. They are also used in bus ties in installations with multiple busbars to allow power to be transmitted from one busbar to another.

Specially designed breakers are used for specific duties such as railways, where they have to extinguish longer-burning arcs (longer half-wave) in $16\ ^{2}/_{3}$-Hz networks. Breakers used with smelting furnaces frequently operate with reduced actuating force and lower breaking capacity. This leads to less wear in spite of the high switching frequency and to long service intervals.

The following points are important when selecting circuit-breakers:

– maximum operating voltage on location
– installation height above sea-level
– maximum load current occurring on location
– maximum short-circuit current occurring on location
– network frequency
– duration of short-circuit current
– switching cycle
– special operational and climatic conditions

Important national and international standards:

IEC	DIN VDE		
60056	DIN VDE 0670 – 101	(0670 Part 101)	General and definitions
	DIN VDE 0670 – 102	(0670 Part 102)	Classification
	DIN VDE 0670 – 103	(0670 Part 103)	Design and construction
	DIN VDE 0670 – 104	(0670 Part 104)	Type and routine testing
	DIN VDE 0670 – 105	(0670 Part 105)	Selection of circuit-breakers for service
	DIN VDE 0670 – 106	(0670 Part 106)	Information in enquiries, tenders and orders
60427	DIN EN 60 427	(0670 Part 108)	Synthetic testing
60694	DIN EN 60 694	(0670 Part 1000)	Common specifications for high voltage switchgear and controlgear standards

ANSI (**A**merican **N**ational **S**tandards **I**nstitution)

C 37 04	–1979	Rating structure
C 37 06	–1979	Preferred ratings
C 37 09	–1979	Test procedure
C 37 010	–1979	Application guide
C 37 011	–1979	Application guide for transient recovery voltage
C 37 012	–1979	Capacitance current switching

10.4.2 Design of circuit-breakers for high-voltage (> 52 kV)

Fig. 10-8 shows the basic design of HV outdoor circuit-breakers with the following components: operating mechanism, insulators, interrupting chamber and grading capacitor. HV circuit-breakers have a modular design. Higher voltages and higher capacities are dealt with by increasing the number of interrupting chambers. Self-blast interrupting chambers with low operating energy requirements are used for voltages of up to 170 kV and breaking currents of up to 40 kA (see Section 10.4.4). Single-chamber breakers are used for voltages of up to 300 kV and breaking currents of 50 kA. Multiple-chamber breakers are used for higher currents of up to 80 kA in this voltage range. Multiple-chamber breakers are used for voltages > 300 kV. Two-chamber breakers are used up to 550 kV and a breaking current of 63 kA.

In the lower voltage range and for three-phase autoreclosure, it is best to mount the three poles on a common base frame. Single-pole mounting and a separate mechanism for each pole are standard for voltages above 245 kV. HV circuit-breakers can also be mounted on trolleys with sprocket or plain rollers. Fig. 10-8 shows examples from the ABB outdoor breaker range.

The outdoor circuit-breaker design shown in Fig. 10-8 is the current type preferred in Europe. In America, the “dead tank” design is also common. This design, which is based on the earlier oil tank breaker, has the interrupting unit in an earthed metal tank filled with SF_6. The terminals of the interrupting unit are connected on both sides to SF_6-air bushings.

The same interrupting chambers and mechanisms as in outdoor circuit-breakers are also used with the integrated circuit-breakers of gas-insulated switchgear installations (GIS). An example of such breakers is shown in Fig. 10-9 with the section through the circuit-breaker of the SF_6-insulated switchgear installation EXK-01 for 123 kV and 40 kA. The self-blast interrupting chamber is identical to that of the outdoor circuit-breaker type LTB-D1; the three-pole circuit-breaker is operated by the HMB-1 mechanism.

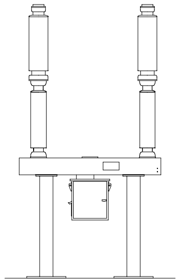
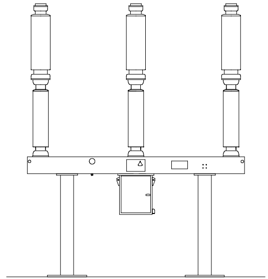
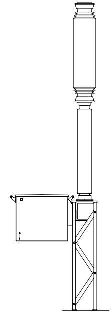
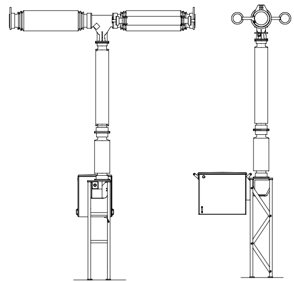
Rated voltage kV	123	123-170	245-300	420-(550)
Rated short-circuit breaking current kA	40	40	50	63
Breaker arrangement				
Breaker type	ELF-SD3-1 16 ⅔ Hz	LTB-D1	HPL-B1	HPL-B2
Mechanism type	HMB-1	HMB-1/HMB-1S	HMB-4	HMB-8

Fig.10-8

ABB SF_6 outdoor circuit-breaker, standard types for the central European region

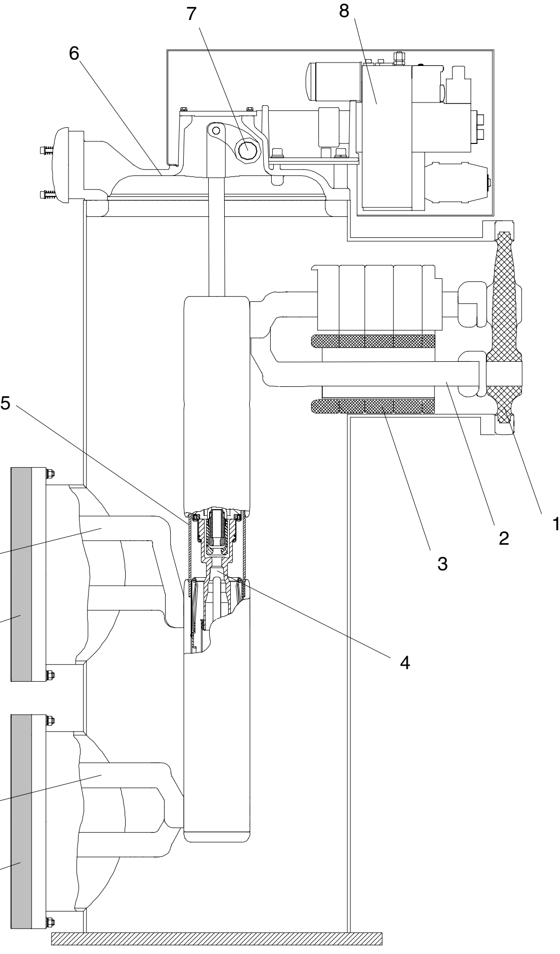


Fig.10-9

GIS circuit-breaker EXK-01 with SF_6 self-blast interrupting chamber and hydraulic spring mechanism HMB-1

1 Barrier insulator
2 Feed conductor
3 Current transformer
4 Interrupting chamber
5 Chamber insulator
6 Cover
7 Rotary feed
8 Mechanism

10.4.3 Interrupting principle and important switching cases

There are two basic arc-extinction processes.

Direct current extinction, Fig. 10-10

A d.c. arc can only be extinguished by forcing a current zero. This means that the arc voltage U_s must be higher than the voltage at the breaker LS. A sufficiently high arc voltage can be built up – by reasonable means – only in low and medium voltage d.c. circuits (magnetic blow-out breakers). In high-voltage d.c. circuits, the voltage must be lowered appropriately to extinguish the d.c. arc and/or artificial current zeros must be created by inserting a resonant circuit (see Fig. 11-39).

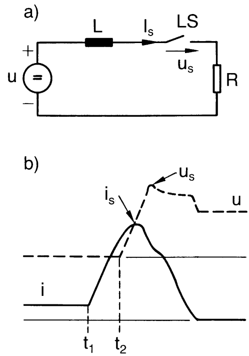


Fig.10-10

Direct current extinction a) simplified equivalent circuit, b) curves of current i_s and arc voltage u_s, t_1 initiation of short circuit, t_2 contact separation

Alternating current extinction,
Fig. 10-11

A.C. arcs may extinguish at every current zero. In high-voltage circuits and without special measures, the arc re-ignites immediately after passing zero crossing, so that the arc continues to burn. The arc plasma is intensively cooled in the interrupting chambers of HV circuit-breakers with the result that it loses its electrical conductivity at current zero and the recovery voltage is not sufficient for re-ignition.

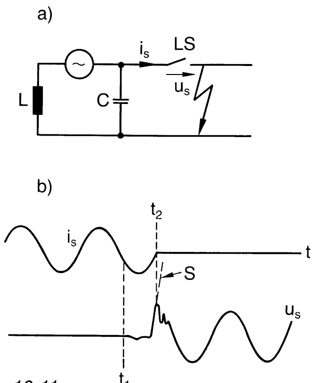


Fig.10-11

Alternating current extinction,
a) simplified equivalent circuit, b) curves of short-circuit current i_s and recovery voltage u_s, t_1 contact separation, t_2 arc extinction, S rate of rise of recovery voltage

Voltage stress of the breaker, Fig. 10-12

When interrupting an inductive load (Fig. 10-12a), the breaker voltage oscillates to the peak value of the recovery voltage. The breaker must be able to withstand the rate of rise of the recovery voltage and its peak value. Once the arc is quenched, the dielectric strength between the contacts must build up more quickly than the recovery voltage to prevent re-ignition.

When interrupting a purely resistive load (Fig. 10-12b), current zero and voltage zero coincide. The recovery voltage at the breaker rises sinusoidally with the operating frequency. The breaker gap has sufficient time to recover dielectric strength.

When switching a capacitive load (Fig. 10-12c), the supply-side voltage (infeed breaker terminal) oscillates at system frequency after current interruption between ± û, while the capacitor-side terminal remains charged at + û.

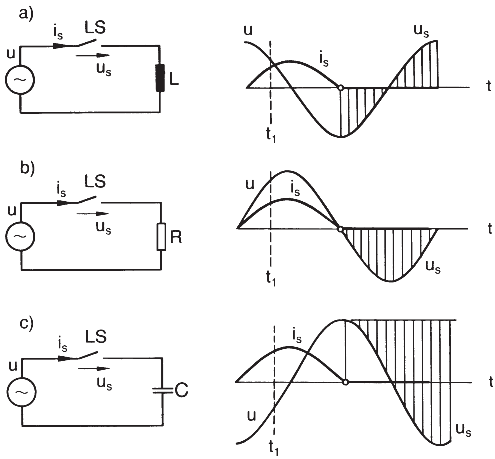


Fig.10-12

Recovery voltage u_S when breaking a) inductive load, b) resistive load, c) capacitive load

Various switching cases

Circuit-breakers must handle various switching cases that place different requirements on the breaker depending on their location.

Terminal fault (symmetrical short-circuit current), Fig. 10-13

The terminal fault is a short circuit on the load side of a breaker in the immediate vicinity of the breaker terminals. The short-circuit current is symmetrical if the fault begins at the voltage maximum. The recovery voltage oscillates to the value of the driving voltage. Rate of rise and amplitude of the transient voltage are determined by the network parameters. The values to be used in testing are defined in the relevant standards (Section 10.4.1).

Terminal fault (asymmetrical short-circuit current), Fig. 10-13

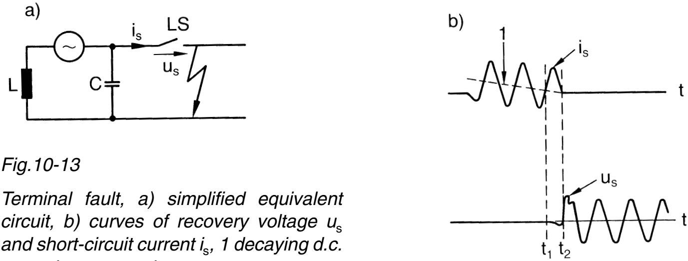


Fig.10-13

Terminal fault, a) simplified equivalent circuit, b) curves of recovery voltage u_s and short-circuit current i_s, 1 decaying d.c. current component

A more or less high d.c. current component must be switched in addition to the symmetrical short-circuit current depending on the opening time of the breaker. The d.c. current component of the short-circuit current depends on the moment of short-circuit initiation (max. at voltage zero) and on the time constants of the network supply-side components, such as generators, transformers, cables and HV lines. In accordance with IEC and DIN VDE, a time constant of 45 ms is set as standard. This means a d.c. current component of about 40% to 50% with the usual opening times of modern SF_6 outdoor breakers.

Short-line fault, Fig. 10-14

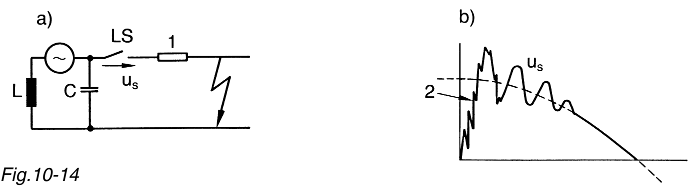


Fig.10-14

Short-line fault, a) simplified equivalent circuit, b) recovery voltage u_s across the breaker, 1 Line, 2 Sawtooth shape of u_s

Short line faults are short circuits on overhead lines at a short distance (up to a few kilometres) from the breaker. They impose a particularly severe stress on the breaker because two transient voltages are superimposed: the transient voltage of the supply network and the transient voltage on the line side. The superimposition results in a particularly high rate of rise of the voltage with only a minor reduction of the short-circuit current. The critical distance of the short circuit depends on the current, voltage and arc-quenching medium.

10

Switching under out-of-phase conditions (phase opposition), Fig. 10-15

The (power-frequency) voltage stress is severe if the phase angle of the systems on either side of the breaker are different (system components fall out of step because of overload or incorrect synchronization of generator circuit-breakers).

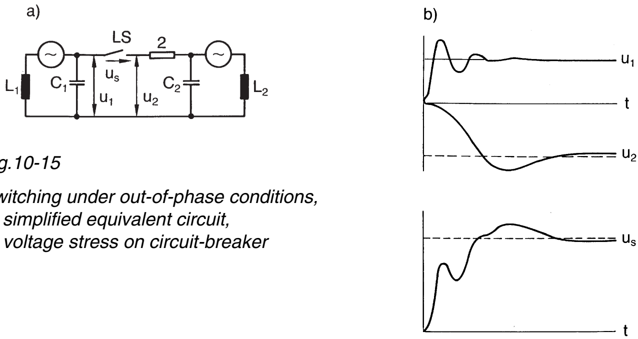


Fig.10-15

Switching under out-of-phase conditions,
a) simplified equivalent circuit,
b) voltage stress on circuit-breaker

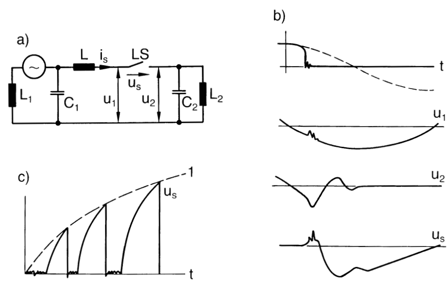
Interruption of small inductive currents, Fig. 10-16

Depending on the network configuration, interruption of small inductive currents, such as reactor coils or magnetizing currents from transformers, causes a rapid rise of the recovery voltage and under some circumstances high overvoltage resulting from current chopping before the natural zero crossing.

The overvoltages are also heavily dependent on the individual properties of the load circuit (inductance L_2 and capacitance C_2). There is no generally applicable test circuit that covers all load cases occurring in the network. However, in transmission networks an overvoltage of 2.5 pu is normally not exceeded.

Fig.10-16

Interruption of small inductive currents,
a) simplified equivalent circuit, b) curve of current and voltages with current chopping without restriking,
c) voltage curve when restriking occurs

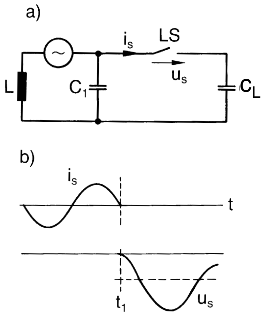


Switching of capacitive currents, Fig. 10-17

Since breakers that prevent restriking are generally available, this switching case does not cause extreme stress (see Fig. 10-12c). However, theoretically, repeated restriking can increase the voltage load to several times the peak value of the driving voltage.

Switching of unloaded lines and cables:

The capacitance per unit length of line or cable imposes a similar situation as with the switching of capacitors



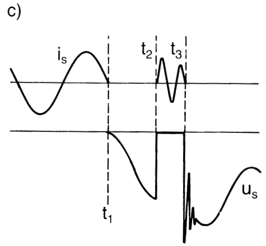


Fig.10-17

Breaking capacitive currents, a) Simplified equivalent circuit, b) Curves of current and voltage, c) Current and voltage characteristics when restriking occurs

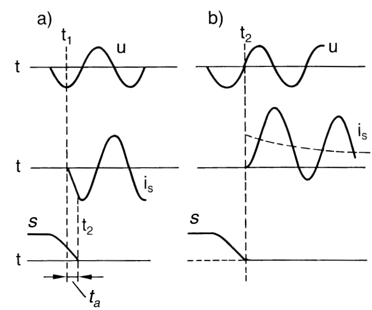
Closing of inductive currents, Fig. 10-18

The most important switching case of this type for switchgear technology is the closing on short circuit. The timing of the contact making with reference to the driving voltage determines the effects on the contact system. Fig. 10-18a shows the closing operation with pre-arcing on contact proximity in the area of the peak value of the persistent voltage and the associated symmetrical fault current curve. Fig. 10-18b shows the curve on contact making in the area of the zero crossing of the persistent voltage with the peak value increased to almost double the value (1.8 times) by a transient direct current component in the current path.

One breaker pole nearly always reaches this curve during three-pole switching with simultaneous closing time of the three breaker poles.

Fig.10-18

Making inductive currents:
t_1 = instant of pre-arcing
t_2 = instant of contact touch
S = contact path
a) symmetrical current with pre-arcing
t_a = pre-arcing duration
b) asymmetrical current with maximum peak current



Closing of unloaded overhead lines

Overhead lines can be shown in the electrical equivalent circuit diagram as combinations of series-connected inductances and capacitances to earth. During closing of long overhead lines, due to reflections of the voltage at the open end of the line, voltage increase of about 100% can occur. For this reason, at high transmission voltages and very long lines (> 300 km) circuit-breakers are fitted with closing resistors or closing is single-phase synchronized at the instant of zero crossing of the persistent voltage.

Short-circuit making and breaking tests

Making and breaking tests of circuit-breakers are performed in high-power test laboratories. The short-circuit current for the test is supplied by specially designed generators. The single-phase breaking power of a 420 kV circuit-breaker with a rated short-circuit current of 63 kA is approximately 15 000 MVA, which cannot be performed in a direct test circuit even by the most powerful test laboratory. Therefore, as early as the 1940s synthetic test circuits were developed for testing breakers with high short-circuit switching capability.

The basic reasoning behind a synthetic breaking test is that in the event of a short circuit, the short-circuit current and the recovery voltage do not occur simultaneously. This allows current and voltage to be supplied from two different sources. Fig. 10-19a shows the simplified test circuit for a synthetic test with current injection.

When test- and auxiliary-breakers are closed, the short circuit is initiated by closing the making switch. Auxiliary-breaker and test-breaker open at approximately the same time. Shortly before current zero of the current that is to be interrupted, the spark gap is ignited and an oscillating current of high frequency with an amplitude of some kA is superimposed on the short-circuit current in the test-breaker (Fig. 10-19b). The test-circuit elements must be selected so that the rate of current rise of the oscillating current at zero crossing coincides with the rate of rise of the high current.

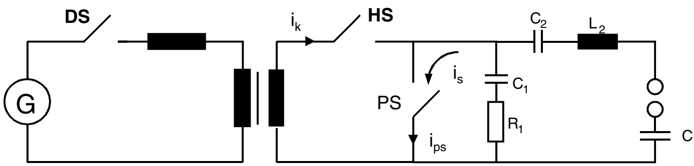


Fig.10-19a:

Synthetic test circuit with current injection
G: short-circuit generator, DS: making switch, HS: auxiliary breaker, PS: test breaker, i_k: short-circuit current, i_s: injection current, $i_{ps} = (i_k + i_s)$: test current through the test breaker, C, C_1, C_2, R_1, L_2: element of the synthetic circuit

An oscillogram of a make (c)/break (o) operation in a synthetic test circuit is shown in Fig. 10-19c.

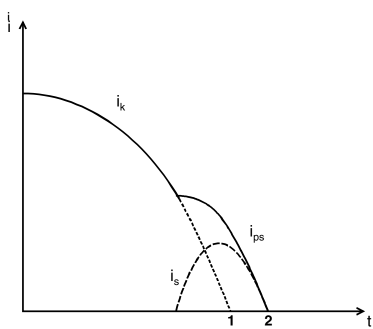


Fig.10-19b:

Current versus time in the synthetic test circuit

The auxiliary breaker interrupts the short-circuit current i_k at zero crossing 1, the test breaker interrupts the test current i_{ps} at zero crossing 2, i_s is the injection current.

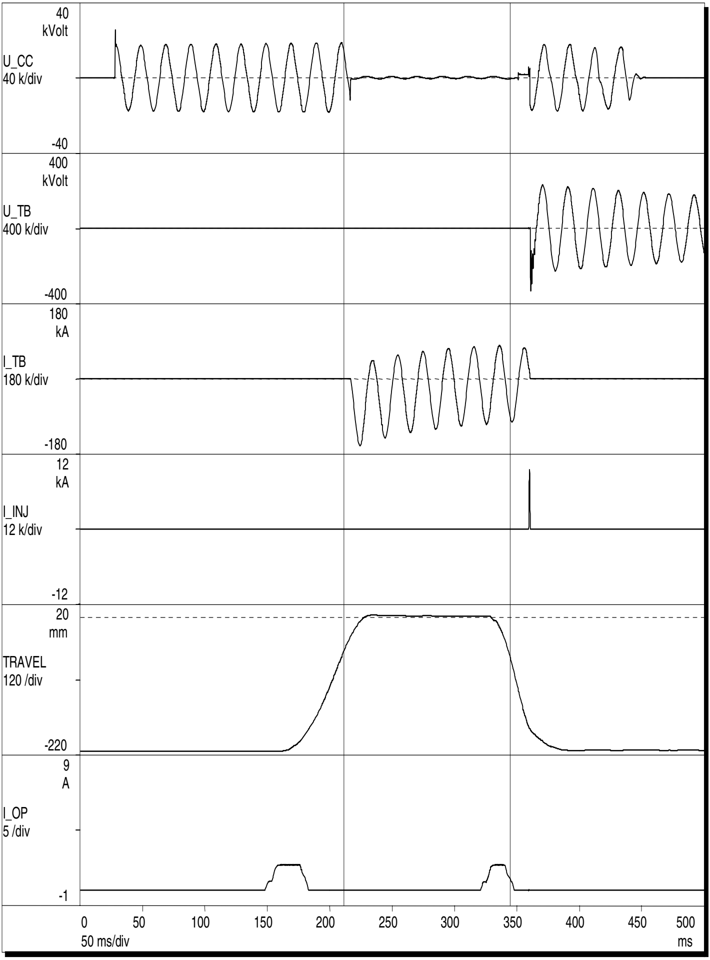


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Fig.10-19c:

Oscillogram of a CO operation in the synthetic test circuit (half-pole test)

U_{CC}	*Generator voltage*	I_{INJ} (= i_S)	*injected oscillating current*
U_{TB}	*recovery voltage across the breaker gap*	*Travel*	*contact travel of breaker contacts*
I_{TB} (= i_{ps})	*current through the test object*	I_{OP}	*closing command and opening command*

10.4.4 Quenching media and operating principle

SF_6 gas

High-voltage circuit-breakers with SF_6 gas as the insulation and quenching medium have been in use throughout the world for more than 30 years. This gas is particularly suitable as a quenching medium because of its high dielectric strength and thermal conductivity (see also Section 11.2.2). Puffer-type breakers are used for high breaking capacity, while the self-blast technique is used for medium breaking capacity.

Puffer (piston) principle

Fig. 10-20 shows the design and operation of the interrupting chamber of the puffer principle. The extinction unit consists of the fixed contact and the moving contact with the blast cylinder. During the opening movement, the volume of the blast cylinder is steadily reduced and thereby increases the pressure of the enclosed gas until the fixed contact and the movable contact separate. The contact separation causes an arc to be drawn, which further increases the pressure of the SF_6 gas in the blast cylinder. At sufficiently high pressure, the compressed gas is released and blows the arc, depleting its energy and causing it to be extinguished. The nozzle shape of the two contacts provides optimum flow and quenching properties.

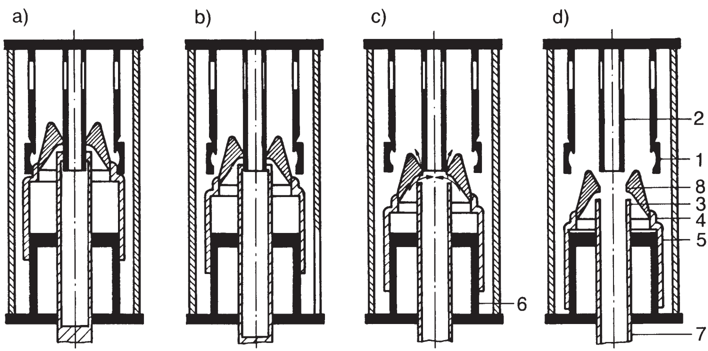


Fig.10-20

Puffer (piston) method showing the 4 stages of the opening process, a) closed position, b) beginning of the opening movement, c) arcing contacts separate, d) open position, 1 fixed continuous current contact, 2 fixed arcing contact, 3 movable arcing contact, 4 movable continuous current contact, 5 compression cylinder, 6 compression piston, 7 actuating rod, 8 quenching nozzle

Self-blast principle

In 1985, ABB introduced the self-blast quenching principle, which has been in use with SF_6 medium-voltage breakers for many years (see Fig. 8-15), in a modified form for HV circuit-breakers, without any need for a magnetic coil to rotate the arc. Fig. 10-21 shows the design and operation of the self-blast interrupting chamber up to 170 kV, 40 kA.

For small currents, the required extinction pressure is generated by compressing the gas in volume 5 as with a puffer-type breaker during the opening movement (Fig. 10-21 c). In contrast, for short-circuit currents the energy of the high-amp arc heats the quenching gas and increases its pressure in the heating volume 6 (Fig. 10-21 d). This overpressure does not affect the mechanism in any way. Its energy only needs to be dimensioned for switching normal operating currents.

Compared to the puffer principle, the self-blast principle only requires about 20% of the actuating energy for the same circuit-breaker performance data. The operational advantages are the compact mechanisms, low mechanical stresses on the overall system, low dynamic foundation loads, low noise level and generally improved reliability.

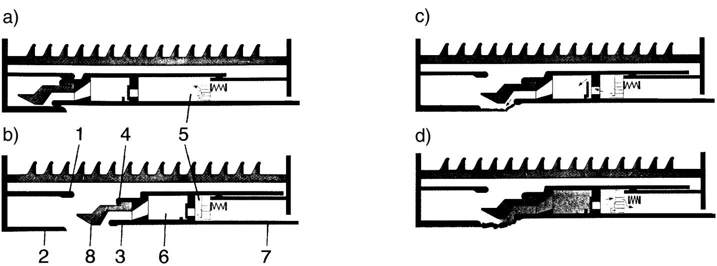


Fig.10-21

Self-blast principle for high-voltage circuit-breakers, a) closed position, b) open position, c) interruption of small currents (by the puffer method), d) interruption of short-circuit currents (by the self-blast method)
1 fixed continuous current contact, 2 fixed arcing contact, 3 movable arcing contact, 4 movable continuous current contact, 5 compression volume, 6 heating volume, 7 actuating rod, 8 quenching nozzle

The dielectric behaviour of the insulating media SF_6 gas, transformer oil, compressed air and air at atmospheric pressure is shown in Fig. 10-22.

The external dielectric strength of the interrupting chamber depends on the pressure of the ambient air, but not on the SF_6 gas pressure inside the chamber. The SF_6 gas pressure and the contact distance determine the dielectric strength inside the chamber.

Fig. 10-23 shows the current status of interrupting chamber breaking capacity of the ABB outdoor circuit-breakers

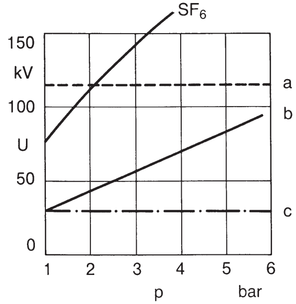


Fig. 10-22

General dielectric behaviour of various insulation materials; breakdown strength U (a.c. voltage) with electrode distance 38 mm in function of the pressure p, a transformer oil, b compressed air, c reference line of air at atmospheric pressure

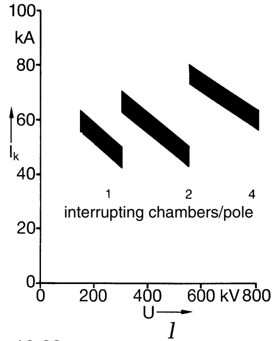


Fig. 10-23

Interrupting chamber switching capacity U = rated voltage I_k = rated short-circuit breaking current

Oil

Up to about 1930, HV circuit-breakers were exclusively of the bulk-oil circuit-breaker type. The oil was used for insulation and arc extinction. The breaking arc heats the oil in its vicinity, induces an oil flow and causes the arc extinction. The minimum-oil breakers with a small volume of oil in the quenching chamber provided great advantages compared with the bulk-oil circuit-breakers with their large volume of oil. The arc also heats the oil in this type of breaker and extinguishes the arc in this way. When breaking small currents, the arc extinction is supported by pump action.

Compressed air

Until the end of the 1970s, air-blast breakers using compressed air as a quenching, insulation and actuating medium were widely used. They contain the quenching medium at a pressure of up to around 30 bar in the breaker tank and inside the breaker. At the instant of contact separation, compressed air is forced through the nozzle-shaped contacts thereby extinguishing the arc and establishing the insulating distance. Compressors, storage and distribution systems supply the air-blast breaker with clean and dry compressed air, see Section 15.5.

10.4.5 Operating mechanism and control

Operating mechanisms for circuit-breakers consist of energy storage unit, controller unit and power-transmitter unit. The energy-storage unit must be suited for storing energy for an autoreclosure cycle (OCO). This can be performed with different actuating systems.

Spring-operated mechanism

The spring-operated mechanism is a mechanical actuating system using a powerful spring as energy storage. The spring is tensioned with an electric motor and held by a latch system. When the breaker trips, the latch is released by magnetic force, and the spring energy moves the contacts by mechanical power transmission.

Pneumatic operating mechanism

The pneumatic operating mechanism operates by compressed air, which is fed directly to the breaker from a compressed air tank used as energy storage. Solenoid valves allow the compressed air into the actuating cylinder (for closing) or into the atmosphere (for opening). The compressed-air tank is replenished by a compressor unit. Compressed-air mechanisms have not been used for ABB circuit-breakers for many years.

Hydraulic operating mechanism

The hydraulic operating mechanism has a nitrogen accumulator for storing the actuation energy. The hydraulic fluid is pressurized by a compressed cushion of nitrogen. A hydraulic piston transmits the power to actuate the breaker contacts.

The mechanism operates on the differential piston principle. The piston rod side is permanently under system pressure. The piston face side is subject to system pressure for closing and pressure is released for opening. The system is recharged by a motor-driven hydraulic pump, which pumps oil from the low-pressure chamber to the nitrogen storage chamber. The hydraulic mechanisms from ABB were replaced by the hydraulic spring-operated mechanism in 1986.

Hydraulic spring -operated mechanism

The hydraulic spring-operated mechanism is an operating mechanism combining hydraulics and springs. Energy is stored in a spring set which is tensioned hydraulically. Power is transmitted hydraulically with the actuating forces for the circuit-breaker contacts being generated as with a hydraulic mechanism by a differential piston integrated into the actuation unit. As an example, Fig. 10-24 shows a section through the hydraulic spring operating mechanism type HMB-1.

The ABB hydraulic spring-operated mechanism is available in several different sizes (Fig. 10-25). Circuit-breakers with common base frames, i.e. outdoor breakers up to 170 kV, GIS circuit-breakers and dead-tank breakers, have a common mechanism for all three poles. All mechanisms are designed to eliminate external pipe joints.

The hydraulic spring operating mechanism offers the following advantages:

- temperature-independent disc-spring set, allowing the lowest possible oil volume (example: < 1.5 litres for the HMB-1)
- compact
- high repeat accuracy of operating times
- integrated hydraulic damping
- high mechanical endurance
- easily adaptable to different breaker types.

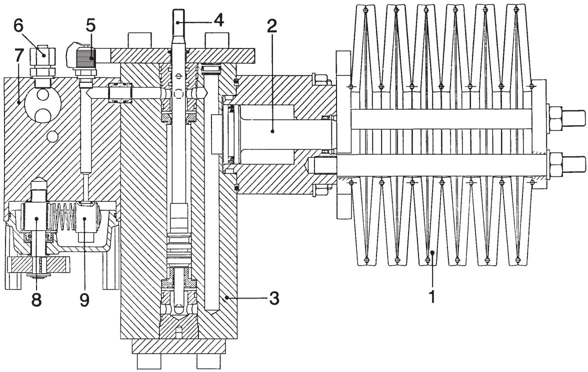


Fig.10-24

Section through the hydraulic spring operating mechanism for SF_6 self-blast breakers, 1 Springs, 2 Spring piston, 3 Actuating cylinder, 4 Piston rod, 5 Measuring connection, 6 Oil filler connection, 7 Pump block, 8 Pump drive shaft, 9 Pump unit

Modern ABB HV circuit-breakers are operated exclusively with the hydraulic spring mechanism or the mechanical spring mechanism.

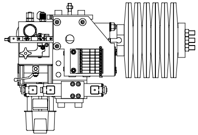
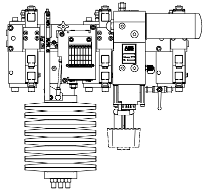
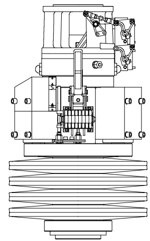
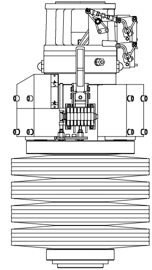
Design / Type / Used for	HMB-1	HMB-1 S	HMB-4	HMB-8
Design				
Outdoor circuit-breaker type	LTB-D1	LTB-D1	HPL-B1	HPL-B2
GIS circuit-breaker type	ELK	ELK	ELK	ELK
Generator circuit-breaker type	HG	–	HE	HE
Dead-tank circuit-breaker type	PM, PASS	PM	PM, PASS	PM, PASS

Fig.10-25

Sizes of hydraulic spring operating mechanisms for high-voltage circuit-breakers

Requirements for electrical control of circuit-breakers

Phase-discrepancy monitoring

Breakers with a single-phase mechanism are fitted with phase-discrepancy monitoring.

If the three breaker poles are in different positions during a three-pole closing, the phase-discrepancy monitoring detects the differential position. All three breaker poles are tripped together after a preset waiting time of 2 seconds.

Anti-pumping control

The anti-pumping control prevents repeated, undesired operation of one or more breaker poles if an existing OFF command is followed by several ON commands. The breaker must then close only once followed by a lockout, i.e. it must remain in the OFF position regardless of whether and how long control commands are applied.

Non-stop motor operation

Depending on the design and the type of switching cycle performed, the pump or the compressor requires a specific period to restore the consumed energy. If there is a leak in the pressure system, the motor will run more often or will run continuously. Continuous running is detected and reported as a fault.

SF_6 gas monitoring

The breaking capacity of a circuit-breaker is dependent on the gas density in the breaker chamber. This is measured by a temperature-compensated pressure gauge. If the gas pressure falls to a specified value, an alarm is triggered, and if it falls further to a lower limit value, the breaker is blocked.

Local/remote control

To allow work on the breaker, it can generally be controlled from the local control cubicle; control can be switched from remote to local by a selector switch.

Energy monitoring

The air or oil pressure is monitored and controlled in pneumatic and hydraulic mechanisms by a multiphase pressure switch. The pressure switch has the following functions:
– control of compressor or pump motor
– OFF blocking, ON blocking, autoreclosure blocking, dependent on available pressure

A pressure control is not required for hydraulic spring mechanisms. Instead of that they have a gate control, which monitors and controls the tension of the spring (spring travel) as a measure of the available energy.

Autoreclosure

A single- or three-pole autoreclosure is selected depending on the type of system earthing, the degree of interconnection, the length of the lines and the amount of infeed from large power plants. The trip commands of the network protection (overcurrent and line protection, Section 14.2) are accordingly evaluated differently for the tripping action of the circuit-breaker.

Circuit-breakers for three-pole autoreclosure only require one hydraulic spring mechanism with one actuation cylinder, allowing *one* tripping initiates the closing and opening of all poles.

For single-pole autoreclosure, these breakers have a hydraulic spring mechanism with three actuation cylinders, which are controlled separately. This allows any pole to be tripped independently. Power is fed to the three poles from one power unit. Single-phase autoreclosure is intended to trip short-time faults and restrict them in time and place without allowing larger system units to fail for any length of time. Single-pole tripping improves network stability and prevents the network from going out of phase. At the same time, breakers with single-pole autoreclosure can be operated as three-pole autoreclosure by opening and closing the three poles together.

Circuit-breakers with separate poles and single-pole actuation are equally suited for both single-pole and three-pole autoreclosure.

Synchronized switching

Synchronized switching of circuit-breakers in which every breaker pole is synchronously actuated by a suitable control unit at the instantaneous value of the current or the phase-to-earth voltage are becoming increasingly important. Examples of applications of synchronized switching include closing overhead lines under no load without closing resistors and switching capacitor banks in transmission networks.

The operating mechanisms of the HMB series have already proven very suitable for this because of their very constant operating times.

10.5 Instrument transformers for switchgear installations

Instrument transformers are used to transform high voltages and currents to values that can be unified or measured safely with low internal losses. With current transformers, the primary winding carries the load current, while with voltage transformers, the primary winding is connected to the service voltage. The voltage or the current of the secondary winding is identical to the value on the primary side in phase and ratio except for the transformer error. Current transformers operate almost under short-circuit conditions while voltage transformers operate at no-load. Primary and secondary sides are nearly always electrically independent and insulated from one another as required by the service voltage. Above a service voltage of 110 kV, instrument transformers are frequently manufactured as combined current and voltage transformers.

In modern substation and bay control systems, current and voltage transformers can be replaced by sensors. They offer the same accuracy as conventional instrument transformers. The output signal, A/D-converted, is processed by the digital bay control unit.

10.5.1 Definitions and electrical quantities

A distinction is made between transformers for measurement purposes used to connect instruments, meters and similar devices and transformers for protection needs for connection of protection devices.

Instrument transformers are classified according to their measurement precision and identified accordingly. They are used as shown in Table 10-2.

Table 10-2

Selection of instrument transformers by application

Application	VDE class	IEC class	ANSI class
Precision measurements and calibration	0.1	0.1	0.3
Accurate power measurement and tariff metering	0.2	0.2	0.3
Tariff metering and accurate measuring instruments	0.5	0.5	0.6
Industrial meters: voltage, current, power, meters	1	1	1.2
Ammeters or voltmeters, overcurrent or voltage relays	3	3	1.2
Current transformer protective cores	5P, 10P	5P, 10P	C, T

Current transformer – DIN VDE 0414-1 (VDE 0414 Part 1) –

- Primary rated current: the value of the primary current that identifies the current transformer and for which it is rated.
- Secondary rated current: the value of the secondary current that identifies the current transformer and for which it is rated.
- Burden: impedance of the secondary circuit expressed in ohms with the power factor. The burden is usually given as apparent power in volt amperes, which is assumed at a specified power factor and secondary rated current intensity.
- Rated burden: the value of the burden on which the accuracy requirements of this standard are based.
- Rated output: the value of the apparent power (in volt amperes at a specified power factor), which the current transformer yields at secondary rated current intensity and rated burden.
- Current error (transformation ratio error): the deviation of a current transformer when measuring a current intensity and derived from the deviation of the actual transformation from the rated transformation. The current error is given by the equation below and expressed as a percentage.

$$\text{Current error in \%} = \frac{(K_n \cdot I_s - I_p) \cdot 100}{I_p}$$

Here:

K_n rated error
I_s actual primary current intensity
I_p actual secondary current intensity, if flowing I_p under measuring conditions

- Phase displacement: the angular difference between the primary and secondary current vectors. The direction of the meter is specified so that on an ideal current transformer the phase displacement is equal to zero. The phase displacement is considered positive when the secondary current meter is ahead of the primary current meter. It is usually expressed in minutes or in centiradians.

  Note: the definition is strictly speaking only applicable to sinusoidal currents.

- Composite error: in its stationary state, the composite error ε_c based on the rms value of the primary current is the difference between
  a) the instantaneous values of the primary current intensity
  b) the instantaneous values of the secondary current intensities multiplied by the rated transformation.

The positive signs of the primary and secondary current must be specified in accordance with the agreement on connection labels.

The composite error in general is expressed as a percentage of the rms values of the primary current intensity as given by the following equation.

$$\varepsilon_c = \frac{100}{I_p} \sqrt{\frac{1}{T} \int_0^T (K_N \cdot i_s - i_p)^2 \, d\,t}$$

Here:

- K_n Rated transformation ratio of the current transformer
- I_p Rms value of the primary current
- i_p Instantaneous value of the primary current
- i_s Instantaneous value of the secondary current
- T Period duration

– Rated limiting current (IPL): the value of the lowest primary current at which the composite error of the current transformer at the secondary rated burden for measurements is equal to or greater than 10 %.

Note: the composite error should exceed 10 % to protect the device fed from the current transformer against the high current values occurring if there is a fault in the network.

– Overcurrent limit factor (FS): the ratio of the rated limiting current to the primary rated current.

Note: if a short-circuit current flows through the primary winding of the current transformer, the load on the instruments connected to the current transformer is smaller in proportion to smallness of the overcurrent limit factor.

– Rated accuracy limit current: the value of the primary current up to which the current transformer for protection needs meets the requirements for the composite error.

– Accuracy limit factor: the ratio of the primary rated accuracy limit current to the primary rated current.

– Thermal rated continuous current: unless otherwise specified, the thermal rated continuous current intensity is equal to the primary rated current.

– Current transformer with extended current measuring range: the thermal rated continuous current must be equal to the extended primary rated current. Standard values: 120 %, 150 % and 200 %.

– Rated short-time thermal current: the rated short-time thermal current (I_{th}) must be given for every current transformer. (see definition in Section 3.25 in DIN VDE 0414-1).

Note: if a current transformer is a component of another device (e.g. switchgear installation), a time different from one second may be given.

– Rated peak short-circuit current: the value of the rated peak short-circuit current (I_{dyn}) must in general be 2.5 I_{th}. Only in the event of deviation from this value must I_{dyn} be given on the nameplate. (see definition in Section 3.26 in DIN VDE 0414-1).

- Primary rated voltage: the value of the primary voltage that identifies the voltage transformer and for which it is rated.
- Secondary rated voltage: the value of the secondary voltage that identifies the voltage transformer and for which it is rated.
- Rated transformation ratio: the ratio of the primary rated voltage to the secondary rated voltage.
- Burden: the admittance of the secondary circuit given in Siemens with indication of the power factor (inductive or capacitive).

  Note: The burden is usually given as apparent power in volt amperes, which is assumed at a specified power factor and secondary rated voltage.
- Rated burden: the value of the burden on which the accuracy requirements of this standard are based.
- Rated output: the value of the apparent power (in volt amperes at a specified power factor), which the voltage transformer yields at secondary rated voltage and rated burden.
- Thermal limiting output: the value of the apparent power – based on the rated voltage – that can be drawn at a secondary winding at primary rated voltage without exceeding the limit values for overtemperature (dependent on the rated voltage factor).

  Note 1: the limit values for measurement deviations may be exceeded here.

  Note 2: if there is more than one secondary winding, the thermal limiting output must be given for each winding.

  Note 3: the simultaneous load of more than one secondary winding is not approved without special consultation between manufacturer and purchaser.
- Rated thermal limiting output of windings for ground fault detection: the rated thermal limiting output of the winding for ground fault detection must be given in volt-amperes; the values must be 15, 25, 50, 70, 100 VA and their decimal multiples, based on the secondary rated voltage and a power factor of 1.

  Note: because the windings for ground fault detection are connected in the open delta, they are subject to load only in the event of malfunction.

The thermal rated burden rating of the winding for ground fault detection should be based on a load duration of 8 h.

- Rated voltage factor: the multiple of the primary rated voltage at which a voltage transformer must respond to the thermal requirements for a specified load duration and its accuracy class.

– Voltage error (transformation ratio error): the deviation of a voltage transformer when measuring a voltage resulting from the deviation of the actual transformation from the rated transformation. The voltage error is given by the equation below and expressed as a percentage.

$$\text{Voltage error in \%} = \frac{(K_n \cdot U_s - U_p) \cdot 100}{U_p}$$

Here:

K_n rated transformation ratio
U_p actual primary voltage
U_s actual secondary voltage when U_p is subject to measuring conditions.

– Phase displacement: the angular difference between the primary and secondary voltage vectors. The direction of the vector is specified so on an ideal voltage transformer the phase displacement is equal to zero. The phase displacement is considered positive when the secondary vector is ahead of the primary vector. It is usually expressed in minutes or in centiradians.

Note: the definition is strictly speaking only applicable to sinusoidal voltage

10.5.2 Current transformer

The primary winding is incorporated in the line and carries the current flowing in the network. It has various secondary cores. The current transformers are designed to carry the primary current with respect to magnitude and phase angle within preset error limits. The main source of transmission errors is the magnetizing current. To ensure that this and the resulting transmission errors remain small, the current transformers without exception are fitted with high-grade core magnets. The core material are made of silicon-iron or high-alloy nickel-iron. Fig. 10-26 shows the magnetizing curves of different core materials. In special cases, cores with an air gap are used to influence the behaviour of a transformer core in the event of transient processes.

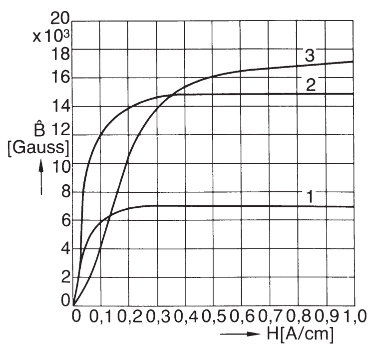


Fig.10-26

Magnetizing curves of various core materials. Measuring cores use core material 1 and protective cores core material 3.

H = field intensity (A/cm), B = peak value of the induction (Gauss),
1 = nickel-iron with approx. 75 % Ni,
2 = nickel-iron with approx. 50% Ni,
3 = cold-rolled silicon-iron with mill pattern

Depending on the design of the primary winding, current transformers are divided into single-turn transformers and wound-type transformers. Single-turn transformers are designed as outdoor inverted-type transformers, straight-through transformers, slipover and bar transformers. Wound-type transformers are bushing transformers, post-type transformers and miniature transformers and also outdoor post-type and tank transformers with oil-paper insulation. Fig. 10-27 shows the structural design of an top-core type transformer (Fig. 10-27a) and a tank transformer (Fig. 10-27b).

The various designs of current transformers classified by the insulating medium are shown in Table 10-3.

Table 10-3

Designs of current transformers

Insulation	Type	Voltage range	Application
Dry	Slipover, wound and cable current transformer	Low voltage	Indoor switchgear
Cast resin	Post-type and bushing transformer	Medium voltage	Indoor and SF_6 installations
Oil-paper/ porcelain	Tank and top-core type transformers	High and highest voltage	Outdoor installations
SF_6/compound*)	top-core type transformer	High and highest voltage	Outdoor installations

*) Compound material of fibre glass and silicone rubber

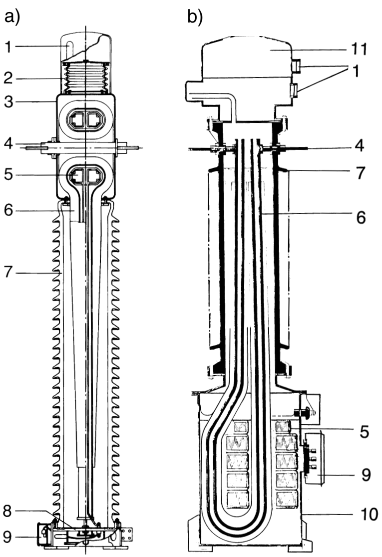


Fig. 10-27

a) Top-Core-type transformer type AOK for 145 ... 525 kV, 40 ... 6000 A, b) Hairpin-type transformer type IMBD for 36 ... 300 kV, 50 ... 2000 A

1 Oil-level indicator, 2 Bellows, 3 Terminal, 4 Primary connections, 5 Cores with secondary winding, 6 Core and coil assembly with main insulation, 7 Insulator, 8 Base plate, 9 Terminal box, 10 Tank, 11 Nitrogen cushion

If desired, current transformers can be provided with switching facilities for two or more primary currents.

The following designs are possible.

Primary reconnection

The reconnection takes the form of series/series-parallel or parallel switching of two or more partial primary windings. The rated output and rated overcurrent factor remain unchanged.

Secondary tappings

The changeover takes the form of tappings at the secondary winding.

When the primary rated current intensity is reduced in this way, the rated output in classes 0.1 . . . 3 decreases approximately as the square of the reduction in primary current and in safety classes 5 P and 10 P approximately proportional to the reduction of the primary current.

The absolute values of the rated short-time thermal current and the rated peak short-circuit current remain unchanged for all ratios.

Selection of current transformers

The choice of a current transformer is based on the values of the primary and secondary rated current, the rated output of the transformer cores at a given accuracy class rating and the overcurrent limit factor. The overcurrent limit factor must be adjusted to the load current of the consumer.

Determining the secondary output of a current transformer

The secondary output of a current transformer depends on the number of ampere turns, the core material and the core design. The output varies approximately as the square of the number of ampere turns (approximately linear with protective cores). However, it also decreases roughly as the square (approximately linear with protective cores) of the difference between the load current and the rated current of the current transformer. So with a transformer with 30 VA rated power with a load of half the rated current, the output is reduced by a quarter, about 7.5 VA.

The rated output of a current transformer is the product of the rated burden Z and the square of the secondary rated current I_{2n}^2, i.e.: $S_n = Z \cdot I_{2n}^2$ in VA. A current transformer with secondary I_{2n} = 5 A and a connected burden of 1.2 Ω has a rated output of 1.2 Ω · $5^2 A^2$ = 30 VA. The transformer may be loaded with the rated output on the nameplate without exceeding the error limits. All current paths of the instruments, meters, protection relays and the resistance of the associated connecting lines connected in series in the secondary current circuit must not reach more than the resistance value of this rated burden as a maximum (Table 10-4).

Table 10-4

Rated output and rated burden of current transformers (at 50 Hz)

Rated output in VA	5	10	15	30	60
Rated burden at 5 A in Ω	0.2	0.4	0.6	1.2	2.4
Rated burden at 1 A in Ω	5	10	15	30	60

The transformer output at 16⅔ Hz must be multiplied with the factor 0.33 and at 60 Hz by 1.2.

When selecting the current transformers, not only the output but also the overcurrent limit factor of the transformer must be considered. The overcurrent limit factor is given on the nameplate.

In the case of *measuring and metering cores,* the overcurrent limit factor should be as small as possible, e. g. 5 or 10, to protect the connected instrumentation against excessive overcurrents or short-circuit currents. Because the overcurrent limit factor only applies for the rated burden but actually rises with a smaller burden or smaller transformer load in approximately an inverse ratio, the operating burden of the connected instrumentation including the required connection lines must be equal to the rated burden of the transformer so far as possible to protect the measuring mechanisms from destruction. Otherwise, the secondary circuit should include an additional burden.

For additional details on selecting classes, error limits, rated outputs and designations, see DIN VDE 0414-1.

Example:

Current transformer for 100/5 A, 30 VA 0.5 FS 5

Power requirement:	1 ammeter	2.5 VA
	1 wattmeter	3 VA
	25 m of lines of 2.5 mm^2	4.5 VA
Total power requirement		10 VA

Since the product of the rated output of the core and overcurrent limit factor is approximately constant, the example gives 30 VA • 5 = 150 VA. Then for a burden of only 10 VA, an overcurrent factor of 150 : 10 = 15 is reached. Instrument protection is therefore not sufficient. If a transformer of only 15 VA is selected, the overcurrent factor is 7.5. The transformer output could therefore be even smaller, or an additional burden would have to be included.

Protective cores for connection of protection relays, in contrast to the measuring cores, must be selected so that their total error even with short-circuit currents in the range in which the protection relays should function accurately according to their settings, e.g. 6 to 8 times rated current, is not too large. Therefore, the protective core must be designed so the product of the rated output and the overcurrent limit factor is at least equal to the product of the power requirement of the secondary transformer circuit at rated current and the required overcurrent limit factor. This is particularly important when verifying the thermal short-circuit stress indicates a large primary conductor cross-section. In this case, a current transformer for higher rated current can be selected, where the primary winding number and also the output will be lower because the load current is less than the rated current, or a special transformer can be used.

Example:

Transformer for 400/5 A, 15 VA 5 P 10

Power requirement:	Overcurrent relay	8 VA
	Differential relay	1 VA
	Lines	3 VA
Total power requirement		12 VA

The overcurrent factor is then $\frac{15\text{ VA} \cdot 10}{12\text{ VA}} = 12.5$

i.e. the transformer is correctly selected.

An overcurrent relay set to 8 I_n will trip, because the current in the above case to 12.5 x rated current increases in proportion to the primary current.

The direct current component occurring at the beginning of a short circuit results in transmission errors by core saturation with fully displaced short-circuit current. Specially dimensioned cores with a high overcurrent limit factor (e.g. 200) or the selection of a high transformation ratio for the protective core can remedy this.

The above selection criteria also apply for current transformers in enclosed switchgear installations.

Current transformers according to international standards (e.g. ANSI) are in principle selected under similar criteria. Transformer dimensioning is made easier under the above provisions by using the following short overview with Tables 10-5 to 10-9.

Definition and standardized values as per IEC 60185 and DIN VDE 0414-1

Measuring core rated output: 2.5 – 5.0 – 10 – 15 – 30 VA;
burden output factor cos β = 0.8

Classes: 0.1 – 0.2 – 0.5 – 1: valid in the range of 25 % and 100 % of the rated burden.

0.2 s and 0.5 s: For special applications (electrical meters that measure correctly between 50 mA and 6 A, i.e. between 1% and 120% of the rated current of 5A)

3 – 5: valid in the range 50% to 100% of the rated burden

Label: measuring cores are identified by a combination of the rated output with the overcurrent limit factor and with the class, e.g.

15 VA class 0.5 FS 10
15 VA class 0.5 ext. 150%
(extended current measuring range)

Protective cores Rated output: preferably 10 – 15 – 30 VA

Classes: 5 P and 10 P: the numbers identify the maximum permissible total error with limit error current; the letter P stands for “protection”.

Accuracy limit factors: 5 – 10 – 15 – 20 – 30

Table 10-5

Error limits for measuring cores as per DIN VDE 0414-1

Accuracy class	Current error in % at rated current percentage value						± phase displacement at rated current percentage value									
							in minutes					in centiradians				
	1	5	20	50	100	120%	1	5	20	100	120%	1	5	20	100	120%
0.1	–	0.4	0.2	–	0.1	0.1	–	15	8	5	5	–	0.45	0.24	0.15	0,15
0.2	–	0.75	0.35	–	0.2	0.2	–	30	15	10	10	–	0.9	0.45	0.3	0,3
0.5	–	1.5	0.75	–	0.5	0.5	–	90	45	30	30	–	2.7	1.35	0.9	0,9
1	–	3	1.5	–	1.0	1.0	–	180	90	60	60	–	5.4	2.7	1.8	1,8
3	–	–	–	3	–	3	–	–	–	–	–	–	–	–	–	–
5	–	–	–	5	–	5	–	–	–	–	–	–	–	–	–	–
0.2S	0.75	0.35	0.2	–	0.2	0.2	30	15	10	10	10	0.9	0.45	0.3	0.3	0,3
0.5S	1.5	0.75	0.5	–	0.5	0.5	90	45	30	30	30	2.7	1.35	0.9	0.9	0,9

NOTE: the limit values given for current error and phase displacement are generally applicable for any position of an outside conductor with a distance no less than the insulation distance in air for the maximum voltage for equipment (U_m).

Special application conditions, enclosed low service voltages in connection with high current values should be subject to separate agreement between manufacturer and purchaser.

Table 10-6

Error limits for protective cores as per DIN VDE 0414-1

Accuracy class	Current error in % at primary	Phase displacement at primary rated current		Composite error in % at
	Rated current	in minutes	in centiradians	Rated accuracy limits
5 P	± 1	± 60	± 1.8	5
10 P	± 3	–	–	10

Definition and standardized values as per ANSI/IEEE – Standard C57.13-1978
(based on rated frequency 60 Hz)

Measuring cores Classes: 0.3 – 0.6 – 1.2

Designation: measuring cores are identified by a combination of the class with the burden identification, e.g.

0.3 B-0.1 or 0.6 B-0.5

Table 10-7

Normal burdens (for 5 A – secondary current)

Des. of burden	resistance (Ω)	inductance (mH)	impedance (Ω)	rated power (VA)	cos β
B-0.1	0.09	0.116	0.1	2.5	0.9
B-0.2	0.18	0.232	0.2	5.0	0.9
B-0.5	0.45	0.580	0.5	12.5	0.9
B-0.9	0.81	1.04	0.9	22.5	0.9
B-1.8	1.62	2.08	1.8	45.0	0.9

Table 10-8

Error limits in the range cos β = 0.6 – 1.0

Class	Ratio error (factor) at rated current 100 %		10 %		± Phase displacement at rated current 100 %	10 %	corresp. IEC class
	min.	max.	min.	max.	minutes[1)]	minutes[1)]	
0.3	0.997	1.003	0.994	1.006	16	33	0.2
0.6	0.994	1.006	0.988	1.012	33	65	0.5
1.2	0.968	1.012	0.976	1.024	65	130	1

[1)] approximate values derived from diagram

Protective cores

Table 10-9

Normal burdens: (for 5 A secondary current)[1)]

Designation of burden	Resistance Ω	Inductance (mH)	Impedance Ω	Rated power (VA)	cos β
B-1	0.5	2.3	1.0	25	0.5
B-2	1.0	4.6	2.0	50	0.5
B-4	2.0	9.2	4.0	100	0.5
B-8	4.0	18.4	8.0	200	0.5

1) In the case of other secondary currents, the burden values are converted at unchanged rated power and cos ß

Classes/Error limits

"C" and "T" at max. total error ≦ 10% in the range 1–20 x primary rated current (corresponding to IEC Class 10 P 20).

With "C" transformers, the magnetic flux in the transformer core does not influence the transformation ratio. With "T" transformers, magnetic flux influence at a limited level is permissible, but must be verified by testing.

Secondary terminal voltage

The transformer must supply this voltage at the rated burden at 20 times the secondary rated current without exceeding the max. ratio error of 10%.

Sec. terminal voltage (V)	Rated burden
100	B-1
200	B-2
400	B-4
800	B-8

Label

Protective cores are identified by class and secondary terminal voltage, e.g. C 100, a C-transformer with secondary terminal voltage 100 V for rated burden B-1.

Testing (100%) of current transformers

The transformers are subjected to the testing (100%) required under the standards before delivery. Table 10-10 shows an overview of the tests according to DIN VDE, IEC and ANSI.

Table 10-10

Testing (100%) of current transformers

Test	DIN VDE*) 0414-1	IEC 60185 (1987)	ANSI C 57.13 (1978)
1. connection labels	×	×	×
2. insulating capacity/alternating voltage test of the primary winding against ground	×	×	×
3. insulating capacity/alternating voltage test of the secondary windings against one another and against ground	×	×	×
4. winding test	×	×	
5. verification/accuracy measurement, current error and phase displacement	×	×	×
6. verification/accuracy measurement, total error with protective cores	×	×	
7. measurement of the magnetizing current with protective cores			×
8. partial-discharge measurement	× VDE 0414 Part10	× IEC 60044-4	
9. polarity measurement			×

*) largely identical to IEC 60185

10.5.3 Inductive voltage transformers

Inductive voltage transformers are transformers of low output with which the secondary voltage is practically proportional to and in phase with the primary voltage. Voltage transformers are used to transform the system voltage to be measured to a secondary voltage to be fed to measuring and protection devices. The primary and secondary windings are galvanically separated from each other.

Inductive voltage transformers are supplied in the following designs:

1. Two-phase isolated voltage transformers

   for connection between two phases, ratio 6000/100 V, for example. Two voltage transformers in V connection are normally used for measuring power in three-phase networks.

2. Single-phase isolated voltage transformers

   for connection between one phase and ground, ratio
   110 000 / $\sqrt{3}$ // 100 / $\sqrt{3}$ V.
   Three voltage transformers connected in star are required for measuring power in three-phase networks. If single-phase isolated voltage transformers have an auxiliary winding for ground-fault monitoring, in three-phase networks, this must be measured for the ratio of 100/3 V. The "open delta" in the three-phase set can also have a fixed resistance for damping relaxation oscillations (resulting from ferroresonances in insulated networks with small capacitances).

3. Three-phase voltage transformers

   with the measuring windings connected in star and an auxiliary winding on the 4th and 5th limb for ground-fault detection. The auxiliary winding has a voltage of 100 V in the event of a ground fault.

Inductive voltage transformers are selected by the primary and secondary rated voltage and the accuracy class and rated output of the secondary windings in accordance with the requirements of the devices to which they are to be connected.

If there is a winding for ground fault detection, its rated thermal limit output must be given. For the short-time withstand, the rated voltage factor and the specified load duration at increased voltage are required.

10.5.4 Capacitive voltage transformers

Voltage transformers at higher system voltages to 765 kV that operate under the principle of the capacitive voltage divider can also be used. The capacitive voltage transformers are designed for connection of all standard operational instrumentation and network protection relays; they are also approved for tariff metering.

Fig. 10-28 shows the line diagram of a capacitive voltage transformer. Network protection relays with transistorized circuits for the shortest closing times are also securely fed from capacitive transformers, particularly if the transformers have a sampling device that damps all transient oscillations of the transformer in the shortest time.

Capacitive voltage transformers also have the advantage of being usable for coupling high-frequency power-line carrier systems, e.g. for telecommunications, remote-control installations and similar purposes. The required supplementary elements (choke, surge arrester) can be installed in terminal boxes.

When selecting capacitive voltage transformers, primary and secondary rated voltage, rated frequency, rated output and class are the essential features. In addition, the rated thermal limiting output of a ground-fault detector winding, rated voltage factor and the specified load duration at increased voltage must be considered.

Capacitive voltage transformers are selected similarly to the inductive transformers, but the capacitances of the high-voltage capacitors (C_1), of the intermediate-voltage capacitor (C_2) and the rated capacity (C_n) must also be given. A dimensioning example for a capacitive voltage transformer is shown below:

Primary rated voltage	$\frac{110\,000}{\sqrt{3}}$ V
Secondary rated voltage of the measuring effect	$\frac{110}{\sqrt{3}}$ V
of the winding for the ground fault detection	$\frac{100}{3}$ V
Rated output	75 VA, Cl. 0.5
Rated voltage factor	1.9 U_n, 4h
Thermal rated burden rating	120 VA, 8h
Rated capacity	4.400 pF ± 10 %
Rated frequency	50 Hz

The properties with transient processes are also important with capacitive transformers (interaction with network protection).

SF_6-insulated switchgear installations also include inductive and capacitive voltage transformers, see Section 11.2.

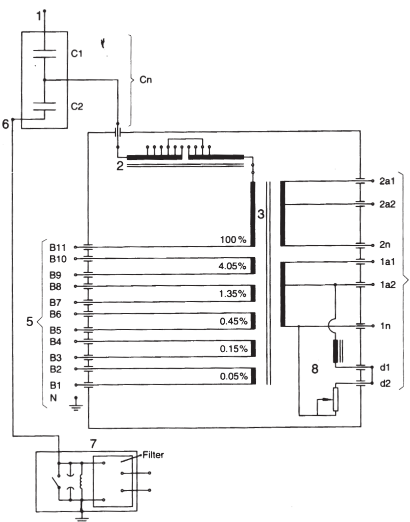


Fig.10-28

Basic diagram of a capacitive voltage transformer

1 High-voltage terminal, 2 Medium-voltage choke coil, 3 Transformer, 4 Secondary terminals, 5 Terminal box trimming winding, 6 TFH terminal, 7 TFH coupling, 8 Damping device, C_n C_1 C_2 capacitive voltage divider

10.5.5 Non-conventional transformers

In contrast to conventional transformers, non-conventional current and voltage transformers are distinguished by compact size and low weight. They are generally not saturable and have high transmission bandwidths. The measured values are best transmitted by fibre-optic cables, which are practically immune to electromagnetic fields (EMC). The non-conventional type of measured value acquisition and transmission requires only limited output in the area of 0.1 ... 5 VA on the secondary side.

Non-conventional transformers consist of a measurement recorder, a measured value transmission line bridging the potential difference between high voltage and ground potential and an electronic interface at ground potential for measured-value processing and connections to protection devices in the station control system.

Measurement recorders can be divided into active and passive systems depending on the method used.

Active non-conventional transformers

Hall-effect elements, Rogowski coils or specially designed bar-type current transformers with linear characteristics are used for current detection. Voltage acquisition is generally done using resistive or capacitive voltage dividers. In substation technology for rated voltages below 52 kV and also for GIS installations for higher voltages, active non-conventional transformers offer very attractive solutions.

However, in outdoor substation technology for transmission networks, the electrical measured quantities must still be converted to a digital or analogue optical signal at high-voltage potential. This requires devices for providing the required auxiliary energy at high-voltage potential. This energy requirement may be taken from the high-voltage system that is being monitored and also provided by optical means, whether by solar cell or by energy transmission via fibre-optic lines.

Passive non-conventional transformers

Passive measurement recorders do not require auxiliary energy at high-voltage potential. They are normally completely constructed of dielectric materials.

Passive optical voltage transformers

Linear electro-optic effects (Pockel effect) linked to specific classes of crystals are used for voltage measurement with optical voltage transformers. The physical principle of the Pockel effect is a change of the polarization state of light that is sent within an electrical field through a transparent material. The change in polarization is linearly proportional to the applied electrical field.

In the ABB-developed EOVT (electro optical voltage transducer) the Pockel cell, a BGO crystal ($Bi_{12}GeO_{20}$) is installed directly between the high voltage electrode and ground with the light path parallel to the electrical field (Fig. 10-29).

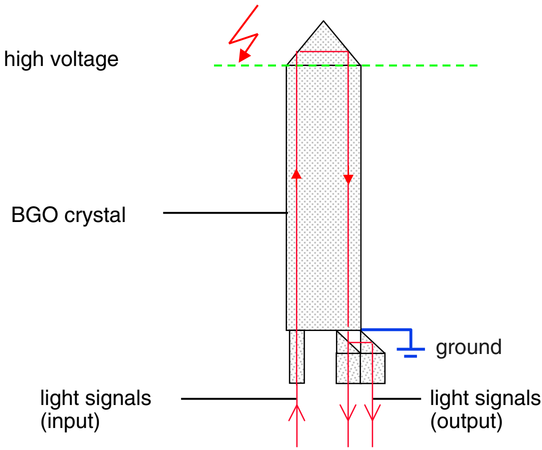


Fig.10-29

Principle of the light circuit in a crystal (BGO) for passive optical voltage measurement using the Pockel effect

The monochromatic polarized light beam entering at ground potential in the end face of the crystal is reflected at the prismatic end of the crystal at high-voltage potential so the dielectrically stressed range is run through twice by light. This doubles the polarity change caused by the electrical field. The light beam exiting the end face is split into two directional components by an optical system. These are transmitted to the photodiodes by fibre-optic cables. They indicate the phase difference (polarization change) arising in the dielectric field from the intensities of the two components and therefore a scale for the applied voltage. The use of two light signals at the output has the advantage of providing an accurate measurement result in spite of relatively small output signals and parasitic effects (phase change by temperature influence and natural double refraction properties of the crystal) are eliminated.

The EOVT was designed from the outset for voltage levels to at least 420 kV. Therefore, the BGO crystal is basically surrounded by an SF_6 atmosphere. Fig. 10-30 shows the EOVT in an enclosed SF_6-insulated switchgear installation for 123 kV. The BGO crystal is surrounded by a glass tube between two field-control electrodes, the lower at high-voltage potential and the upper at ground potential. The monochromatic light feed and the return line of the subcomponents after the polarization change is through fibre-optic cables, which feed through the grounded installation enclosure to the processing device.

For applications in outdoor installations, the active component of the EOVT, as shown in Fig. 10-33 as a combination solution with a current transformer, is installed inside an appropriate SF_6-filled composite insulator. The technical data of the EOVT optical voltage transformer is shown in Table 10-11.

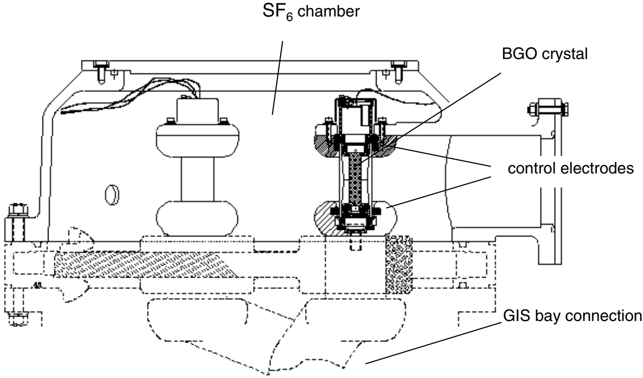


Fig.10-30

View of a voltage transformer (EOVT) for a gas-insulated switchgear installation (GIS). The transformers for two phases of a GIS bay.

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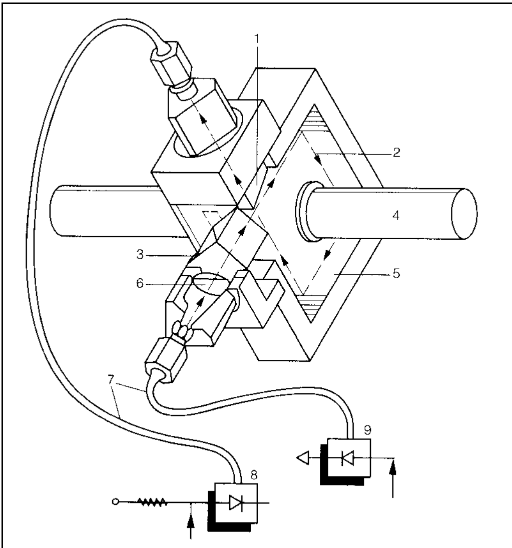
Passive optical current transformer

An optical current transformer like the ABB-developed MOCT (magneto optical current transducer) uses the Faraday effect in crystalline structures for passive measurement of currents. Again monochromatic light is sent polarized into a solid body of glass, which surrounds the current carrying conductor. Reflection from the bevelled corners of the glass container directs the light beam around the conducting line before it exits again on one side (Fig. 10-31).

The magnetic field around the conductor rotates the polarization plane of the light, whose phase difference is proportional to the magnetic field intensity H. Because the light in the glass body completely surrounds the current path as a line integral along a closed curve, the phase difference at the end of the path in the glass body is directly proportional to the current. A polarization filter at the exit point of the light from the glass body only allows one subcomponent of the light generated by the rotation to pass. It is fed to the processing unit through fibre-optic cables. The intensity of this subcomponent is the scale for the polarization change and so for the magnitude of the current.



Legend

1 Analyzer
2 Light path in sensor
3 Polarizer
4 Primary conductor
5 Faraday sensor
6 Lens
7 fibre-optic cable
8 Detector
9 Light source

Fig.10-31

Passive non-conventional current transformer (MOCT). The Faraday sensor around the conductor line is structured as a glass block.

The technical data of the MOCT optical current transformer are summarized in Table 10-12. Its low space requirements and low weight (Fig. 10-32) provide new options in the design of outdoor switchgear installations, such as by a (already implemented) combination of circuit-breaker and MOCT. In addition, the combined solution of EOVT and MOCT shown in Fig. 10-33 is distinguished on one hand by the environmental aspect – no danger of contamination by leaking oil – and on the other hand by a substantial reduction in weight compared to conventional solutions.

Connection to protection technology

Devices and systems in conventional secondary technology are generally directly linked to the primary quantity with standardized current and voltage ports (typically 100 V or 1 A). The former specification of these ports is based on the requirements of analogue secondary devices with high power requirements and the attempt to attain security with reference to electromagnetic influence by relatively high signal levels.

However, modern secondary devices, in general digital, only require a small part of the input power that was formerly required (typically 0.1 VA to 1 VA).

In non-conventional metering transformers, the processing device sends a small signal that is generally suitable for digital secondary devices. However, if necessary, supplementary amplifier inserts can generate current and voltage signals suitable for the interfaces of conventional secondary technology.

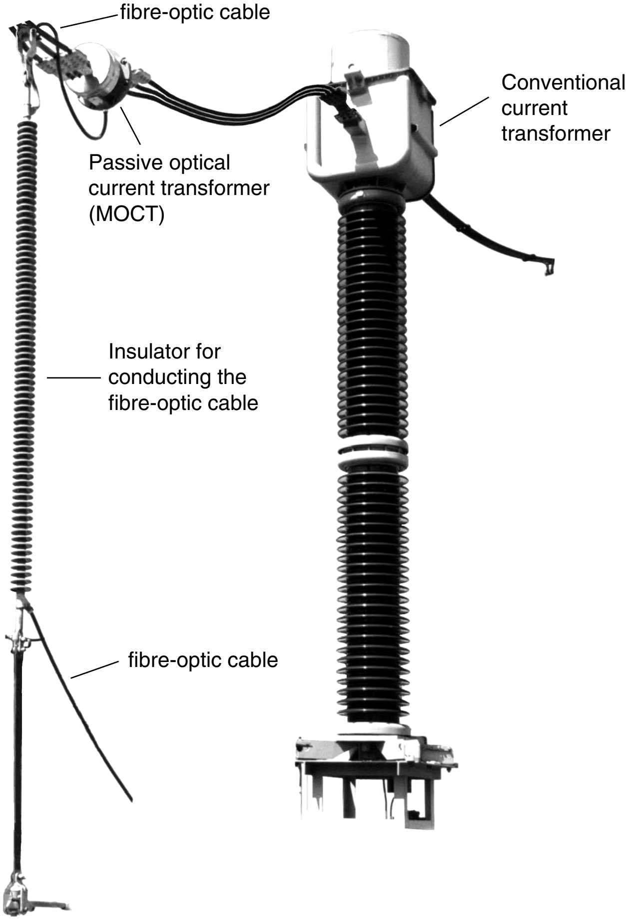


Fig.10-32

Comparison of a non-conventional current transformer (left in the picture) with a conventional outdoor transformer with paper-oil insulation

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Table 10-11

Technical data of the non-conventional passive voltage transformer (EOVT)

Voltage level outdoor transformer	420 kV
Voltage level GIS transformer	66 to 170 kV
Accuracy class rating	0.2
Frequency range	> 5 kHz
Output signal (secondary electronics)	4.8 V AC at U_{rated} (100 V interface for conventional connection also available)
Operating temperature range	– 25 °C to + 70 °C

Table 10-12

Technical data of the non-conventional passive current transformer (MOCT)

Measurement range	0 to 32 kA_{eff}
Rated current	2 000 A
Rated short-time current	50 kA (1 s)
Voltage level	420 kV
Accuracy class rating	0.2 in the range 4 .... 4 000 A
Frequency range	> 5 kHz
Output signal measurement (secondary electronics)	2.0 V AC (at I_{rated})
Output signal protection (secondary electronics)	2.0 V AC (at 10 x I_{rated}) (1 A interface for conventional connection also available)
Operating temperature range	– 50 °C to + 70 °C
Max. transmission length	800 m
Weight of measurement recorder	approx. 18 kg

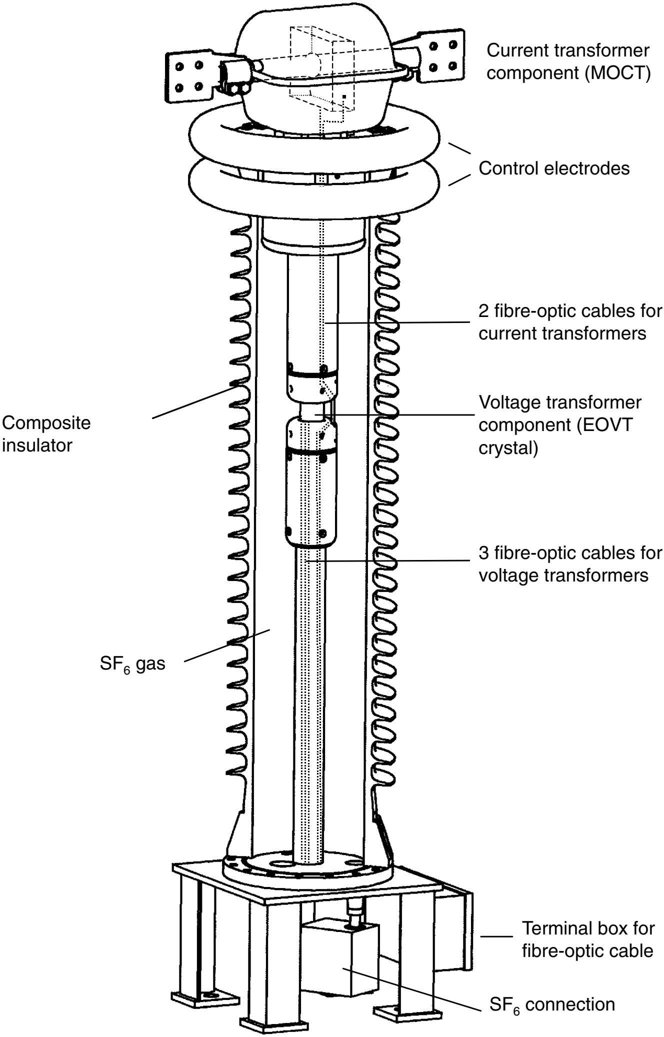


Fig. 10-33

Outdoor design of a combined non-conventional current/voltage transformer in passive optical technology

10.6 Surge arresters

10.6.1 Design, operating principle

The operation and design of the surge arrester has radically changed over the last twenty years.

Arresters with spark gap with series-connected silicon carbide (SiC) resistors have been replaced by surge arrester technology without spark gap and with metal-oxide resistors. The former porcelain housing is also being replaced more and more by polymer insulation. DIN EN 60 099-4 (VDE 0675 Part 4) contains detailed information on the new arrester technology.

The gapless arresters are based on metal oxide (MO) resistors, which have an extremely non-linear U/I characteristic and a high energy-absorption capability. They are known as metal oxide surge arresters, MO arresters for short.

The MO arrester is characterized electrically by a current/voltage curve (Fig. 10-34). The current range is specified from the continuous operating range (range A of the curve, order of magnitude 10^{-3} A) to a minimum of the double value of the rated discharge current (order of magnitude 10^3 A). The MO arrester corresponding to the characteristic is transferred from the high-resistance to the low-resistance range at rising voltage without delay. When the voltage returns to the continuous operating voltage U_c or below, the arrester again becomes high-ohmic.

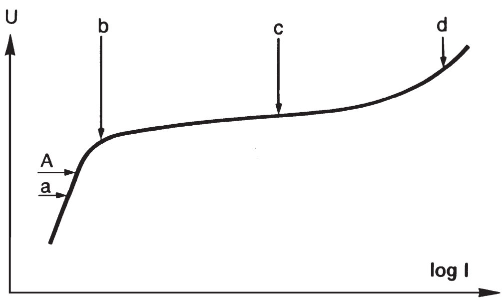


Fig. 10-34

Current-voltage characteristic of a metal oxide resistor; a Lower linear part, b Knee point, c Strongly non-linear part, d Upper linear part ("turn up" area), A Operating point (continuous persistent voltage)

The protective level of the MO arrester is set by its residual voltage U_P. The residual voltage is defined as the peak value of the voltage at the terminals of the arrester when a surge current flows. A surge current with a front time of about 1 μs, a time to half-value of up to 10 μs and a current of up to 10 kA represents very steep overvoltage waves, and the associated residual voltage is comparable to the front sparkover voltage of spark-gapped arresters.

A surge current with a front time of about 8 μs and a current intensity of up to 10 kA yields a residual voltage that is approximately equal to the protection level with lightning surge voltage. The current wave with a front time between 30 μs and 100 μs corresponds to a switching voltage pulse. The residual voltage with this wave form at 1 kA yields the protection level for switching voltages.

Surge arresters are protective devices that may be overloaded under extreme fault conditions. In such cases, e.g. when voltage leaks from one network level to the other, a single-phase earth fault occurs in the resistor assembly of the arrester. The pressure relief ensures that porcelain housings do not explode. The earth-fault current of the network at the arrester site must be less than the guaranteed current for the pressure relief of the relevant arrester. Fig. 10-35 shows the structural design of an MO arrester with a polymer housing.

Today, MO arresters for protection of medium-voltage equipment almost always have composite housings of silicon polymer. This insulation material allows the metal oxide resistors to be directly surrounded without gas inclusions. This type, in contrast to arresters with porcelain or other tube material, does not require a pressure-relief device for a possible overload. Because the polymeric arresters are substantially lighter, have a better response under contamination layer conditions and the arrester cannot fall apart in the event of an overload, this new technology is becoming more and more common even for arresters for high voltage.

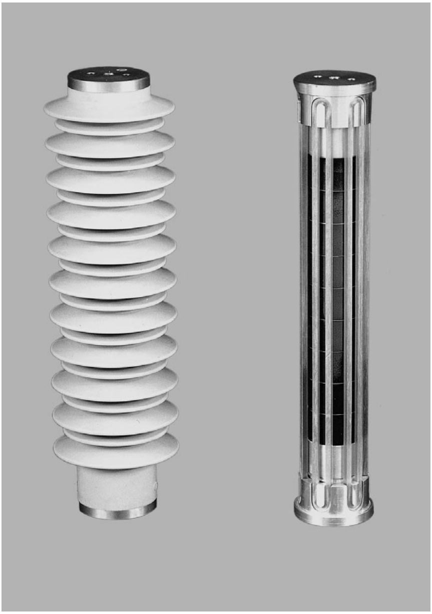


Fig.10-35

Cutaway view (principle design) of a metal oxide surge arrester, type POLIM-H

10.6.2 Application and selection of MO surge arresters

Surge arresters are used for protection of important equipment, particularly transformers, from atmospheric overvoltages and switching overvoltages. MO arresters are primarily selected on the basis of two basic requirements:

– the arrester must be designed for stable continuous operation,
– it must provide sufficient protection for the protected equipment.

Stable continuous operation means that the arrester is electrically and mechanically designed for all load cases that occur under standard operation and when system faults occur. This requires that the electrical and mechanical requirements are known as precisely as possible. The magnitude of the maximum power-frequency voltage, magnitude and duration of the temporary overvoltages and the anticipated stresses caused by switching and lightning overvoltages must all be known. In addition, the stress caused by short-circuit current forces and special environmental conditions, e.g. pollution, ambient temperatures over 45 °C, installation in earthquake regions etc., are very important.

When selecting the arrester by its electrical data, there must be an appropriate margin between the protection level of the arrester and the insulation levels standardized for the applicable operating voltage to meet the requirements of the insulation coordination as per DIN EN 60 071-1 (VDE 0111 Part 1) (Fig. 10-36).

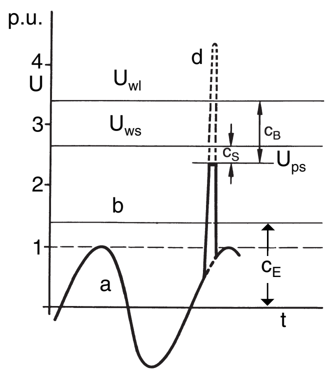
Parallel connecting of MO resistor columns allows every technically necessary dimension of the energy-absorption capability to be implemented at equivalent protection levels. Doubling the number of columns can reduce the protection level and almost double the energy-absorption capability.

DIN EN 60099-5 (VDE 0675 Part 5) outlines the correct selection of MO arresters.

Fig.10-36

Arrester selection for a low-resistance earthed network (c_E = 1,4) in range II (U_m ≥ 245 kV) as per DIN EN 600099-5 (VDE 0675 Part 5)

- *a* *maximum power frequency conductor-ground voltage in the normally operating network (1 p.u. = peak value)*
- *b* *peak value of the maximum temporary power frequency conductor-ground voltage at earth fault in an adjacent phase*
- c_E *earth fault factor (= 1.4)*
- *d* *switching impulse overvoltage (limited by arrester to U_{ps})*
- U_{ps} *switching impulse protection level of the arrester*
- U_{wL} *rated lightning impulse voltage for equipment-standardized values*
- U_{wS} *rated switching impulse voltage for equipment-standardized values*



C_B, C_S *safety margins*

For MO arresters, the *continuous operating voltage* U_c is defined as the maximum power frequency voltage that the arrester can withstand continuously. The peak value of the continuous operating voltage of the arrester must be higher than the peak value of the operating voltage. On one hand, it is determined by the power-frequency voltage that corresponds to the maximum voltage in the network; but on the other hand, possible harmonics of the voltage must be considered. In normal networks, a safety margin of 5% over the power frequency system voltage is sufficient.

The *rated voltage* U_r of an MO arrester is the reference value to the power frequency voltage versus time characteristic and is decisive for the selection of the arrester with reference to temporary overvoltages. During the operating duty test of an MO arrester type, a test voltage of U_r is applied immediately following the surge current for a period of 10 s to the test object.

U_r is the 10 s value in the power frequency voltage versus time characteristic of the arrester. Peak values of the permissible power-frequency alternating voltage for other periods (U_t , T_t) are taken from the characteristic submitted by the manufacturer or derived approximately for period T_t in s between 0.1 s and 100 s by calculation as in the following equation:

$$U_t = \sqrt{2}\, U_r \left(\frac{10}{T_t}\right)^m$$

m = arrester-specific exponent, average value 0.02

Possible causes of the occurrence of temporary overvoltages include

- Earth fault
- Load shedding
- Resonance phenomena and
- Voltage increases over long lines

The following selection recommendations can be formulated based on the neutral treatment in networks:

Arresters between line and earth

- In networks with automatic earth-fault interruption, the continuous operating voltage U_c of the arrester should be equal to or greater than the peak value of the maximum operating voltage of the network against ground divided by $\sqrt{2}$
- In networks with earth-fault neutralizing or isolated neutral point without automatic fault disconnection, the continuous operating voltage should be greater than or at least equal to the maximum operating voltage of the network.

Arresters between phases

- The continuous operating voltage must be at least 1.05 times the maximum service voltage.

Neutral-point arresters

- For networks with low-resistance neutral-point configuration, the continuous operating voltage U_c of the arresters is derived from the dielectric strength specified for the neutral point of the equipment.
- For networks with earth-fault compensation or with insulated neutral point, the continuous operating voltage should be at least equal to the maximum service voltage divided by $\sqrt{3}$

Table 10-13 shows recommended standard values for selecting MO arresters (under the asumption that no additional temporary overvoltages occur) for some current nominal system voltages and the earth-fault factors appearing there.

Table 10-13

Recommended values for MO arresters according to the continuous operating voltage U_c and the associated rated voltage U_r

Nominal system voltage kV	Phase arrester				Neutral-point arrester			
	at $C_E = 1.4$		at $C_E = \sqrt{3}$		at $C_E = 1.4$		at $C_E = \sqrt{3}$	
	U_c kV	U_r kV	U_c kV	U_r kV	U_c kV	U_r kV	U_c kV	U_r kV
6	–	–	7,2	9	–	–	> 4,7	> 5,9
10	–	–	12	15	–	–	> 7,8	> 9,75
20	–	–	24	30	–	–	> 15,6	> 12,5
30	–	–	36	45	–	–	> 23,4	> 29,3
110	75	126	123[1)]	144[1)]	50	78	72	84
220	160	216[2)]	–	–	60	108	–	–
380	260	360[2)]	–	–	110	168	–	–

[1)] Lower values are possible if the duration of the earth fault is accurately known.

[2)] Higher values are set for generator transformers.

After specifying the continuous operating voltage and the rated voltage of the arrester that is to be used, selection is based on the energy-absorption capability required by the system conditions (rated discharge current and line discharge class). The following selection recommendation for rated discharge current can be set as a general guideline:

Distribution networks of up to 52 kV

– sufficient under standard conditions	5 kA
– at higher lightning intensity, cable units, capacitors, specially important analogues	10 kA
– specially high lightning loads	20 kA
Transmission networks of up to 420 kV	10 kA
Transmission networks over 420 kV	20 kA

In specially supported cases, it may be necessary to determine the required energy-absorption capability more accurately, e.g. as follows

– Closing or reclosing long lines,
– Switching capacitors or cables with non-restrike-free switching devices,
– Lightning strikes in overhead lines with high insulation level or back flashovers near the installation site.

If the calculated energy content exceeds the energy quantity absorbed at the duty test of the arresters, an arrester with higher rated discharge current or parallel connected arresters must be selected.

Surge arresters are preferably installed parallel to the object to be protected between phase and earth. Because of the limited protection distance with steep lightning impulse voltages, the arresters must be installed immediately adjacent to the equipment that is to be protected (e.g. transformer) as much as possible. The size of the protection distance of an arrester is dependent on a whole series of influencing parameters. It increases as follows:

– the difference between rated lightning impulse voltage of the equipment and the protection level (U_{pl}) of the arrester,
– the limitation of the peak value of the incoming lightning surge voltage wave by the mast type of the overhead line before the substation (e.g. grounded cross-arms or timber masts),

but also from the point of view of the insulation coordination with

– the decrease of the lightning strike rate of the overhead line (e.g. shielding by overhead ground wire) and with

– the increase of the fault rate that is still considered acceptable for the equipment that must be estimated.

Examples for the size of protection ranges in outdoor switchgear installations for various rated system voltages under practice-relevant conditions are shown in Table 10-14. Permissible fault rates of 0.25% per year for the equipment and lightning strike rates of 6 per 100 km x year for the 24 kV overhead lines and of 2 per 100 km x year for the high-voltage lines are assumed.

Table 10-14

Guidance values for the protection range of MO arresters

Network nominal voltage kV	Arrester protection level kV	Rated lightning impulse withstand voltage kV	Protection distance m
24	80	125	3[1)]/15[2)]
123	350	550	24
420	900	1425	32

[1)] Overhead line with timber masts (without grounding)
[2)] Overhead line with grounded cross-arms

The ABB travelling wave program for testing larger switchgear installations can be used to calculate the temporal course of the voltage at all interesting points of the installation.

In overhead lines with cable feed, the travelling wave through the cable with overvoltages must be calculated by reflection in spite of the depression. Arrester A1 is to be provided for protection of the cable in short cable units ($l_k \leq 5$ m) and arrester A3 for protection of the transformer, see fig. 10-37. however, if $l_k > 5$ m, the cable must be protected on both sides with arresters A1 and A2. In this case, arrester A3 can only be omitted with the transformer if the protection range of arrester A2 is greater thanl_1.

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Cable units within an overhead line should be protected immediately adjacent to the two end seals with arresters.

Surge counters may be used to monitor surge arresters. They are installed in the ground conductor of the arrester that is to be monitored; the arresters must be installed insulated against ground.

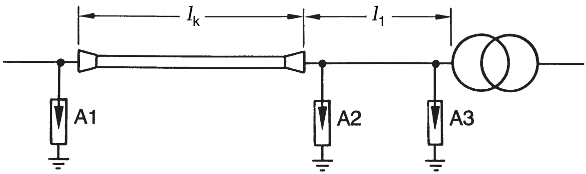

Fig. 10-37

Overvoltage protection of the cable link of overhead lines, l_K*: length of cable unit,* l_1*: distance cable / transformer, A1 & A2 arresters for protection of the cable, A3 arrester for protection of the transformer*