11 High-Voltage Switchgear Installations

11.1 Summary and circuit configuration

11.1.1 Summary

A switchgear installation contains all the apparatus and auxiliary equipment necessary to ensure reliable operation of the installation and a secure supply of electricity. Three-phase a.c. high-voltage switchgear installations with operating voltages of up to 800 kV are used for distributing electricity in towns and cities, regions and industrial centres, and also for power transmission. The voltage level employed is determined by the transmission capacity and the short-circuit capacity of the power system.

Distribution networks are operated predominantly up to 123 kV. Power transmission systems and ring mains round urban areas operate with 123, 245 or 420 kV, depending on local conditions. Over very large distances, extra high powers are also transmitted at 765 kV or by high-voltage direct-current systems.

Switchgear installations can be placed indoors or outdoors. SF_6 gas-insulated switching stations have the important advantage of taking up little space and being unaffected by pollution and environmental factors.

Indoor installations are built both with SF_6 gas-insulated equipment for all voltage ratings above 36 kV and also with conventional, open equipment up to 123 kV. SF_6 technology, requiring very little floor area and building volume, is particularly suitable for supplying load centres for cities and industrial complexes. This kind of equipment is also applied in underground installations.

Outdoor switching stations are used for all voltage levels from 52 to 765 kV. They are built outside cities, usually at points along the cross-country lines of bulk transmission systems. Switchgear for HVDC applications is also predominantly of the outdoor type.

Transformer stations comprise not only the h.v. equipment and power transformers but also medium- and low-voltage switchgear and a variety of auxiliary services. These must additionally be accounted for in the station layout.

Depending on the intended plant site, the construction of a switchgear installation must conform to IEC requirements, VDE specifications (DIN VDE 0101) or particular national codes.

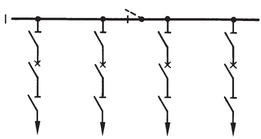
The starting point for planning a switchgear installation is its single-line diagram. This indicates the extent of the installation, such as the number of busbars and branches, and also their associated apparatus. The most common circuit configurations of high and medium-voltage switchgear installations are shown in the form of single-line diagrams in Section 11.12.

11.1.2 Circuit configurations for high- and medium-voltage switchgear installations

The circuit configurations for high- and medium-voltage switchgear installations are governed by operational considerations. Whether single or multiple busbars are necessary will depend mainly on how the system is operated and on the need for sectionalizing, to avoid excessive breaking capacities. Account is taken of the need to isolate parts of the installations for purposes of cleaning and maintenance, and also of future extensions.

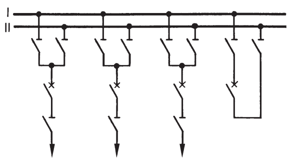
When drawing up a single line-diagram, a great number of possible combinations of incoming and outgoing connections have to be considered. The most common ones are shown in the following diagrams.

Common circuit configurations



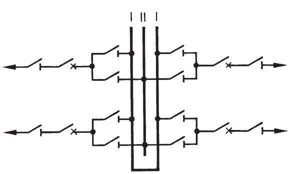
Single busbars

Suitable for smaller installations. A sectionalizer allows the station to be split into two separate parts and the parts to be disconnected for maintenance purposes.



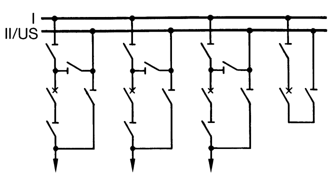
Double busbars

Preferred for larger installations. Advantages: cleaning and maintenance without interrupting supply. Separate operation of station sections possible from bus I and bus II. Busbar sectionalizing increases operational flexibility.



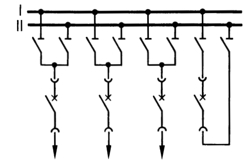
Double busbars in U connection

Low-cost, space-saving arrangement for installations with double busbars and branches to both sides.



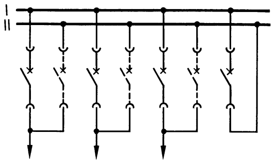
Composite double bus/bypass bus

This arrangement can be adapted to operational requirements. The station can be operated with a double bus, or with a single bus plus bypass bus.



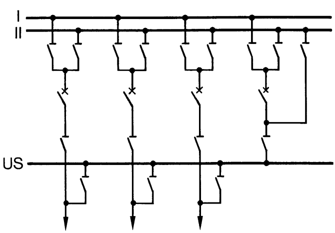
Double busbars with draw-out circuit-breaker

In medium-voltage stations, draw-out breakers reduce downtime when servicing the switchgear; also, a feeder isolator is eliminated.



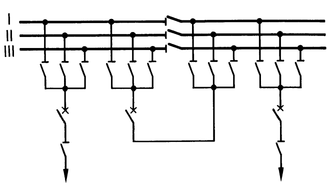
Two-breaker method with draw-out circuit-breakers

Draw-out circuit-breakers result in economical medium-voltage stations. There are no busbar isolators or feeder isolators. For station operation, the draw-out breaker can be inserted in a cubicle for either bus I or bus II.



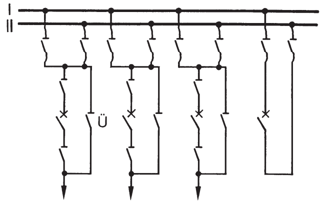
Double busbars with bypass busbar (US)

The bypass bus is an additional busbar connected via the bypass branch. Advantage: each branch of the installation can be isolated for maintenance without interrupting supply.



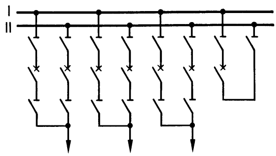
Triple (multiple) busbars

For vital installations feeding electrically separate networks or if rapid sectionalizing is required in the event of a fault to limit the short-circuit power. This layout is frequently provided with a bypass bus.



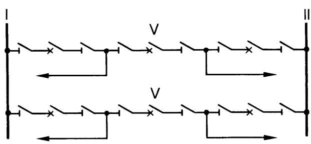
Double busbars with shunt disconnector

Shunt disconnector "U" can disconnect each branch without supply interruption. In shunt operation, the tie breaker acts as the branch circuit-breaker.



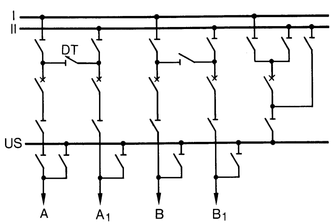
Two-breaker method with fixed switchgear

Circuit-breaker, branch disconnector and instrument transformers are duplicated in each branch. Busbar interchange and isolation of one bus is possible, one branch breaker can be taken out for maintenance at any time without interrupting operation.



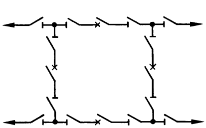
1 ½-breaker method

Fewer circuit-breakers are needed for the same flexibility as above. Isolation without interruption. All breakers are normally closed. Uninterrupted supply is thus maintained even if one busbar fails. The branches can be through-connected by means of linking breaker V.



Cross-tie method

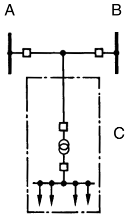
With cross-tie disconnector "DT", the power of line A can be switched to branch A_1, bypassing the busbar. The busbars are then accessible for maintenance.



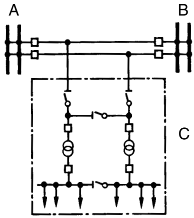
Ring busbars

Each branch requires only one circuit-breaker, and yet each breaker can be isolated without interrupting the power supply in the outgoing feeders. The ring busbar layout is often used as the first stage of 1 ½-breaker configurations.

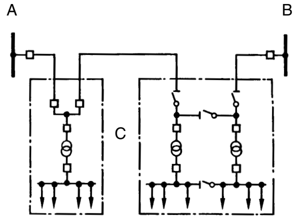
Configurations for load-centre substations



Single-feed station



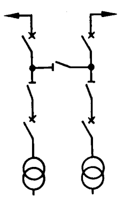
Double-feed station



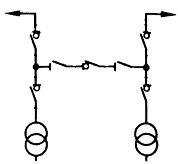
Ring stations

A and B = Main transformer station, C = Load-centre substation with circuit-breaker or switch disconnector. The use of switch-disconnectors instead of circuit-breakers imposes operational restrictions.

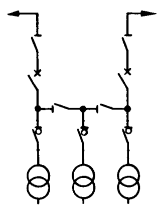
Switch-disconnectors are frequently used in load-centre substations for the feeders to overhead lines, cables or transformers. Their use is determined by the operating conditions and economic considerations.



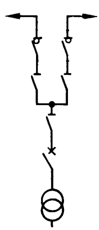
H connection with circuit-breakers



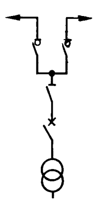
H connection with switch-disconnectors



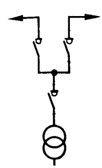
H connection with 3 transformers



Ring main cable connection allowing isolation in all directions

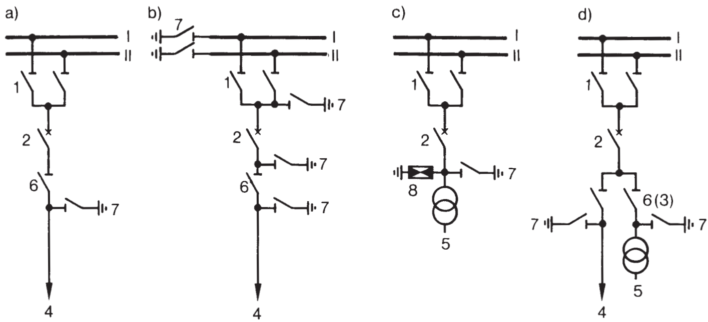


Simple ring main cable connection



Cable loop

Branch connections, variations a) to d)



1 Busbar disconnector, 2 Circuit-breaker, 3 Switch-disconnector, 4 Overhead-line or cable branch, 5 Transformer branch, 6 Branch disconnector, 7 Earthing switch, 8 Surge arrester

a) Overhead-line and cable branches

Earthing switch 7 eliminates capacitive charges and provides protection against atmospheric charges on the overhead line.

b) Branch with unit earthing

Stationary earthing switches 7 are made necessary by the increase in short-circuit powers and (in impedance-earthed systems) earth-fault currents.

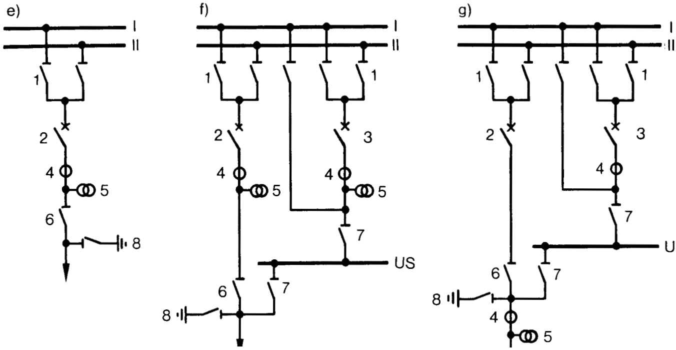
c) Transformer branches

Feeder disconnectors can usually be dispensed with in transformer branches because the transformer is disconnected on both h.v. and l.v. sides. For maintenance work, an earthing switch 7 is recommended.

d) Double branches

Double branches for two parallel feeders are generally fitted with branch disconnectors 6. In load-centre substations, by installing switch-disconnectors 3, it is possible to connect and disconnect, and also through-connect, branches 4 and 5.

Connections of instrument transformers, variations e) to g)



1 Busbar disconnectors, 2 Branch circuit-breaker, 3 Bypass circuit-breaker, 4 Current transformers, 5 Voltage transformers, 6 Branch disconnector, 7 Bypass disconnectors, 8 Earthing switch

e) Normal branches

The instrument transformers are usually placed beyond the circuit-breaker 2, with voltage transformer 5 after current transformer 4. This is the correct arrangement for synchronizing purposes. Some kinds of operation require the voltage transformer beyond the branch disconnectors, direct on the cable or overhead line.

f) Station with bypass busbar

Instrument transformers within branch.

The instrument transformers cease to function when the bypass is in operation. Line protection of the branch must be provided by the instrument transformers and protection relays of the bypass. This is possible only if the ratios of all transformers in all branches are approximately equal. The protection relays of the bypass must also be set for the appropriate values. Maintenance of the branch transformers is easier and can be done during bypass operation. If capacitive voltage transformers are used which also act as coupling capacitors for a high-frequency telephone link, this link is similarly inoperative in the bypass mode.

g) Station with bypass busbar

Instrument transformers outside branch.

In bypass operation, the branch protection relays continue to function, as does the telephone link if capacitive voltage transformers are used. It is only necessary to switch the relay tripping circuit to the bypass circuit-breaker 3. Servicing the transformers is more difficult since the branch must then be out of operation.

The decision as to whether the instrument transformers should be inside or outside the branch depends on the branch currents, the protection relays, the possibility of maintenance and, in the case of capacitive voltage transformers, on the h.f. telephone link.

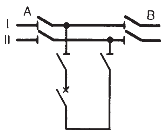
Busbar coupling connections

A and B = Busbar sections, LTr = Busbar sectioning disconnector

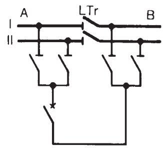
In the configurations earlier in this chapter, the tie-breaker branches are shown in a simple form. Experience shows, however, that more complex coupling arrangements are usually needed in order to meet practical requirements concerning security of supply and the necessary flexibility when switching over or disconnecting. This greater complexity is evident in the layouts for medium- and high-voltage installations.

Division into two bays is generally required in order to accommodate the equipment for these tie-breaker branches.

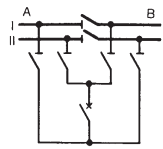
Double busbars



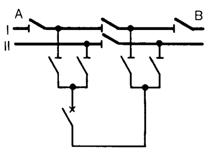
Bus coupling SSI/II for A or B



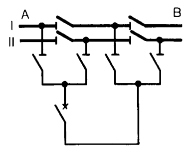
Section coupling for A-B Bus coupling SSI/II via disconnector LTr



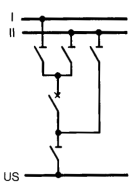
6-tie coupling Section coupling for A-B Bus coupling SSI/II for A or B



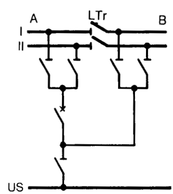
Section coupling for A-B Bus coupling SSI/II for A or B via tie-breaker bus II



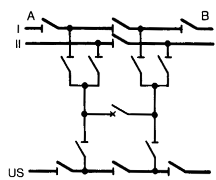
8-tie coupling Section coupling for A-B Bus coupling SSI/II for A or B



Bus coupling SSI/II Bypass (US) coupling SSI or II to bypass

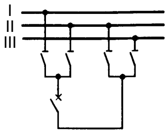


Section coupling for A-B Bus coupling SSI/II via LTr Bypass coupling A direct, B via LTr to bypass

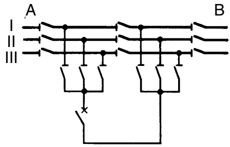


13-tie coupling Most flexible method of section, bus and bypass coupling

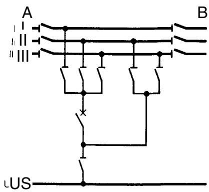
Triple busbars



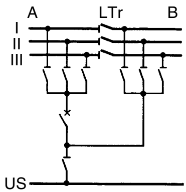
Bus coupling SSI/II/III



Section- and bus coupling for all possible ties between the 6 sections A-B



Bus coupling SSI/II/III for A or B
Bypass coupling SSI/II/III
to bypass (US) for A or B



Section coupling for A-B,
Bus coupling SSI/II/III via LTr,
Bypass coupling A SSI/II/III
to bypass,
Bypass coupling B/ bypass via LTr

11.2 SF_6 gas-insulated switchgear (GIS)

11.2.1 General

The range of application of SF_6 gas-insulated switchgear extends from voltage ratings of 72.5 up to 800 kV with breaking currents of up to 63 kA, and in special cases up to 80 kA. Both small transformer substations and large load-centre substations can be designed with GIS technology.

The distinctive advantages of SF_6 gas-insulated switchgear are: compact, low weight, high reliability, safety against touch contact, low maintenance and long life. Extensive in-plant preassembly and testing of large units and complete bays reduces assembly and commissioning time on the construction site.

GIS equipment is usually of modular construction. All components such as busbars, disconnectors, circuit-breakers, instrument transformers, cable terminations and joints are contained in earthed enclosures filled with sulphur hexafluoride gas (SF_6).

The “User Guide for the application of GIS” issued by CIGRÈ WG 23-10 includes comprehensive application information.

Up to ratings of 170 kV, the three phases of GIS are generally in a common enclosure, at higher voltages the phases are segregated. The encapsulation consists of non-magnetic and corrosion-resistant cast aluminium or welded aluminium sheet.

Table 11-1 shows an overview of the various sizes.

Table 11-1

Rating data and dimensions of the GIS range from 72.5 to 800 kV

Range	EXK-01	ELK-04	ELK-14	ELK-34	ELK-4
Service voltage in kV	72.5 – 123	145 – 170	245 – 300	362 – 550	800
Lightning impulse voltage	550	750	1050	1550	2000
Breaking current in kA	40	40 – 50	40 – 63	40– 63	40 – 50
Load current in A	2 500	3150	4000	6300	6300
Bay width in m	0.8/1.0	1.2	1.7	2.7	4.5
Bay height in m	2.3	3.0	3.5	4.8	7.5
Bay depth in m	3.2	4.6	5.1	6.0	8.0
Bay weight in t	2.5	3.7	7.0	11.0	14.0

11.2.2 SF_6 gas as insulating and arc-quenching medium

Sulphur hexafluoride gas (SF_6) is employed as insulation in all parts of the installation, and in the circuit-breaker also for arc-quenching. SF_6 is an electronegative gas, its dielectric strength at atmospheric pressure is approximately three times that of air. It is incombustible, non-toxic, odourless, chemically inert with arc-quenching properties 3 to 4 times better than air at the same pressure, see also Section 10.4.4.

Commercially available SF_6 is not dangerous, and so is not subject to the Hazardous Substances Order or Technical Regulations on Hazardous Substances (TRGS). New SF_6 gas must comply with IEC 60376 (VDE 0373 Part 1). Gas returned from SF_6 installations and apparatus is dealt with in IEC 60480 (VDE 0373 Part 2). SF_6 released into the atmosphere is considered a greenhouse gas. With its contribution to the greenhouse effect below 0.1%, the proportion of SF_6 is low compared to that of the better known greenhouse gases (carbon dioxide, methane, nitrous oxide etc.). To prevent any increase of SF_6 in the atmosphere, its use should in future be confined to closed systems. Devices suitable for processing and storing SF_6 gas are available for this purpose. The gas pressure is monitored in the individually sealed gas compartments and in the circuit-breaker housing. The low gas losses (below 1 % per year) are taken into account with the first gas filling. Automatic make-up facilities are not necessary.

The isolating gas pressure is generally 350 to 450 kPa at 20 °C. In some cases this can be up to 600 kPa. The quenching gas pressure is 600 to 700 kPa. Outdoor apparatus exposed to arctic conditions contains a mixture of SF_6 and N_2, to prevent the gas from liquefying. The pressure-temperature relationship of pure SF_6 gas is shown in Fig. 11-1.

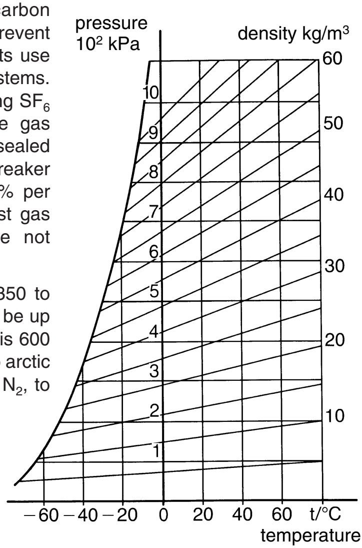


Fig. 11-1

p/t diagram of pure SF_6 gas

Arcing causes the decomposition of very small amounts of SF_6 gas. The decomposition products react with water, therefore the gas's moisture content, particularly in the circuit-breaker, is controlled by drying (molecular) filters. Careful evacuation before first gas filling greatly reduces the initial moisture content. Fig. 11-2 illustrates the conversion of water vapour content into dewpoint, see also Section 15.5.2.

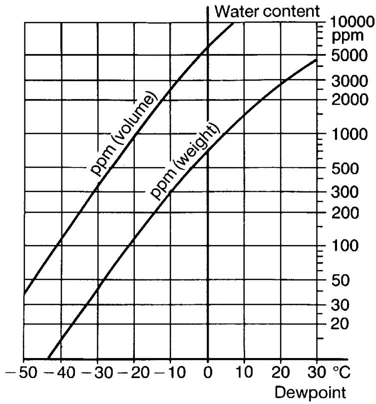


Fig. 11-2

Conversion of water vapour content into dewpoint

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11.2.3 GIS for 72.5 to 800 kV

SF_6 switchgear type EXK/ELK

For voltages from 72.5 to 800 kV ABB has five graduated module sizes of the same basic design available. The modular construction offers the advantages of quantity production, standard components, simple stocking of spares and uniform performance. By combining the various components of a module size, it is possible to assemble switching installations for all the basic circuit configurations in Section 11.1.2.They are thus able to meet every layout requirement.

As a general recommendation, the intended location for totally enclosed equipment should comply with the requirements of DIN VDE 0101 for indoor switchgear installations. The buildings can be of lightweight construction, affording some protection against the outdoor elements. With minor modifications, GIS apparatus can also be installed outdoors.

Components

The *busbars* are segregated by barrier insulators at each bay and form a unit with the busbar disconnectors and the maintenance earthing switches.

The *circuit-breaker* operates on the self-blast principle. Conventional puffer-type breakers use the mechanical energy of the actuator to generate the breaker gas stream while the self-blast breaker uses the thermal energy of the short-circuit arc for this purpose. This saves up to 80% of the actuation energy. Depending on their size, the breakers have one to four breaker gaps per pole. They have single- or triple-pole actuation with hydraulic spring mechanisms, see also Section 10.4.4 and 10.4.5.

Switch-disconnectors are used in smaller distribution substations. These are able to switch load currents and connect and disconnect transformers as well as unloaded lines and cables. They are able to close onto short-circuit currents and carry them for a short time. They also work on the single-pressure puffer principle and have a motor-driven spring operating mechanism.

The *current transformers* for measuring and protection purposes are of the toroidal-core type and can be arranged before or after the circuit-breaker, depending on the protection concept. Primary insulation is provided by SF_6 gas, so it is resistant to ageing. Iron-free current transformers using the Rogowski coil principle are used with SMART-GIS. They allow quantized evaluation of short-circuit currents and so make it possible to create a contact erosion image of the circuit-breaker.

Voltage transformers for measurement and protection can be equipped on the secondary side with two measuring windings and an open delta winding for detecting earth faults.

Inductive voltage transformers are contained in a housing filled with SF_6 gas. Foil-insulated voltage transformers are used, with SF_6 as the main insulation.

Capacitive voltage transformers can also be employed, usually for voltages above 300 kV. The high-voltage capacitor is oil-insulated and contained in a housing filled with SF_6 gas. The low-voltage capacitors and the inductive matching devices are placed in a separate container on earth potential. Capacitive tappings in conjunction with electronic measuring amplifiers are also available.

Electro-optical voltage transformers using the Pockels principle are also used with SMART-GIS.

The *cable sealing end* can accommodate any kind of high voltage cable with conductor cross-sections up to 2000 mm^2. Isolating contacts and connection facilities are provided for testing the cables with d.c. voltage. If there is a branch disconnector, it is sufficient to open this during testing.

Plug-in cable sealing ends for cross-linked polyethylene cables are available for voltages of up to 170 kV. They consist of gas-tight plug-in sockets, which are installed in the switchgear installation, and prefabricated plugs with grading elements of silicone rubber. Plug-in cable sealing ends do not have insulating compound. They are half as long as the standard end seal.

The make-proof *earthing switch* can safely break the full short-circuit current. A stored-energy mechanism with a motorized winding mechanism gives it a high closing speed. It may also be manually actuated.

Maintenance earthing switches, which may be required during servicing, are usually placed before and after the circuit-breaker. Normally mounted on or integrated in the isolator housing, they are operated by hand or motor only when the high-voltage part is dead. The maintenance earthing switch after the circuit-breaker may be omitted if there is a high-speed earthing switch on the line side.

SF_6 outdoor bushings allow the enclosed switchgear to be connected to overhead lines or the bare terminals of transformers. To obtain the necessary air clearances at the outdoor terminals, the bushings are splayed using suitably shaped enclosure sections.

SF_6 oil bushings enable transformers to be connected directly to the switchgear, without outdoor link. The bushing is bolted straight to the transformer tank. A flexible bellows takes up thermal expansion and erection tolerances and prevents vibration of the tank due to the power frequency from being transmitted to the switchgear enclosure.

SF_6 busbar connections are chiefly suitable for transmitting high powers and currents. They can be used for large distances, e.g. from an underground power plant or transformer station to the distant overhead line terminal, also refer to Section 11.2.7.

The *surge arresters* are generally of the gap-less type and contain metal oxide resistors. If the installation is bigger than the protected zone of the line-side arrester, arresters can also be arranged inside the installation. It is generally advisable to study and optimize the overvoltage protection system, particularly with distances of more than 50 m.

Each bay has a control cubicle containing all the equipment needed for control, signalling, supervision and auxiliary power supply.

The gastight enclosure of high-grade aluminium is of low weight so that only light foundations are required. The enclosure surrounds all the live parts, which are supported on moulded-resin insulators and insulated from the enclosure by SF_6 gas at a pressure of 350 to 450 kPa.

Barrier insulators divide the bay into separate gas compartments sealed off from each other. This minimizes the effects on other components during plant extensions, for example, or in case of faults, and also simplifies inspection and maintenance. The flanged joints contain non-ageing gaskets. Any slight leakage of gas can pass only to the outside, but not between the compartments.

The circuit-breaker in Fig. 11-3 has one extinction chamber per phase, that in Fig. 11-6 has three. Depending on the breaking capacity, a pole can have up to four extinction chambers connected in series. As shown in Table 11-1, the breakers can handle breaking currents of up to 63 kA.

In branches where only load currents have to be switched, up to a rated voltage of 362 kV switch-disconnectors can be used instead of circuit-breakers for economic reasons.

Each switching device is provided with an easily accessible operating mechanism (arranged outside the enclosure) with manual emergency operation. The contact position can be seen from reliable mechanical position indicators.

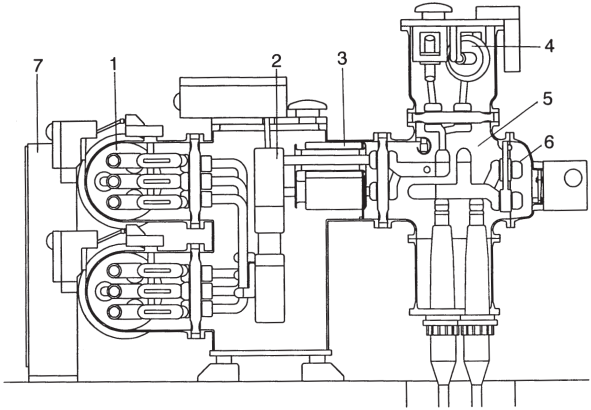


Fig. 11-3

SF_6 GIS for 123 to 170 kV, section through a bay, double busbar and cable branch
1 Busbar with combined disconnector / maintenance earthing switch, 2 Circuit-breaker, 3 Current transformer, 4 Voltage transformer, 5 Combined disconnector / maintenance earthing switch with cable sealing end, 6 High-speed earthing switch, 7 Control cubicle

11.2.4 SMART-GIS

A characteristic of SMART-GIS is replacement of conventional secondary technology, such as transformers, contactors and auxiliary switches with modern sensor technology and actuators. Inductive proximity switches and rotary transducers detect the position of the switching devices; the SF_6 gas density is calculated from the gas pressure and temperature. Actuators control the trip solenoids and the electric motors of the mechanisms. Specially designed sensors detect current and voltage. Rogowski coils and electro-optical voltage transformers without ferromagnetic components are generally used for this purpose. To ensure secure transmission of signals, fibre-optic cables instead of the conventional hard-wired connections are used within the bay and for connection to the station control system.

The process is controlled and monitored by decentralized distributed computer-supported modules (PISA = Process Interface for Sensors and Actuators), which communicate with one another and with higher-order control components via a process bus.

All sensors and the entire electronics for data processing and communications are self-monitoring and software routines continuously check the hardware in use.

Timer controls can be set for important data. Critical states can be avoided before they affect operation and maintenance. This results in a reduced reserve and redundancy requirement in the system and improved economy of operation.

11.2.5 Station arrangement

Gas supply

All enclosed compartments are filled with gas once at the time of commissioning. This includes allowance for any leakage during operation (less than 1 % per year). All the gas compartments have vacuum couplings, making gas maintenance very easy, most of which can be done while the station remains in operation. The gas is monitored by density relays mounted directly on the components.

Electrical protection system

A reliable protection system and electrical or mechanical interlocks provide protection for service staff when carrying out inspections and maintenance or during station extension, and safeguard the equipment against failure and serious damage.

The fast-response busbar protection system is recommended for protecting the equipment internally.

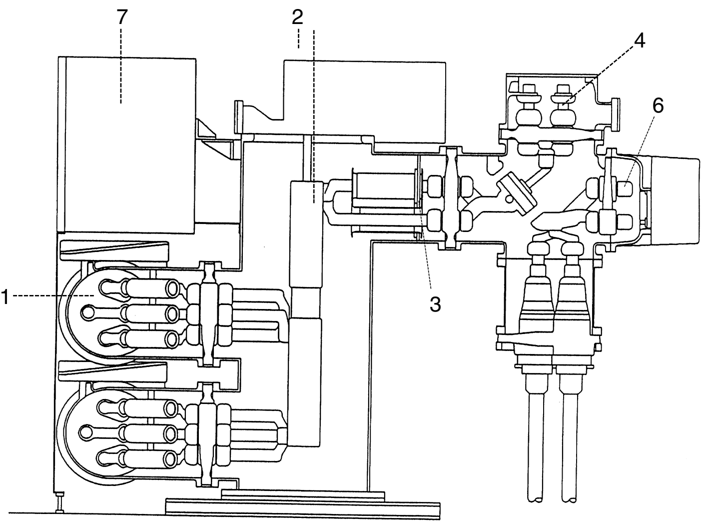


Fig. 11-4

SMART-GIS Type EXK-01 for 72.5 to 123 kV, section through a switchbay with double busbar and cable feeder, 1 Busbar with combined disconnector and earthing switch, 2 Circuit-breaker, 3 Current sensor (Rogowski coil), 4 Electro-optical voltage transformer, 6 Make-proof earthing switch, 7 Control cubicle

11

Earthing

Being electrically connected throughout, the switchgear enclosure acts as an earth bus. It is connected at various points to the station earthing system. For inspection or during station extension, parts of the installation can be earthed with suitably positioned maintenance earthing switches. Protective earthing for disconnected cables, overhead lines or transformers is provided by short-circuit make-proof earthing switches located at the outgoing feeders.

By short-circuiting the insulation between earthing switch and metal enclosure during operation, it is possible to use the earthing switch to supply low-voltage power or to measure switching times and resistances. Thus there is no need to intervene inside the enclosure.

Erection and commissioning

Only lightweight cranes and scaffolding are required. Cranes of 5000 kg capacity are recommended for complete bays, lifting gear of 2000 to 4000 kg capacity is sufficient for assembling prefabricated units.

Cleanliness on site is very important, particularly when erecting outdoors, in order to avoid dirt on the exposed parts of joints.

The completely installed substation undergoes a voltage test before entering operation. This is done with eighty per cent of the rated power-frequency test voltage or impulse withstand voltage. If a test transformer of suitable size is available, testing is done with a.c. voltage. Resonance test equipment or generators for oscillating switching surges are commonly used with rated voltages above 245 kV.

11.2.6 Station layouts

The modular construction of SF_6 switchgear means that station layouts of all the basic circuit configurations shown in Section 11.1 are possible.

For layout engineering, attention must be paid to DIN VDE 0101. Sufficiently dimensioned gangways must allow unhindered access to the components for erection and maintenance. Minimum gangway distances must be observed even when the cubicle doors are open. A somewhat larger floor area, if necessary at the end of the installation, facilitates erection and later extensions or inspection.

A separate cable basement simplifies cable installation and distribution. Where outdoor lines terminate only at one side of the building, the required clearances between bushings determine the position of the SF_6-switchgear bay. These are usually at intervals of three to four bays. If overhead line connections are brought out on both sides of the building or are taken some distance by means of SF_6 tube connections, the respective feeder bays can be next to each other.

Installations of the model ranges EXK-01 for 72.5/123 kV and ELK-0 for 145/170 kV as shown in Fig. 11-5 are extremely compact because of the three-phase encapsulation of all components. Combining busbar, disconnector and earthing switch into one assembly reduces the depth of the building.

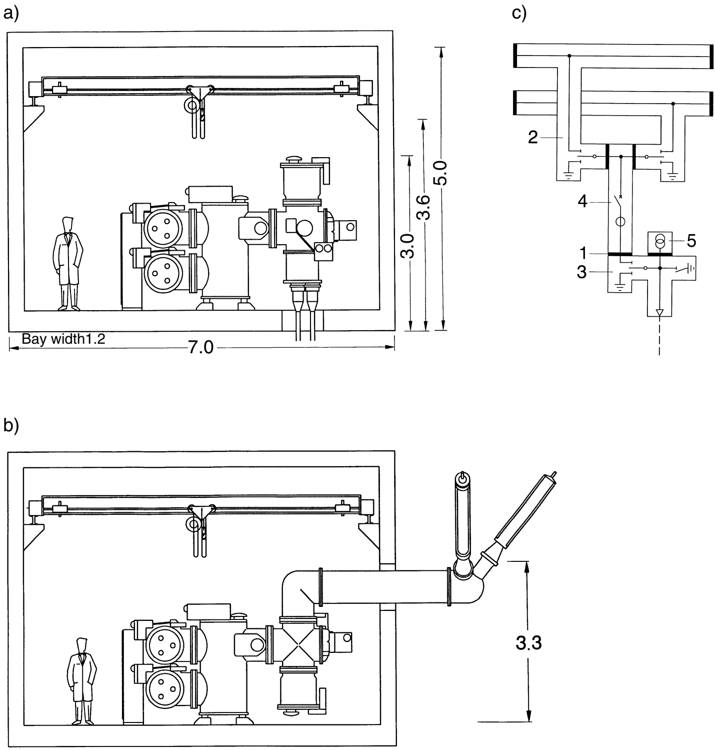
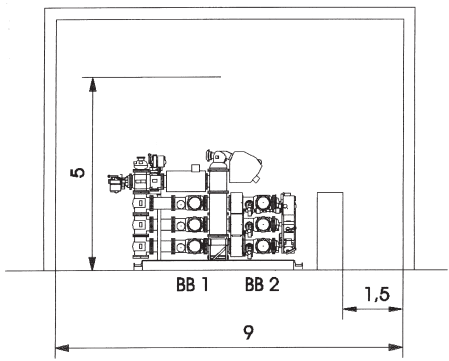


Fig. 11-5

SF_6 switchgear type ELK-04 for 123 to 170 kV with double busbar (dimensions in m)
a) Section at cable bay, b) Section at overhead line bay, c) Circuit and gas diagram at a)
1 Barrier insulator, 2 Busbar gas compartment, 3 Feeder gas compartment, 4 Circuit-breaker gas compartment, 5 Voltage transformer

Installations for rated voltages of 245 kV or more are single-phase encapsulated. This makes the components smaller and easier to handle. Busbar and busbar disconnector are combined in one assembly. The busbars are partitioned at each bay so that if access to the busbar compartment is necessary (e.g. for station extension) only small amounts of gas have to be stored. Partitioning each bay avoids damage to adjacent bays in the event of a fault.

a)



b)

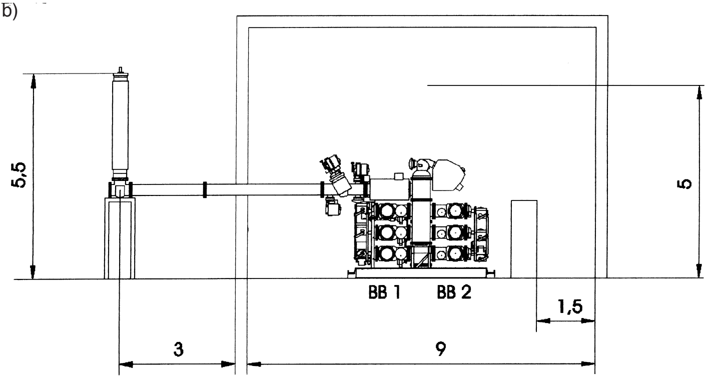


Fig. 11-6

SF_6 switchgear installation type ELK-14 for rated voltage 245 to 300 kV (dimensions in m) a) Cable feeder, b) Overhead Line branch

The structural type with standing breaker is preferred in all installation layouts. This allows the interrupter chambers to be easily removed from the circuit-breakers with a crane or lifting gear.

Single busbars, formerly used only for small installations, have become more important owing to the high reliability of the apparatus and its outstanding availability. Plant operation has become less complicated by dividing the station into sections by means of bus-ties.

Bypass buses with their disconnectors add another busbar system to stations with single or double busbars. The bypass bus enables any circuit-breaker to be isolated without interrupting the feeders.

A special form of the single busbar is the H connection or double H connection. It is employed chiefly for load centres in urban and industrial areas. These stations often have switch-disconnectors instead of circuit-breakers.

Combined busbars: In GIS stations with double busbars the second busbar is increasingly used as a bypass bus with the aid of an additional disconnector, resulting in a so-called combined busbar. This greatly improves the station availability at little extra cost.

11.2.7 SF_6-insulated busbar links

SF_6-insulated busbar links are particularly suitable for transmitting high power. They complement the usual cables and overhead lines for voltages above 72.5 kV, see Table 11-2.

They have the following advantages over cable links: greater transmission capacity with smaller losses, low charging power, non-ageing oil-free insulation, earthed enclosure with full earth-fault current carrying capacity. Large differences in height are easily overcome. Bridging considerable distances is possible without shunt reactors.

SF_6-insulated tie links are often left exposed, particularly for shorter distances or in walkable, covered ducts. Owing to the low ohmic losses, extra cooling is generally unnecessary.

Table 11-2

Rating data and dimensions of the SF_6 insulated busbar connections type CGI (typical values)

Service voltage	kV	72.5	123	145	245	420	550	800
Transmission output								
above ground	MVA	175	450	525	1200	3250	4800	7400
underground	MVA	125	250	300	650	1600	2200	3300
Rated current, underground	A	1000	1200	1200	1500	2100	2300	2400
Losses at rated current, 3ph	W/m	115	105	105	120	148	154	180
Weight with SF_6 gas, 1ph	kg/m	13.2	14.5	14.5	30.9	44.7	50.3	59.3
Gas pressure at 20 °C	kPa	420	420	420	420	420	420	420
External diameter	mm	165	240	240	310	470	510	620
Centre-to-centre distance of phases	mm	305	370	370	460	660	710	810
Right-of-way width	mm	1200	1300	1300	1500	2100	2300	2600

11.3 Outdoor switchgear installations

11.3.1 Requirements, clearances

The minimum clearances in air and gangway widths for outdoor switching stations are as stated in DIN VDE 0101 or specified by IEC. They are listed in the rated insulation levels as per DIN EN 60071-1 (VDE 0111 Part 1) (see Table 4-10 in Section 4.6.1). Where installation conditions are different from the standardized atmospheric conditions, e.g. installations at high altitudes, they must be taken into account by the atmospheric correction factor by determining the required withstand voltage in the course of the insulation coordination (compare Section 4.1).

Where phase opposition cannot be ruled out between components having the same operating voltage, the clearances must be at least 1.2 times the minimum values. The minimum distance between parts at different voltage levels must be at least the value for the higher voltage level.

When wire conductors are used, the phase-to-phase and phase-to-earth clearances during swaying caused by wind and short-circuit forces are allowed to decrease below the minimum values. The values by which the clearances are permitted to extend below the minima in this case are stated in DIN VDE 0101, Para. 4.4.

Equipment for outdoor switching stations is selected according to the maximum operating voltage on site and the local environmental conditions. The amount of air pollution must be taken into account, as on outdoor insulators, it can lead to flashovers. The hazard these represent can be influenced by the shape of the insulator, by extending the creepage distance, by siliconizing and by cleaning. IEC 60815 defines various degrees of contamination and specifies minimum creepage distances in relation to the equipment's maximum voltage U_m (see Table 11-3).

Table 11-3

Degree of contamination		Examples	Minimum creepage distance mm/kV
I	slight	Predominantly rural areas without industry and far from sea air	16
II	moderate	Areas in which little severe pollution is expected	20
III	severe	Industrial areas with relatively severe pollution, sea air, etc.	25
IV	very severe	Areas with heavy industry and much dust, fog, sea air	31

Lengthening the creepage distance with the same insulator height is not an effective method of preventing flashovers due to pollution deposits.

11.3.2 Arrangement and components

Surge arresters

Surge arresters for limiting atmospheric and switching overvoltages are described in Section 10.6. The protection zone of an arrester is limited. For rated voltages of 123 kV, the arrester should therefore not be further than approx. 24 m distant from the protected object, and for 245 to 525 kV, not further than approx. 32 m. The minimum distances from neighbouring apparatus must conform to the arrester manufacturer's specific instructions.

PLC communication

The power line carrier (PLC) system is a means of communicating over high-voltage lines. A PLC link requires a line trap and capacitor or capacitive voltage transformer in one or two phases of the incoming lines, positioned as shown in Fig. 11-14.

Control cubicles and relay kiosks

In outdoor switchyards, the branch control cubicles are of steel or aluminium sheet or of plastic (GFR polyester-reinforced resin). The cubicles contain the controls for local operation, auxiliary equipment and a terminal block for connecting the control, measuring and auxiliary cables. The size depends on how much equipment they have to contain. In large switchyards, the cubicles are replaced by relay kiosks containing all the equipment for controlling and protecting two or more high-voltage branches.

Busbars and connections

Busbars and the necessary connections to the equipment can be of wire or tube. Busbars are usually of aluminium/steel wire strung between double dead-end strings of cap-&-pin type or long-rod insulators with means of arc protection. Bundle conductors are employed for high voltages and high currents, and when single-column disconnectors are used. The tension of the wires is selected to be as small as possible to reduce stresses on the gantries. The choice of tension is further governed by the variation in sag.

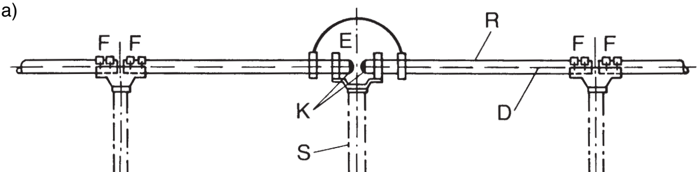
In the case of spans carrying the stirrup contacts of single-column disconnectors, account must be taken of the difference in sag at temperatures of –5 °C plus additional load and +80 °C. The change in sag can be reduced by means of springs located at one end of the span between the dead-end string and the portal structure.

Wires with cross sections of at least 95 mm^2 are used for installations with a rated voltage of 123 kV. At higher operating voltages, wires of not less than 300 mm^2 or two parallel wires forming a bundle-conductor are employed in view of the maximum permissible surface voltage gradients (see Section 4.3.3). Tensioned conductors are usually of aluminium/steel and rarely of aluminium. Aluminium wire is used for connections to HV equipment where the conductors are not tensioned, but only strung loosely. Wires are selected on the basis of mechanical and thermal considerations, see Sections 4.2.2, 4.2.3, 4.3.1 and 13.1.4.

Tubes are more economical than wires with busbar currents of more than 3000 A. Suitable diameters of the aluminium tubes are 100 mm to 250 mm, with wall thicknesses from 6 to 12 mm. For the same conductor cross-section area, a tube of larger diameter has greater dynamic strength than one of smaller diameter. Tubular conductors can be mounted on post insulators in spans of up to 20 m or more. To avoid costly joints, the tubes are welded in lengths of up to 120 m. Aluminium wires are inserted loosely into the tubes to absorb oscillation. Dampers of various makes are another method of suppressing tube oscillations. Tubular conductors for busbars and equipment interconnections are sized according to both thermal and dynamic considerations, see Sections 4.2.1, 4.3.2, 4.4.6 and 13.1.2.

Common tubular conductor arrangements for busbars and equipment links are shown in Fig. 11-7.

a)



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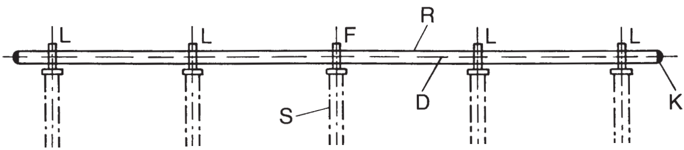


c)

Tube dia. mm	Max. span without damping wire m	Aluminium wire mm²
100	4.5	240
120	5.5	300
160	7.5	500
200	9.5	625
250	12.0	625

Fig. 11-7

Use of tubular conductors for busbars and equipment interconnections
a) Tubes and damping wires cut at each support, b) Tubes welded across several supports, damping wire continuous, c) Recommended damping wires
L = Sliding tube support, F = Fixed tube support, E = Expansion joint, D = Damping wire, K = End cap, S = Support insulator, R = Tube

High-voltage terminals (connectors, clamps)

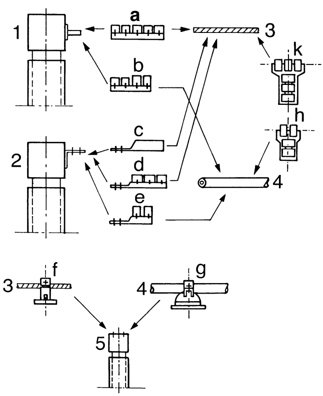
High-voltage HV terminals connect high-voltage apparatus to electrical conductors.

Their purpose is to provide a permanent, corona-free connection of sufficient thermal/ mechanical strength for continuous and short-circuit currents at the maximum operating voltage.

Unless specified otherwise, HV terminals conform to DIN VDE 48084, 46203 and 46206 Parts 2 and 3.

Besides current conducting terminals, the conductors require purely mechanical supports attaching them to the insulators, see Fig. 11-7.

The principal kinds of terminal connection are shown in Fig. 11-8.



1 HV apparatus with connection bolt
2 HV apparatus with flat pad
3 Stranded wire conductor
4 Tubular conductor
5 Support insulator
a Screw type terminal, bolt/wire
b Screw type terminal, bolt/tube
c Compression terminal with flat pad
d Screw type terminal flat pad / wire
e Screw type terminal flat pad / tube
f Conductor support for wire
g Conductor support for tube
h Tube connector
k Wire connector

Fig. 11-8

High-voltage terminals, alternative connections for outdoor switchgear installations

Depending on the installation site, straight, 45° angle or 90° angle HV terminals are used. With stranded wire connections, terminals are used for both a single stranded wire and for bundled wires.

HV terminals have to satisfy a number of technical requirements. To select the correct terminal, the following points need to be considered:

– design, e.g. screw type flat terminal
– material of body, screws
– conductor type, e.g. stranded wire Al 400 mm^2 to DIN 48201, dia. 26.0 mm
– contact area or surface of pin, e.g. flat terminal to DIN 46206 Part 3
– rated voltage, e.g. 380 kV
– surface voltage gradient
– rated current, e.g. 2000 A
– peak short-circuit current, e.g. I_s = 80 kA
– total opening time or short-circuit duration
– ambient temperatures
– ultimate temperatures terminal/conductor
– mechanical stress
– specific environmental factors

When connecting different materials, e.g. terminal bolt of Cu to stranded wire conductor of Al, a cover or plate of Cupal (a Cu/Al bimetal) is usually inserted between terminal and apparatus connector. Two-metal (Al/Cu) terminals are used where the local climate is unfavourable. The two different materials of these terminals are factory-bonded to prevent corrosion.

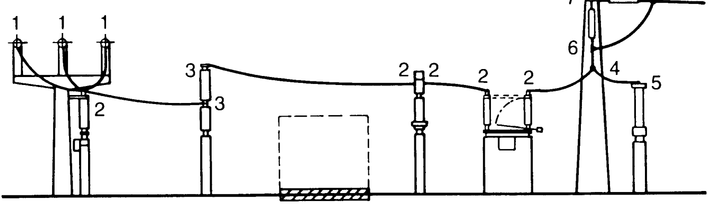
Special care is called for when selecting and using terminals and conductor supports for aluminium tubes $\geqq$ 100 mm diameter. The following additional criteria must be considered:

– elongation in the case of lengthy tubes
– tube supports, fixed or sliding
– tube oscillation induced by wind
– connection to apparatus, fixed or flexible (expansion joint)

see also Fig. 11-7.

Fig. 11-9 shows the terminal arrangement and a terminal listing for 110 kV outdoor branches.

a)



b)

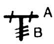
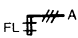
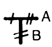
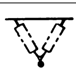
Pos.	Symbol	Mat.	Rated current (A)	Description	Total Qty.	Location	Bay 1 2 3
1		Al	850	T–terminal A = Al tube 63 dia., 2 caps B = Al wire 400 mm² (26.0 dia.) 3 caps	9	BB feeder	3 3 3
2		Al	850	Straight flat terminal, A = Al wire 400 mm² (26.0 dia.) 3 caps FL = flat term. to DIN 46206 P3	54	BB dis-connector, Current transformer, Feeder dis-connector	6 6 6 6 6 6 6 6 6
3		Al	850	90° flat terminal A = Al wire 400 mm² (26.0 dia.) 3 caps, FL = flat term. to DIN 46206 P3	18	Circuit-breaker	6 6 6
4		Al	850	Parallel connector A & B = Al wire 400 mm² (26.0 dia.), 3 screws	9	Voltage transformer drop off	3 3 3
5		Al with Cupal.	850	T–terminal A = Al wire 400 mm² (26.0 dia.) 3 caps B = Cu bolt 30 dia., 2 caps with Cupal cover	9	Voltage transformer connection	3 3 3
6		Al	680	T-terminal with hanger 19 dia. A = Al/St 265/35 mm² (22.4 dia.) 3 caps B = Al wire 400 mm² (26.0 dia.) 3 caps	9	Line connection	3 3 3
7		I_s =	31.5 kA/1s	110 kV V-suspension to GSHP 130212 Sh. 4	9	Line connection	3 3 3

Fig. 11-9

Example of a) terminal arrangement and b) terminal listing for three 110 kV outdoor branches

Support structures

The steel supporting structures for outdoor switchgear are made in the form of wide-flange, frame or lattice constructions (Fig. 11-10). A conductor pull of 10 to 40 N/mm^2 max. is specified for busbar supporting structures.

The strength of supporting structures, portals and foundations is calculated in accordance with DIN VDE 0210 for overhead line construction. The structures should be fitted with a ladder so that the span fixings can be cleaned and repaired. In 525 kV installations, handrails have proved an additional safeguard for personnel.

The supporting structures for switchgear, instrument transformers and arresters are of wide-flange, frame or lattice construction, sometimes precast concrete components are used. The choice depends on economic considerations, but also appearance.

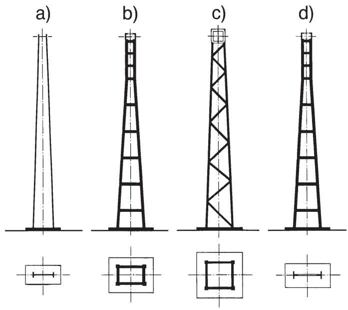


Fig 11-10

Examples of steel supporting structures for outdoor switchgear:
a) Wide-flange construction, b) Frame construction,
c) Lattice construction, d) A-tower construction

Foundations

The foundations for portals, HV switchgear and transformers are in the form of concrete blocks or rafts according to the soil's load-bearing capacity. The bottom of the foundation must be unaffected by frost, i.e. at a depth of some 0.8 to 1.2 m. The foundations must be provided with penetrations and entries for the earth wires and, where appropriate, for cables.

Access roads

Access roads in the usual sense are only rarely laid in 123 kV switchyards. The various items of switchgear, being built on the modular principle, can be brought by light means of transport to their intended position in the compound. The cable trench running in front of the apparatus serves as a footpath. It is usual to provide an equipment access route in large installations with relatively high voltages. A road or railway branch line is provided for moving the transformers.

Cable trenches, see Fig. 11-11

In outdoor installations, the cables are laid in covered trenches. Large switchyards lacking modern control facilities may require a tunnel with walking access and racks on one or both sides to accommodate the large number of control cables.

The main trenches follow the access road, the branch control cubicles being so placed that their foundations adjoin the trench. In view of the size of the covering slabs or plates, these cable trenches should not be more than 100 cm wide. Their depth depends on the number of cables. Cable supports are arranged along the sides. A descent in the lengthwise direction and drain holes ensure reliable drainage. In each branch, ducts are teed off from the control cubicle to the circuit-breaker, the instrument transformers and the isolator groups. The top of the main and branch ducts is slightly above ground level so that the trench remains dry even in heavy rain. Cable connections to individual items of equipment can also be laid in preformed troughing blocks or direct in the ground and covered with tiles.

See also civil construction requirements, Section 4.7.2.

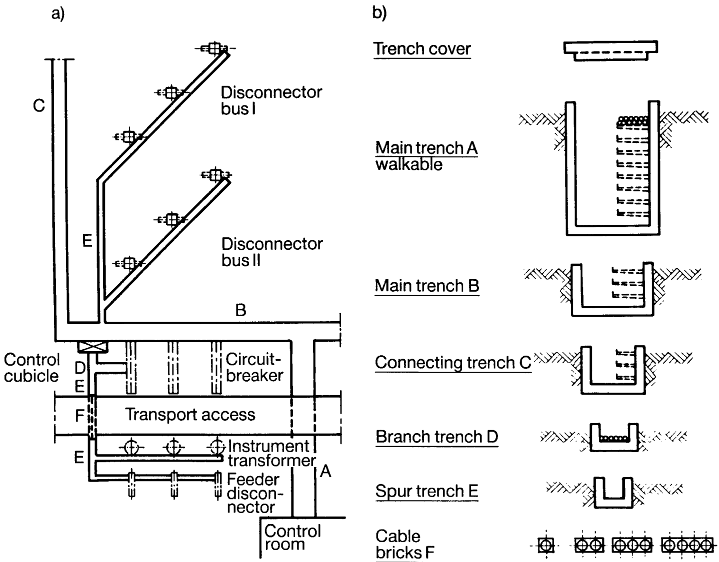


Fig. 11-11

a) Plan view of cable trench arrangement for a feeder, diagonal layout, b) Sizes of cable trenches

Protective screens, see Fig. 11-12

Equipment which stands low, e.g. circuit-breakers and instrument transformers on rails at 600 to 800 mm above ground level, must be provided with wire-mesh screens at least 1800 mm high, or railings at least 1100 mm high. The prescribed protective barrier distances must be observed (see Section 4.6.1).

Protective screens, railings and the like are not necessary within a switchyard if the minimum height to the top edge of the earthed insulator pedestal is 2250 mm, as specified in DIN VDE 0101, with account taken of local snow depths.

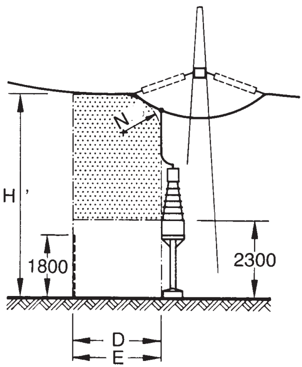


Fig. 11-12

Protective barrier clearances and minimum height H' at the perimeter fence. Distances as Table 4-11, C Solid wall, E wire-mesh screen

Perimeter fencing, see Fig. 11-12

The perimeter fence of an outdoor switching station must be at least 1800 mm high. The minimum clearance (between perimeter fence and live parts) must be observed. The perimeter fence is generally not connected to the station earth, owing to the danger of touch voltages, unless continuous separation is not possible (distance ≦ 2 m).

Station perimeter fences of conducting material must be earthed at intervals of no more than 50 m by means of driven earthrods or earthing strips at least 1 m in length, unless bonding is provided by means of a surface earth connection approximately 1 m outside the fence and about 0.5 m deep.

No special measures are required in the case of perimeter fences of plastic-coated wire mesh with plastic-coated or concrete posts.

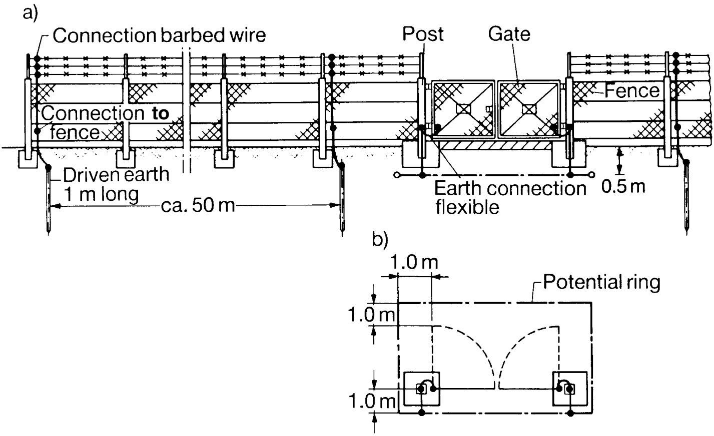


Fig. 11-13

Principle of fence earthing if distance from earth network to fence ⋝ 2 m a) Elevation, b) Plan view at gate

11.3.3 Switchyard layouts

General

The arrangement of outdoor switchgear installations is influenced by economic considerations, in particular adaptation to the space available and the operational requirements of reliability and ease of supervision. To meet these conditions, various layouts (see Table 11-4) have evolved for the circuit configurations in Section 11.1.2. Many electric utilities have a preference for certain arrangements which they have adopted as standard.

The spacing of the branches is determined by the switchyard configuration.

A span length of 50 m is economical for guyed wire (strain) busbars. The number and design of portal structures is governed by the overall length of the installation. The larger bay width T_1 and T_2 of the busbar step-down bays (starting bay, end bay) must be taken into account when planning the layout.

For stations with busbar current ratings above about 3000 A, tubular busbars offer a more economical solution than tensioned wires. In 123 kV stations, the tubular busbars are supported at each alternate bay, but at each bay with higher voltages.

The overhead lines leading from the transformer stations are generally also used for power-line carrier telephony. The necessary equipment (line trap, capacitor) is incorporated in the outgoing overhead lines as shown in Fig. 11-14.

Points in favour of rotary and vertical-break disconnectors are their mechanical simplicity and the fact that they are easier to position as feeder disconnectors. The single-column disconnector makes for a simple station layout owing to its isolating distance between the two line levels; it saves some 20% of the ground area needed for two-column disconnectors.

Table 11-4

Outdoor switchyard configurations, preferred application

Layout	≦ 145 kV	245 kV	420 kV	≧ 525 kV
Low rise (classical) layout	×	×		
In-line layout	×			
Transverse layout	×	×		
High-rise layout	×			
Diagonal layout		×	×	
1½-breaker layout		×	×	×

Each branch (bay) consists of the circuit-breaker with its disconnectors, instrument transformers and control cubicle. The apparatus is best placed at a height such that no fencing is needed. Here, it must be noted that according to DIN VDE 0101 (Fig. 4-37, Section 4.6.1), the height to the top edge of the earthed insulator base must be at least 2250 mm. The high-voltage apparatus is generally mounted directly on equipment support structures.

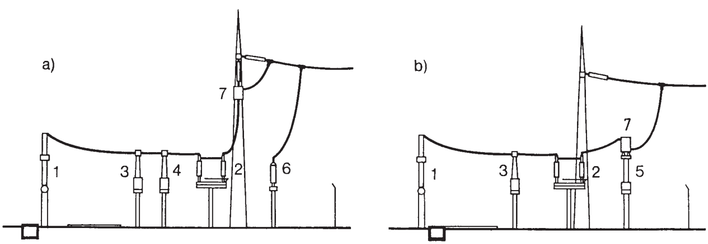


Fig. 11-14

Arrangement of overhead line bays for power-line carrier telephony:

a) Line trap suspended, capacitor standing,
b) Line trap mounted on capacitive voltage transformer,
1 Circuit-breaker, 2 Feeder disconnector, 3 Current transformer, 4 Inductive voltage transformer, 5 Capacitive voltage transformer, 6 Capacitor, 7 Line trap

Selected examples of switchyard layouts

With the *low-rise* (classical) layout (Fig. 11-15), the busbar disconnectors are arranged side by side in line with the feeder. The busbars are strung above these in a second level, and in a third plane are the branch lines, with connections to the circuit-breaker. A great advantage of this layout is that the breaker and transformer can be bypassed by reconnecting this line to the feeder disconnector. Features of this configuration are the narrow spacing between bays, but higher costs for portal structures and for means of tensioning the wires.

The classical layout is also used for stations employing the 2-breaker method.

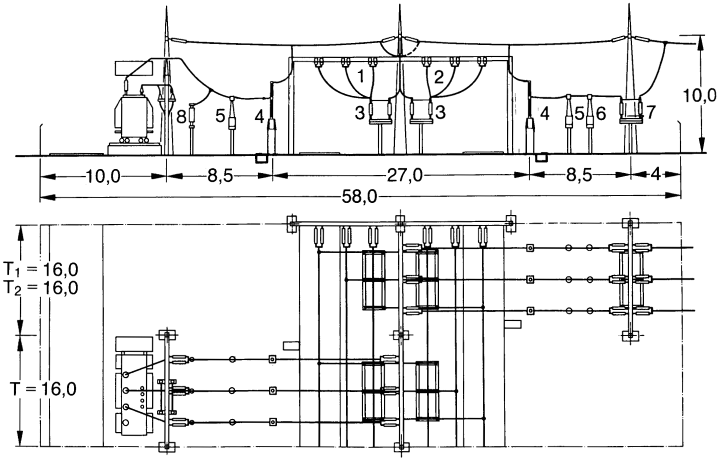


Fig. 11-15

245 kV outdoor switchyard with double busbars, low-rise (classical) layout:
1 Busbar system I, 2 Busbar system II, 3 Busbar disconnector, 4 Circuit-breaker, 5 Current transformer, 6 Voltage transformer, 7 Feeder disconnector, 8 Surge arrester; T Bay width, T_1 Width initial bay, T_2 Width final bay at busbar dead-end

An *in-line* layout with tubular busbars is shown in Fig. 11-16. It is employed with busbar current ratings of more than 3000 A. The poles of the busbar disconnectors stand in line with the busbars. Portals are needed only for the outgoing overhead lines. This arrangement incurs the lower costs for supporting steelwork and results in an extremely clear station layout.

In stations including a bypass bus, the layout chosen for the bypass bus and its disconnectors is the same as for the busbars. In stations with feeders going out on both sides, the bypass bus must be U-shaped so that all branches can be connected to it.

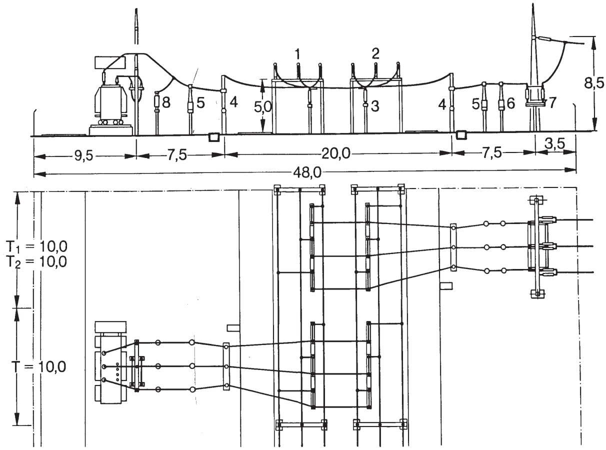


Fig. 11-16

123 kV outdoor switchyard with double busbars, in-line layout:
1 Busbar system I, 2 Busbar system II, 3 Busbar disconnector, 4 Circuit-breaker, 5 Current transformer, 6 Voltage transformer, 7 Feeder disconnector, 8 Surge arrester; T Bay width, T_1 Width initial bay, T_2 Width final bay. The busbars are tubular.

With the *transverse* layout, the poles of the busbar disconnectors are in a row at right angles to the busbar, see Fig. 11-17. With this arrangement too, the busbars can be of wire or tube. The outgoing lines are strung over the top and fixed to strain portals. Though the bay width is small, this arrangement results in a large depth of installation.

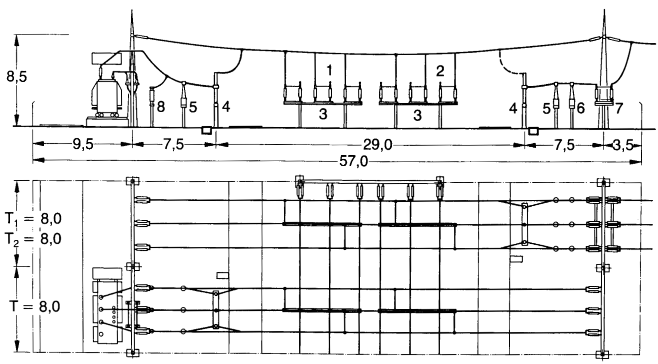


Fig. 11-17

123 kV outdoor switchyard with double busbars, transverse layout:
1 Busbar system I, 2 Busbar system II, 3 Busbar disconnector, 4 Circuit-breaker, 5 Current transformer, 6 Voltage transformer, 7 Feeder disconnector, 8 Surge arrester; T Bay width, T_1 Width initial bay, T_2 Width final bay.

Special layouts

Arrangements with draw-out breakers save a great deal of space, as the draw-out circuit-breaker does away with the need for disconnectors. The outgoing line simply includes an earthing switch. This configuration is used for stations with single busbars. The costs are low. The circuit-breaker is fitted with suitable plug-in contacts and a hydraulically operated truck.

Load-centre substations with one or two power transformers are usually in the form of simplified transformer stations. In Fig. 11-18, two incoming overhead lines connect to two transformers (H-connection). This gives rise to two busbar sections joined via two sectionalizers (two disconnectors in series). In this way, each part of the installation can be isolated for maintenance purposes. The bus sections can be operated separately or crosswise, ensuring great reliability and security of supply.

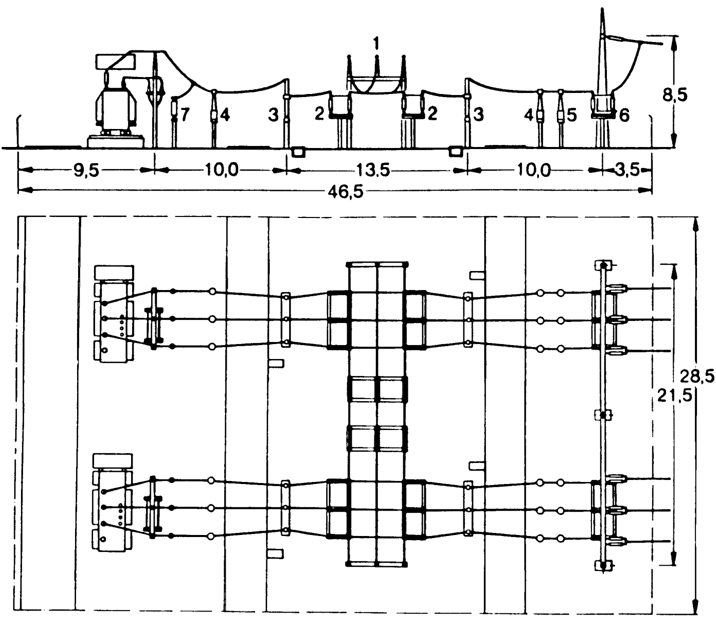


Fig. 11-18

123 kV load-centre station (H-connection): 1 Busbars, 2 Busbar disconnector, 3 Circuit-breaker, 4 Current transformer, 5 Voltage transformer, 6 Feeder disconnector, 7 Surge arrester.

Table 11-5 compares different layouts of 123-kV outdoor switchyards as regards area, foundations (volume) and steelwork (weight) for one line branch and one transformer branch with double busbar, assuming a total size of the substation of 5 bays.

Table 11-5

Comparison of different layouts for 123 kV

Type of branch (bay)	Overhead line			Transformer		
Type of layout	Area	Foun-dations (volume)	Steel-work	Area	Foun-dations (volume)	Steelwork except cable gantry on LV side
In-line (tubular busbars)	225 m^2	23.3 m^3	6.6 t	193 m^2	52.3 m^3	4.3 t
	100 %	100 %	100 %	100 %	100 %	100 %
Transverse (tubular busbars)	282 m^2	27.2 m^3	7.8 t	302 m^2	78.4 m^3	9.6 t
	125 %	117 %	118 %	156 %	150 %	223 %
Low-rise (classical, wire busbars)	192 m^2	33.9 m^3	8.4 t	201 m^2	81.3 m^3	8.8 t
	86 %	145 %	127 %	104 %	155 %	205 %

Table 11-6 compares different layouts of 245-kV outdoor switchyards as regards area, foundations (volume) and steelwork (weight) for one line branch and one transformer branch with double busbar and bypass bus or 1½-breaker layout.

Table 11-6

Comparison of different layouts for 245 kV

Type of branch (bay)	Overhead line			Transformer		
Type of layout	Area	Foundations (volume)	Steelwork	Area	Foundations (volume)	Steelwork except cable gantry on LV side
In-line (tubular busbars)	323 m^2	28.0 m^3	7.9 t	344 m^2	63.2 m^3	7.0 t
	100 %	100 %	100 %	100 %	100 %	100 %
Transverse (tubular busbars)	413 m^2	31.9 m^3	9.1 t	433 m^2	69.2 m^3	9.4 t
	128 %	114 %	115 %	126 %	110 %	134 %
Low-rise (classical, wire busbars)	324 m^2	38.6 m^3	10.4 t	369 m^2	83.1 m^3	12.5 t
	100 %	138 %	132 %	107 %	131 %	179 %
1½-breaker (tubular busbars)	267 m^2	27.4 m^3	8.1 t	301 m^2	47.7 m^3	8.5 t
	83 %	98 %	103 %	88 %	76 %	121 %

Diagonal layout

With this arrangement, the (single-column) busbar disconnectors are arranged diagonally with reference to the busbars. It is commonly used for 245 kV and 420 kV stations.

A distinction is made between two versions, depending on the position (level) of the busbars.

"Busbars above"

The advantage of this layout (Fig. 11-19) is that when a feeder is disconnected, the busbar disconnectors are also disconnected and are thus accessible.

For installations with current ratings of more than 3000 A and high short-circuit stresses, the busbars and jumper connections are made of tubes. Fig. 11-19 shows a 420 kV station in a diagonal layout and using tubes. The tubes are in lengths of one bay and mounted on the post insulators with a fixed point in the middle and sliding supports at either end. The busbars can be welded together over several bays up to about 120 m.

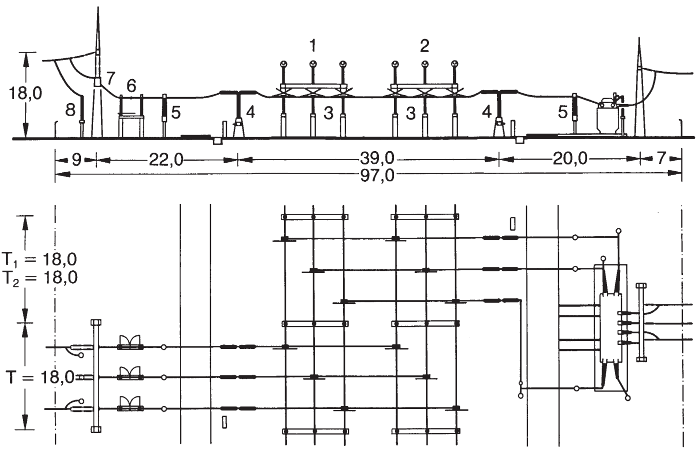


Fig. 11-19

420 kV outdoor switchyard with double busbars of tubular type, diagonal layout, busbars above: 1 Busbar system I, 2 Busbar system II, 3 Busbar disconnector, 4 Circuit-breaker, 5 Current transformer, 6 Feeder disconnector, 7 Line trap, 8 Capacitive voltage transformer. T Bay width, T_1 Width initial bay, T_2 Width final bay

"Busbars below"

With this arrangement, the busbars are mounted on the disconnectors with the outgoing lines strung at right angles to them. At their points of intersection, single-column disconnectors maintain the connection with their vertical isolating distance. This economical layout requires lightweight busbar strain portals only at the ends of the installation, and the bays are narrow. It can be of single or double-row form. The single-row arrangement (Fig. 11-20) is more space-saving. Compared with a two-row layout it requires about 20 % less area. The circuit-breakers for all outgoing lines are on the same side of the busbars so that only one path is needed for transport and operation. The lines to the transformers lie in a third plane.

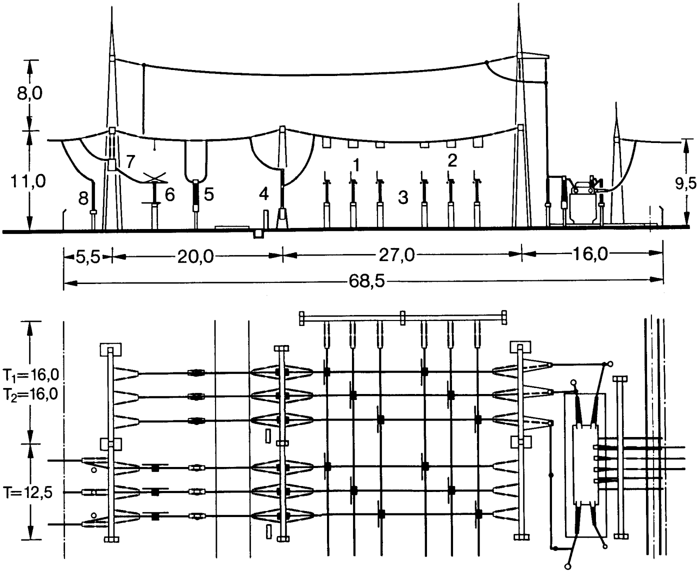


Fig. 11-20

245 kV outdoor switchyard with double busbars, diagonal layout, busbars below, single-row arrangement: 1 Busbar system I, 2 Busbar system II, 3 Busbar disconnector, 4 Circuit-breaker, 5 Current transformer, 6 Feeder disconnector, 7 Line trap, 8 Capacitive voltage transformer. T Bay width, T_1 Width initial bay, T_2 Width final bay with busbar dead-end.

The 420 kV switchyards of the German transmission grid are of the diagonal type. To meet the stringent demands of station operation and reliability, double or triple busbars with sectionalizing and an additional bypass bus are customary. Tube-type busbars are preferred. These can handle high current ratings and high short-circuit stresses.

The space-saving single-row layout with the circuit-breakers of all outgoing lines in one row is very effective here, too. Using two-column isolators on the feeders simplifies the layout. Single-column isolators are used for the busbars and the bypass bus (see Fig. 11-21).

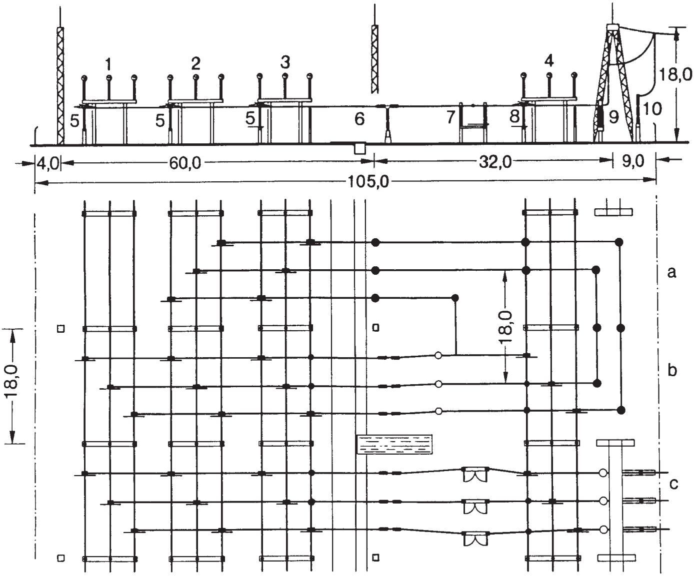


Fig. 11-21

420 kV outdoor switchyard with tubular conductors, triple busbars and bypass bus, diagonal layout, single-row arrangement:
1 Busbar system I, 2 Busbar system II, 3 Busbar system III, 4 Bypass bus, 5 Busbar disconnector, 6 Circuit-breaker, 7 Feeder disconnector, 8 Bypass disconnector, 9 Current transformer, 10 Voltage transformer; a and b Ties for busbars 1, 2 and 3 and bypass bus 4, c Outgoing line.

1 ½-breaker layout

The 1½-breaker configuration is used mainly in countries outside Europe. It is employed for all voltages above 110 kV, but predominantly in the very high voltage range.

The double busbars of these stations are arranged above, both outside or inside, and can be of tube or wire.

The more economical solution of stranded conductors is often used for the links to the apparatus, because with the relatively short distances between supports, even the highest short-circuit currents can exert only limited stresses on the equipment terminals.

The branches are always arranged in two rows. The disconnectors used are of the pantograph and two-column vertical-break types. Vertical-break disconnectors are employed in the outgoing line. Fig. 11-22 shows a section through one bay of a 525 kV station; the busbars are of wire. This arrangement allows the station to be operated on the ring bus principle while construction is still in progress, and before all the switchgear apparatus has been installed.

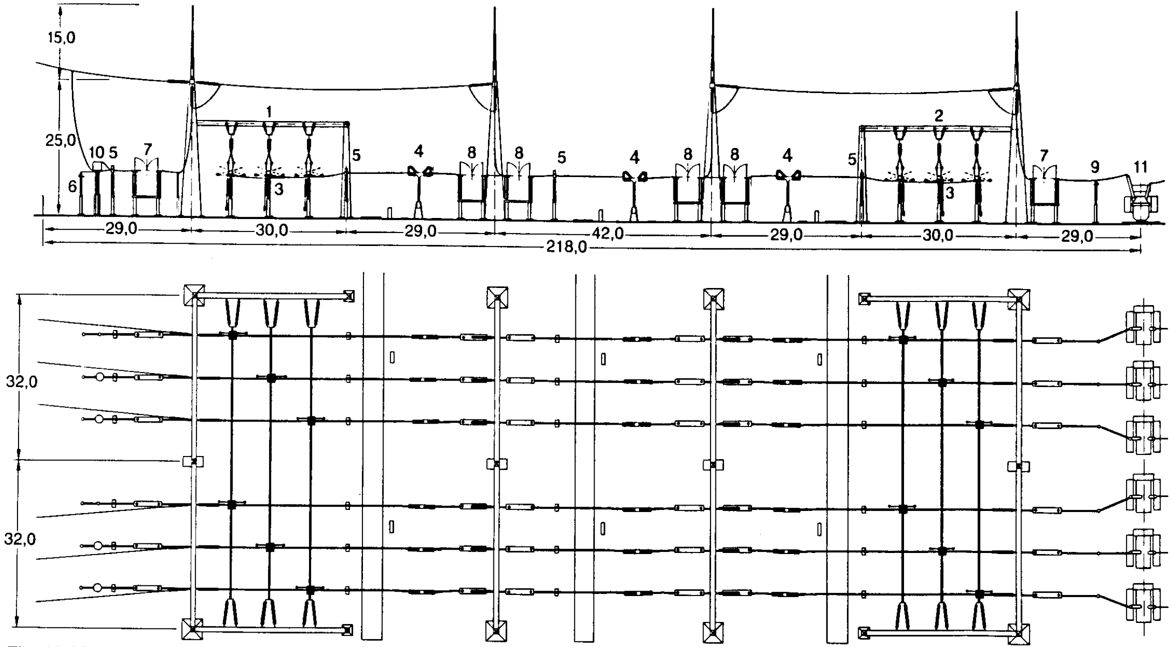


Fig. 11-22

525 kV outdoor switchyard, 1½-breaker layout: 1 Busbar system I, 2 Busbar system II, 3 Busbar disconnector, 4 Circuit-breaker, 5 Current transformer, 6 Voltage transformer, 7 Feeder disconnector, 8 Branch disconnector, 9 Surge arrester, 10 Line trap, 11 Transformer.

11.4 Innovative HV switchgear technology

11.4.1 Concepts for the future

The application of processors and modern information processing technology in substation and network control systems and also in secondary systems of switchgear installations, fast data bus systems that transmit over fibre-optic cables instead of copper wires and newly developed sensors for current and voltage can enable an evolutionary spring to smaller and more compact installations with a simultaneous significant increase in availability and ease of maintenance in the area of high- and very high-voltage equipment and switchgear installations.

11.4.1.1 Process electronics (sensor technology, PISA)

Decentralized distributed computer-supported modules (PISA = Process Interface for Sensors and Actuators) can now be used for direct control of the primary components of switchgear installations. At the same time, these modules enable all parameters, such as switch position, gas density, storage properties of operating mechanisms, to be recorded where they signify the current status of the equipment and therefore provide the necessary prerequisites for monitoring modern switchgear installations.

Examples of equipment used for this purpose are inductive (therefore insensitive to contamination), robust proximity sensors for detecting switch position of circuit-breakers and disconnector mechanisms, gas density sensors for SF_6 gas-insulated switchgear installations and circuit-breakers. Powerful microcomputers are used for decentralized preparation and preprocessing of the sensor signals (PISAS). Complex auxiliary switch packets in operating mechanisms are not needed because the software can double the signals without problems. The main advantages of this technology are therefore the ability to reduce the quantity of moving components, the smaller dimensions and the standardization of mass-produced components as is already done in other industries.

11.4.1.2 Monitoring in switchgear installations

Monitoring includes acquisition, recording and visualizing measured quantities to allow early detection of faults in important equipment such as circuit-breakers, power transformers or instrument transformers. According to international surveys conducted by CIGRÉ, the mechanisms and the electrical control circuits in circuit-breakers are the primary sources of serious faults, i.e. failures causing operational disruptions, and of less serious faults. The most common sources of failure are the mechanically actuated parts such as relays and signalling contacts in the electrical control circuits and the primary components in operating mechanisms.

The influence of the electronics on the total failure response of an installation is taken into consideration by implementing hardware and software processes for self-monitoring to achieve an increase in internal system reliability.

Condition monitoring requires careful evaluation of the large quantities of measured data, because only the combination of status acquisition with an intelligent assessment results in a knowledgeable diagnosis and initiation of the necessary maintenance steps. Special algorithms for reducing the data and calculating trends are basic requirements for a monitoring system. The P-F curve shown in Fig. 11-23 represents the qualitative connection between the state of a system and the time. As a result of the operational load on the system under observation, the fault mechanism starts at a specific time t_1, i.e. the state deteriorates until time t_2 at which the parameter(s) indicating the fault has/have gone down to a quantifiable value. This point P is designated a “potential fault”. In general, it can be assumed that from this time the state of the system continues to deteriorate, usually with increasing speed until the fault (point F) actually occurs at time t_3. A typical example for such a response is the ageing mechanism of oil/paper or plastic insulation. Leakage in a gas-insulated switchgear installation is another example of the above response.

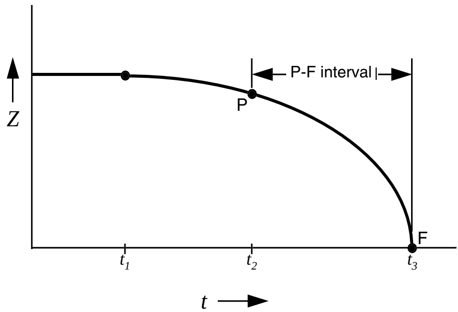


Fig. 11-23

P-F curve for the status of an equipment parameters as a function of time

Z status of the equipment *P potential fault*
t time *F fault*

The goal of a monitoring system must be to allow detection of point P with sufficient sensitivity, so there will be sufficient time, i.e. the P-F interval is still great enough to take appropriate action.

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11.4.1.3 Status-oriented maintenance

From a technical system view, the monitoring system is an aid for recording the operational history and the current operating status of the equipment that is being monitored. The connection to the substation automation system allows installation-based data such as fault record data from the protection devices or the busbar voltage to be simultaneously included in the evaluation. The resulting status-oriented reproduction of the entire switchgear installation forms the basis for a maintenance concept.

When the importance of the equipment from the network point of view is also considered, an optimized sequence in which a maintenance process can be applied to the equipment in question can be determined. This is referred to as Reliability Centred Maintenance (RCM). Powerful computerized tools (e.g. CALPOS-MAIN®) and monitoring systems are now available, enabling this concept to be implemented in the field.

The principle of status-oriented and reliability-based maintenance planning is shown in Fig. 11-24

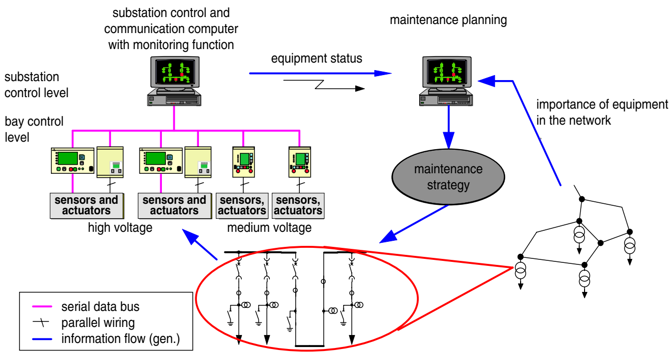
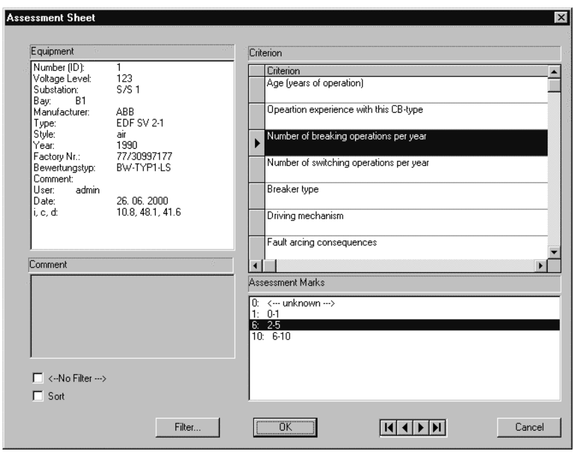


Fig. 11-24

General technical concept of status-oriented and reliability-based maintenance planning

Fig. 11-25 shows how an appropriate software tool can support this task. Fig. a) shows a valuation form for a single item of equipment, a circuit-breaker in this case, and b) shows the result of a simulation. The graph shows the weighted action requirement transferred to the “importance” of the equipment.

a)



b)

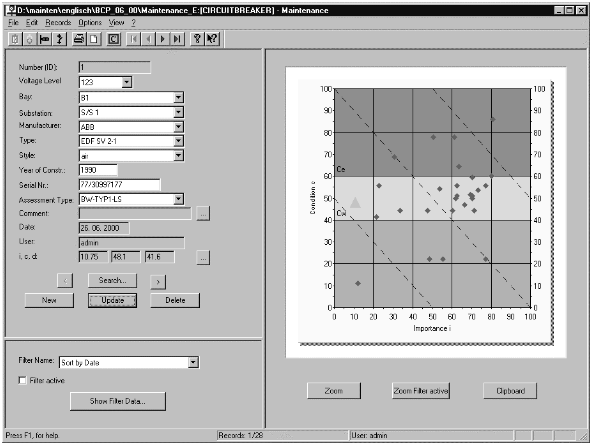


Fig. 11-25

Input screen and results display of the software tool CALPOS-MAIN® for status-oriented maintenance planning of switchgear installations
a) Valuation form *b) Results display*

11.4.2 Innovative solutions

11.4.2.1 Compact outdoor switchgear installations

A significant step toward reducing the space requirements of switchgear installations has been made by combining primary devices into more and more compact multifunctional switchgear units. This concept is not new and has already been implemented many times in applications such as outdoor switchgear installations with draw-out circuit-breakers. The implementation of non-conventional current and voltage transformers now makes it possible to combine a large number of functions on one device bench. As a result, a range of combination switchgear has been developed in the last few years.

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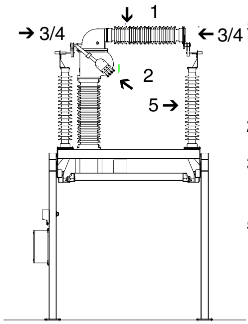
Another possibility for reducing the area required for outdoor installations significantly is to use hybrid installation designs. In this case, gas-insulated switchgear is used in which many primary components (circuit-breakers, transformers, disconnectors etc.) are installed in a common housing. Only the busbars and, depending on the basic design, the associated busbar disconnectors are installed outdoors

All new switchgear components are distinguished by consistent integration of non-conventional sensors (in this case primarily current and voltage sensors), processor-controlled mechanisms (see 11.4.1.1) and connection to the bay control with fibre optics. This yields the following:

– increased availability
– less space required
– shorter project runtimes and
– extended maintenance intervals with a significant increase in ease of maintenance.

Fig. 11-26 shows a design for compact outdoor switchgear installations for $U_n \leq$ 145 kv with transverse LTB circuit-breakers and integrated SF_6 current transformers. The illustrated compact and prefabricated switchgear with prefabricated busbar connections makes it easy to set up simple secondary substations and H-configurations economically and quickly. The circuit is disconnected on both sides of the circuit-breaker by the module moving to the side.



5 Functions in 1 module

1 Circuit-breaker

2 Current transformer

3/4 Disconnector and earthing switch, if required

5 Surge arrester can replace the post insulator

Fig. 11-26

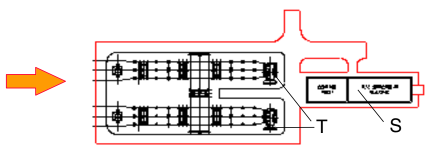
Slide-in, compact switching module with LTB circuit-breaker and integrated SF_6 current transformer for $U_n \leq$ 145 kv

An example of the layout of a simple H-configuration with these modules is shown in comparison to a conventional H-configuration in Fig. 11-27. Dispensing with busbars and outgoing-feeder disconnectors allows smaller dimensions in comparison to conventional outdoor installations.

Conventional Design

total area: ***2600 m²***
switchgear installation: ***930 m²***

earthing system: ***3700 m²***



Compact Design

total area: ***1200 m²***
switchgear installation: ***300 m²***

earthing system: ***1000 m²***

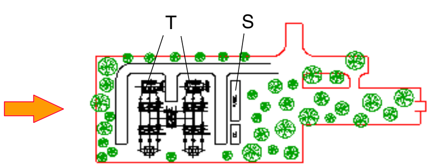


Fig. 11-27

View of two installation layouts in H-configuration for $U_n \leq$ 145 kv in conventional and compact design, T Transformers, S Secondary technology

Another variation of a compact switching module for use up to 170 kV is shown in Fig. 11-28. The disconnector functions are realized with a draw-out circuit-breaker. This means that the conventional disconnectors are replaced by maintenance-free fixed contacts and moving contacts on the circuit-breaker. An option is to install conventional or optical current and voltage transformers and earthing switches. The circuit-breaker can be simply withdrawn for maintenance, or if necessary, quickly replaced by a spare breaker. The main advantages here are also significant space savings, smaller bases, steel frames and reduced cabling requirements. This switching module is particularly suited for single busbars and H-configurations.

1 Draw-out circuit-breaker

2 Circuit-breaker rails

3 Disconnector isolating contact, fixed side (forms the isolating distance for circuit-breaker when withdrawn)

4 Current transformer

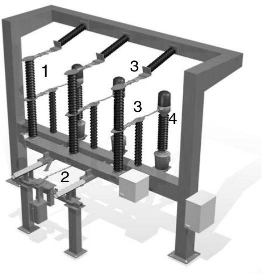


Fig. 11-28

Compact switching module for $U_n \leq$ 170 kv with draw-out circuit-breaker

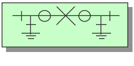
Fig. 11-29 shows a compact switching module for applications of up to 550 kV. It is a combination of a circuit-breaker with one or two non-conventional current transformers installed on the interruptor chambers and two pantograph disconnectors. This compact design is only possible using very small non-conventional current transformers. The current transformer signals are conducted through the tension insulators via fibre-optic cables to the control cubicle. Such compact modules make it possible to reduce the surface area required for an outdoor installation by up to 55 %. This concept is particularly suitable for installations in 1½ circuit-breaker design.

1 Circuit-breakers of up to 550 kV

2 Disconnectors on both sides (earthing switch possible)

3 Optical current transformer

4 Tension insulator for fibre optics



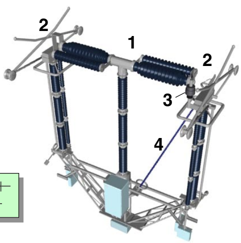


Fig. 11-29

Compact switching module for $U_n \leq$ 550 kv with circuit-breaker, a built-in non-conventional current transformer and two pantograph disconnectors

Fig. 11-30 shows a comparison of a conventional 500 kV outdoor switchgear installation in $1^{1}/_{2}$ circuit-breaker design with an installation in compact design using the modules described above. This makes the saving in surface area with the same functionality particularly clear.

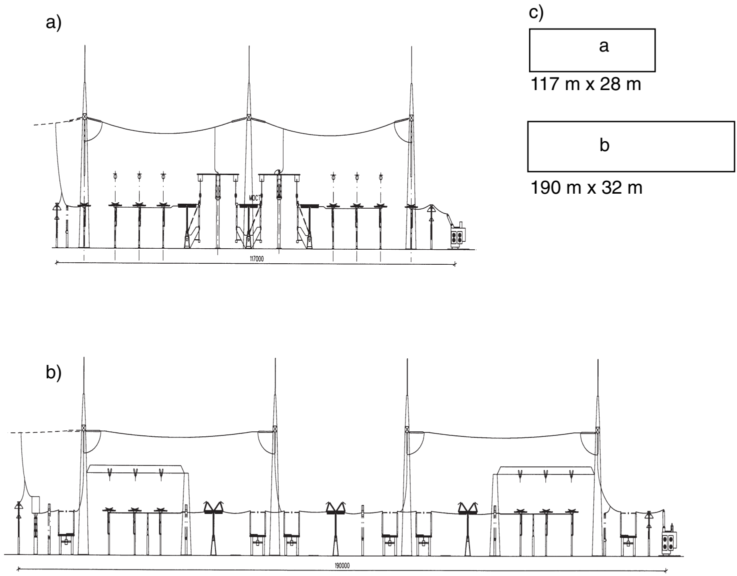


Fig. 11-30

Switchgear installation design of a 500 kV $1^{1}/_{2}$ circuit-breaker installation with compact switching modules a), compared to conventional design b), comparison of areas c)

11.4.2.2 Hybrid switchgear installations

Two insulation media, i.e. air and SF_6, can be combined in high-voltage installations with the modular principle of SF_6-isolated installations. This type of installation is referred to as a “hybrid installation”.

Fig. 11-31 shows a hybrid switching device for voltage levels of up to 550 kV. The name “Plug And Switch System” – PASS – indicates the philosophy of this concept. The highly integrated components allow that in new installations and in retrofit projects compact PASS units can be erected and comissioned quickly. These units are connected to the secondary equipment of the substation by prefabricated cable links, which include both the auxiliary voltage supply cables and the fibre-optic cables to connect to the station control system.

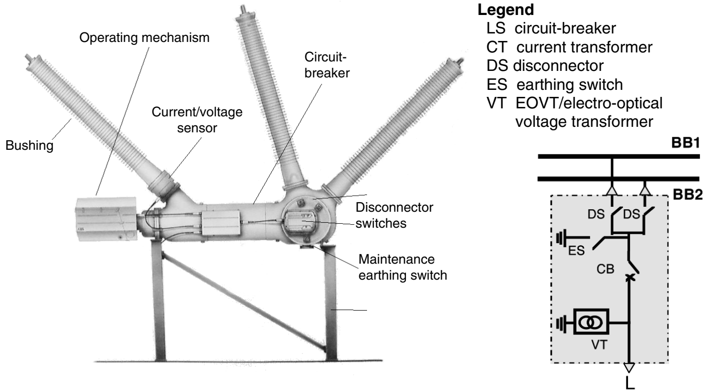


Fig. 11-31

Plug and Switch System, PASS, in single-phase design for U_n of up to 550 kV

Fig. 11-32 shows a double-busbar installation with PASS modules. The saving of space amounts to as much as 60% in new installations. For retrofit projects, the space required by the switchgear installations is generally dictated by the existing busbars and the gantries. In this case, the advantages of the PASS solutions are primarily in the savings in foundations, drastically reduced cabling requirements and fast installation and commissioning.

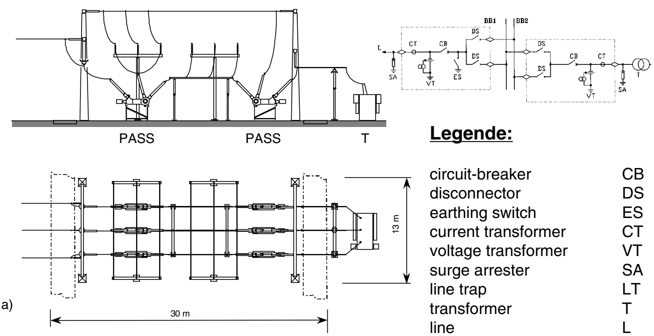


Fig. 11-32

Switchgear installation design with PASS for double-busbar installations for U_n of up to 550 kV

The 1½ circuit-breaker method can also be successfully implemented in hybrid design, see Fig. 11-33.

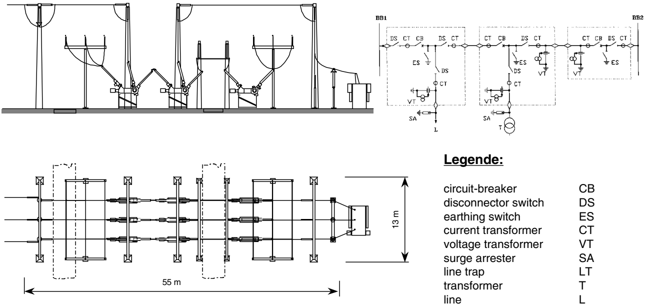


Fig. 11-33

1½ circuit-breaker hybrid switchgear installation with PASS modules for U_n to 550 kV

In addition to saving up to 60 % in surface area required, PASS is also characterized by quick assembly and easy replaceability. It can be connected to the overhead lines as easily as conventional installations.

11.4.2.3 Prefabricated, modular transformer substations (MUW®)

The prefabricated, modular transformer substations (MUW®) with gas or air-insulated switchgear are a special design for transformer substations. The abbreviation “MUW” at ABB is a fixed and defined product term.

The individual modules are delivered ready for installation as flexible assemblies. A number of these modules (e.g. medium voltage, control system/control room, auxiliary power etc.) are fully assembled and tested in the factory in prefabricated and transportable housings, every one conforming to the ISO 668 standard dimensions. The modular principle enables solutions tailor-made to requirements with a high degree of standardization.

Prefabricated ISO steel pit modules with the following dimensions are used as transformer bases:
– up to 16 MVA: 3 pit modules 20 feet x 8 feet
– from 20 to 40 MVA: 3 pit modules 30 feet x 8 feet
– from 63 to 125 MVA: 3 pit modules 40 feet x 8 feet

The pit includes the transformer rails for longitudinal and transverse movement, a flame-suppressant cover and as an option, the required racks for power cables and neutral treatment. Depending on the size of pit selected, space for an auxiliary transformer is also provided. Three pad modules can fit an ISO standard container for shipping. Modular fire-protection walls are available for fire protection between the transformers and towards the building.

Prefabricated, modular transformer substations can be set up and commissioned in a very short time. They also meet the requirements for multiple use. The entire switchgear installation can be converted with minimal effort. Standardized modules that can largely be prefabricated reduce planning, delivery and erection times.

Some advantages of MUW® are:

– faster construction of infrastructure
– shortest possible interruption of power supply in the event of faults and on installation of new equipment and retrofit and service of existing installations
– reusable interim solution (temporary solution)
– stationary, space saving permanent solution
– auxiliary supply in power stations and power station generator busducts

The modular housing design for the MUW consists of hot-galvanized sandwich wall panels for extremely high durability. The steel base frame comprises hot-galvanized rolled steel sections with additional equipment racks. Heating and air-conditioning units in the individual modules allow installation independent of the local climate conditions.

Figs. 11-34 and 11-35 show the ground plan and the sectional view of a 123/24 kV transformer substation with two 63 MVA transformers and an H-configuration with 5 circuit-breakers on the high-voltage side.

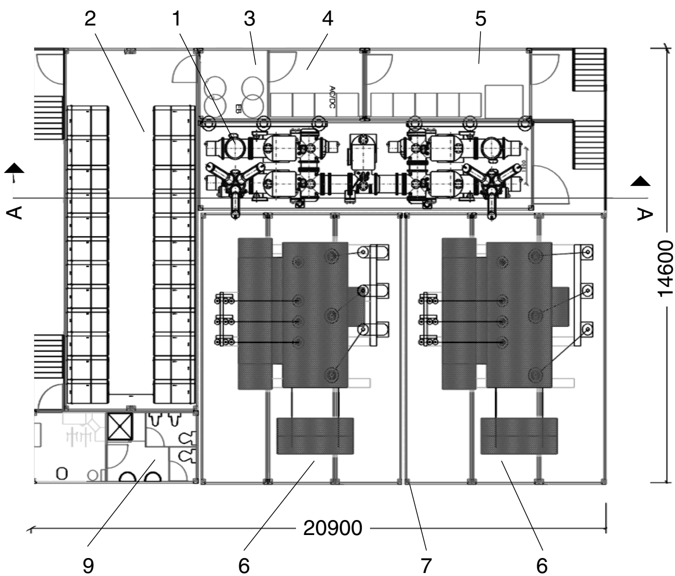


Fig. 11-34

Ground plan of a prefabricated, modular transformer substation, 1 High-voltage substation: H-configuration ELK-0 with 5 circuit-breakers, 2 Medium-voltage switchgear: 24 bays, 3 Neutral treatment (under module 1), 4 Auxiliary supply, 5 Control system/control room, 6 Modular transformer oil pit with 63 MVA transformer, 7 Modular fire protection wall, 9 Personnel module with small sewage system and oil separator

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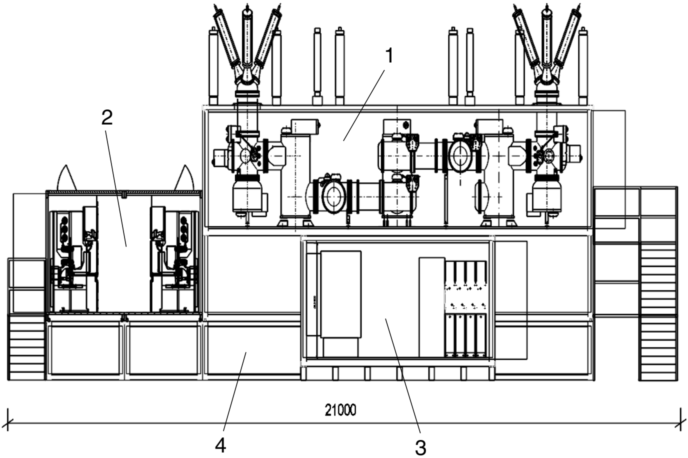

Fig. 11-35

Section through the installation, view A - A:
1 High voltage module, 2 Medium voltage module, 3 Neutral treatment, 4 Foundation modules as cable basement

In addition to transformer substations with gas-insulated switchgear technology, the modular concept can also be implemented with air-insulated components. The modular systems include an outdoor module, which is shown in Fig. 11-36, detail 1, as well as the compact switching modules shown in Section 11.4.2.1. Conventional devices such as circuit-breakers and current or voltage transformers are installed on a steel ISO base frame and the disconnectors are installed on a steel support fixed to the base frame. This module allows all current switchgear configurations to be implemented. The complete module is prefabricated, tested in the factory and then compactly packed for shipping on the base frame under an ISO container cover.

The method of assembly allows direct connections to existing overhead lines without requiring additional gantries with a one-level tower configuration.

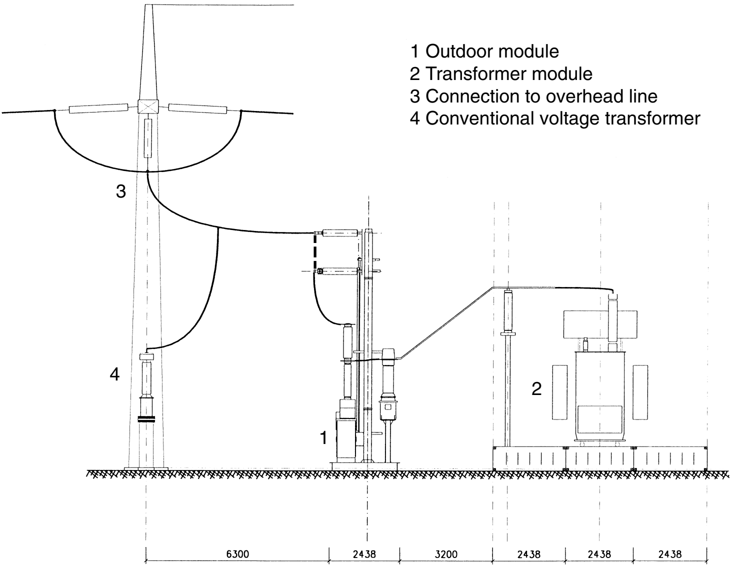

Fig. 11-36

Section through a prefabricated modular transformer substation in air-insulated design for a single transformer feeder connected to a 123 kV overhead line

11.4.3 Modular planning of transformer substations

To deal with ever tighter project schedules, it is essential to continue to increase the degree of prefabrication of switchgear components, to support project management with computerized aids as much as possible, to reduce engineering during the project and to save as much time as possible in assembling and commissioning the equipment.

Efforts similar to the previously achieved progress in modularization and standardization in

– LV switchgear design using type-tested switchgear assemblies (TTA, PTTA) as modular NS switchgear system (ABB MNS system),
– MV switchgear design using type-tested switchbays with standard programs,
– high-current technology with modular structure of generator busducts and circuit-breakers,
– HV switchgear design with gas-insulated switchbay series in modular technology as preassembled, type-tested and pretested bays

have been made with optimized primary and secondary technical design in the area of HV outdoor switchgear installations. Section 11.4.2.3 describes examples of these applications.

11.4.3.1 Definition of modules

More highly integrated modules and function groups as modules are required to reduce the project periods for switchgear installations.

A module in this sense is a unit or a function group,
- that can execute a self-contained function,
- that has a minimum of interfaces, which are as standardized as possible,
- whose complex function can be described with few parameters,
- that can be prefabricated and pretested to a great extent and
- that can be altered within narrow limits by the smallest possible degree of adaptation engineering for customer demands and requirements while adhering to standards as much as possible.

It is essential that any changes to modules do not detract from the rationalization and quality achieved by type testing, degree of prefabrication and pre-testing.

11.4.3.2 From the customer requirement to the modular system solution

The progressive deregulation in energy markets and the accompanying downward pressure on costs is resulting in new requirements on the project planning of transformer substations. In addition to the engineering of classical customized installations, the modular switchgear installation concept offers the chance of developing largely standardized and therefore more economical solutions. This is done by implementing a systematic pattern of thinking to yield products with high functionality and combined installation modules. This means that the interfaces are unified and also reduced in number by grouping products into modules.

For project planning and engineering, this means that system solutions are generated from a modular system of components in which the individual modules are precisely described as derived from the technical and economical requirements of a new transformer substation in the network. The available CAD systems are ideally suited for quick and easy combination of complete station components from a catalogue of individual components. The current integrated enterprise resource planning (ERP) software also offer suitable databases and structures that enable quick access to descriptions, parts lists and prices.

The substation planner will have the greatest optimization effect when the customer provides requirements that describe functions only instead of detailed requirements in the form of comprehensive specifications. This gives the engineer the greatest possible freedom to bring the system requirements into conformity with the available modular solutions. In the modular concept, detailed installation requirements that go far beyond the description of functions result in expensive adaptation work, making the overall installation more expensive. Adaptation work in the modular concept is possible, but it always results in extra work in preparing the tender, project planning, engineering, processing and documentation of the installation.

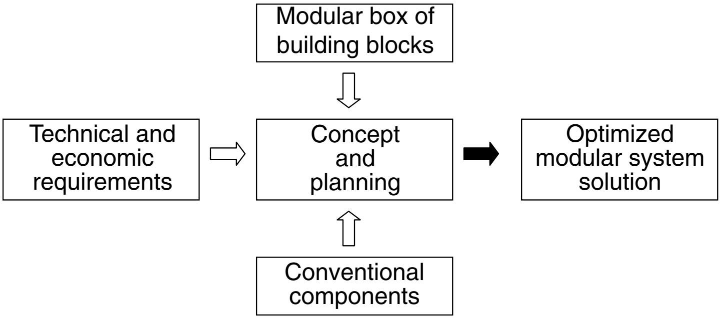

Fig. 11-37

From the functional requirements of the network to the modular system solution

11.5 Installations for high-voltage direct-current (HVDC) transmission

11.5.1 General

Transmitting energy in the form of high-voltage direct current is a technical and economic alternative to alternating-current transmission. It is used for transferring power in bulk over large distances by overhead line or cable, for coupling non-synchronous networks and for supplying densely populated areas if there is a shortage of transmission routes.

The basic principle of a HVDC link is shown in Fig. 11-38. The alternating voltage of a supply system, which may also be a single power station, is first transformed to a value suitable for transmission. It is then rectified in a converter arrangement with controlled valves. A second converter is required at the other end of the link. This is operated as an inverter and converts the direct current back into alternating current, which is then transformed to the voltage of the network being supplied.

The flow of power along the line is determined by the difference between the d.c. voltages at the ends of the line and by the ohmic resistance of the line, according to the formula

$$P_d = U_d \cdot I_d = \frac{U_{d1} + U_{d2}}{2} \cdot \frac{U_{d1} - U_{d2}}{R} = \frac{U^2_{d1} - U^2_{d2}}{2R}.$$

Here, P_d is the power relating to the middle of the line, U_{d1} and U_{d2} are the d.c. voltages at the beginning and end of the line, respectively, and R is the ohmic line resistance.

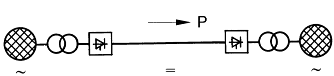

Fig. 11-38

Block diagram of a HVDC link

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The frequency and phase shift of the two networks connected via the HVDC link have no effect on the transmitted power and so transmission stability is no problem; networks of different frequency can be coupled without difficulty. With the three-phase bridge circuit used in HVDC systems, the equation for the d.c. voltage of the converter is

$$U_d = k\,U_v\,(\cos\alpha - \frac{u_k}{2}\,\frac{I_d}{I_{dN}})$$

where U_v is the valve-side voltage of the transformer, α the control angle of the converter, u_k the transformer's relative impedance voltage, I_d the d.c. transmission current and I_{dN} the nominal d.c. transmission current.

Since the d.c. voltage can be altered almost instantly with the phase-angle control system of the converters, the transmitted power can be varied very quickly and within wide limits.

By changing control from rectifier to inverter mode ($\alpha > 90$ °), it is possible to reverse the d.c. voltage and hence the energy flow direction, whereby the speed of reversal can be adapted as necessary to the needs of the coupled networks. The quick response of the converter control can even be used to support stability by slightly modulating the transmitted power to attenuate power fluctuations in one of the networks.

Because of delayed ignition and commutation overlap, line-commutated converters require fundamental-frequency reactive power:

$Q = P_d \tan\varphi$; $\varphi = \text{arc}\cos(\cos\alpha - \frac{u_k}{2}\frac{I_d}{I_{dN}})$ where φ is the displacement angle of the fundamental frequency.

The fundamental-frequency reactive power requirement of a HVDC converter at rated load is about 50 to 60 % of the active power. By means of special control modes, it can be varied within certain limits, so a HVDC converter can assist to maintain voltage stability in the three-phase network.

11.5.2 Selection of main data for HVDC transmission

The described technical characteristics of HVDC transmission are completely independent of the transmission distance and the kind of DC connection used, overhead line or cable; they are also valid for system interties in which rectifier and inverter are assembled in one station.

On the other hand, the main data of a HVDC link are very much influenced by the type of conductor and transmission distance. With an overhead line, optimization of the line costs and losses calls for the highest possible transmission voltage, a limit usually being set by the line's permissible surface voltage gradient. Countering this is the fact that the station costs, which increase with DC voltage, become less significant as the length of line increases. Voltages of up to ± 600 kV already exist.

Submarine cables with a transmission voltage of 450 kV and a length of 250 km are already in use. Links more than twice as long and with transmission voltages of 500 kV are being planned.

For system interties, the main data are governed by optimization of the converter valves. One chooses the rated current attainable with the largest available thyristor without paralleling, at present about 4000 A; the d.c. voltage then follows accordingly.

11.5.3 Components of a HVDC station

The basic circuit of a HVDC converter station is shown in Fig. 11-39.

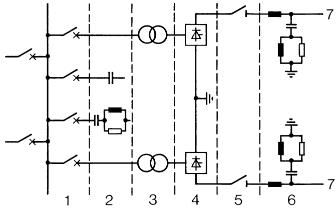


Fig. 11-39

Basic circuit of a HVDC converter station:

1 A.C. switchgear
2 A.C. filter and reactive power compensation
3 Converter transformers
4 Converter bridges
5 D.C. switchgear
6 Smoothing reactor and d.c. filter
7 D.C. line poles 1 and 2

The a.c. switchgear comprises not only the feeders to the converters, but also various branches for filter circuits and capacitor banks. The circuit-breakers must be capable of frequently switching large capacitive powers.

The *a.c. filters* are required to absorb current harmonics generated by the converter, and in this way, reduce distortion of the system voltage.

With 12-pulse converter units, it is customary to use tuned series resonant circuits for the 11th and 13th harmonics together with broad-band high-pass filters for the higher harmonics. These a.c. filters also furnish some of the fundamental-frequency reactive power needed by the converters. The remainder has to be provided by capacitor banks. At low system short-circuit outputs (S_K less than 3 P_D) it may be necessary to provide synchronous compensators instead of the capacitor banks.

The *converter transformers* convert the network voltage into the three-phase voltage needed by the converter bridges. As Fig. 11-40 shows, a 12-pulse converter unit requires two transformers connected differently to produce the two three-phase systems with a phase offset of 30°. Converter transformers for HVDC are built with two or three windings in single-phase or three-phase units. When the converter valves operate, the windings on the valve side are galvanically connected to a high d.c. potential, and the dielectric strength of their main insulation therefore has to be designed for high d.c. voltage. Windings and iron parts have to be specially dimensioned owing to the high harmonic currents and the consequent leakage flux.

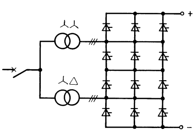


Fig. 11-40

Twelve-pulse converter unit, comprising two three-phase bridges connected in series on the d.c. side.

The converter units each consist of two three-phase bridge arrangements with their respective transformers, one of which is in YyO connection, the other in Yd5 connection. On the d.c. side, they are connected in series and on the a.c. side are brought to a common circuit-breaker to form a twelve-pulse unit. If the station has to be divided into more than two sections which can be operated independently, because of the maximum permissible power in the event of a fault, twelve-pulse units are connected in series or parallel.

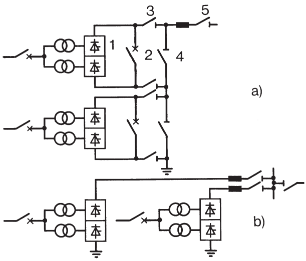


Fig. 11-41

One pole of a HVDC station with several converter units:
a) Series connection, b) Parallel connection of twelve-pulse units,
1 Twelve-pulse converter unit, 2 Bypass breaker, 3 Unit disconnector, 4 Shunt disconnector, 5 Line disconnector

A 12-pulse converter unit consists of twelve valves. HVDC converter valves are made up of thyristors. For high valve voltages, up to a hundred thyristors are connected in series. To obtain a uniform voltage distribution, the thyristors have additional circuitry consisting mainly of RC components. The heat sinks of the thyristors are cooled with forced-circulation air, oil or de-ionized water, the latter being the most common method. The valves are mostly ignited electronically by devices triggered by light pulses fed through fibre-optic cables. Converters with thyristors triggered directly by light are also used.

The d.c. switchgear has to perform a number of very different functions, depending on the converter station's design (cf. Fig. 11-41). The equipment used is mainly apparatus which has proved its performance in a.c. installations and been modified to meet the particular requirements. The purpose of the bypass switch parallel with the twelve-pulse unit is to commutate the station direct current when the unit is put into, or taken out of, operation. The shunt disconnector enables the direct current to be diverted round a disconnected unit.

Ground faults on a d.c. line are cleared by controlling the voltage to zero. D.C. circuit-breakers are therefore not necessary with a straightforward HVDC link. Multiterminal HVDC systems can, however, benefit from HVDC breakers (Fig. 11-42) as these improve the system's performance. A 500 kV HVDC circuit-breaker developed and tested by ABB has been proved in operation. The first multi-terminal HVDC transmission system entered service in North America in early 1992.

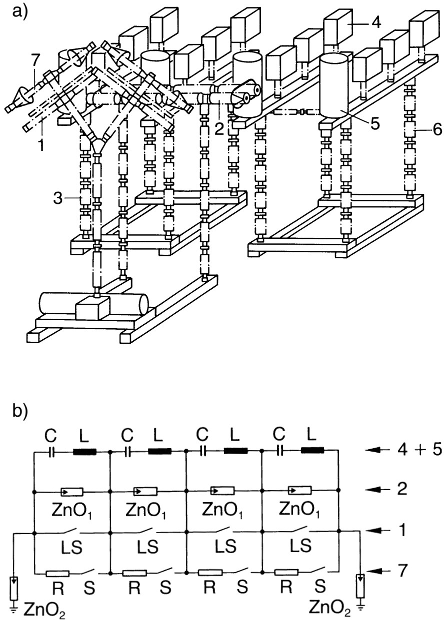


Fig. 11-42

500 kV HVDC circuit-breaker

a) Perspective arrangement
b) Equivalent circuit diagram

1 Air-blast breaker
2 Energy absorber (ZnO arrester)
3 Post insulators
4 Capacitor bank
5 Resonant-circuit reactor
6 Post insulators
7 Closing resistors (open during tripping), added as necessary

The smoothing reactors used on the d.c. side of HVDC stations smooth the direct current and limit the short-circuit current in the event of line faults. Their inductance is usually between 0.1 and 1 H. They are mostly built in the form of an air-insulated air-core reactor.

The d.c. voltage is filtered with DC filters. Their characteristics are matched to the data of the transmission line, it being particularly important to avoid resonance at the 1st and 2nd harmonics of the network frequency.

The lines for the two DC poles are usually carried on one tower. This is called a bipolar line. If there are special requirements for transmission reliability, two bipolar lines can be used on one or two towers. In the second case, the full power of the remaining healthy substation poles can be transmitted without earth return current even if a tower breaks with appropriate switchovers where two line poles fail. Both cases exploit the fact that the lines can take a high thermal overload under the standard economic design.

11.5.4 Station layout

In modern installations, the thyristor valves are air-insulated and placed in a valve hall. Generally, four valves are combined in a stack and connected to one AC phase. Three such assemblies constitute a twelve-pulse unit. Fig. 11-43 shows the layout of a station for bipolar transmission of 1000 MW at a d.c. voltage of ± 400 kV.

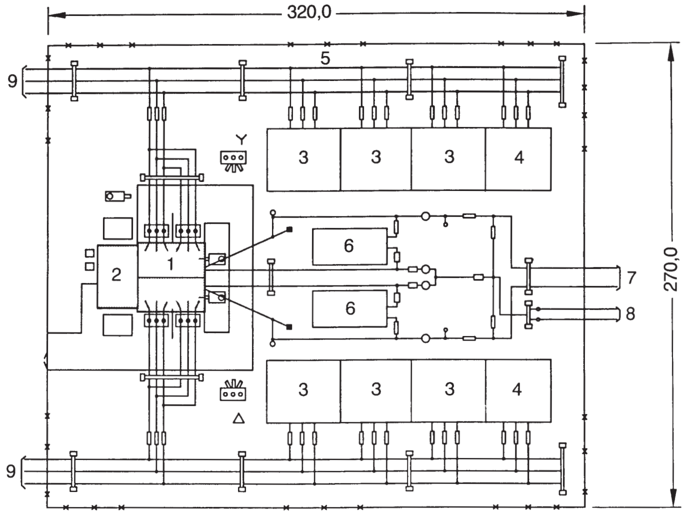


Fig. 11-43

Layout of a HVDC station for a rated voltage of ± 400 kV and rated power 1000 MW: 1 Valve hall, 2 Control house, 3 A.C. filter circuits, 4 Capacitor bank, 5 A.C. switchgear, 6 D.C. filters, 7 D.C. line ± 400 kV, 8 Earth electrode line, 9 A.C. infeed 345 kV

A particularly compact station arrangement is obtained by placing the converter transformers close to the valve hall so that their valve-side bushings pass through the wall. Fig. 11-44 shows the valve building and a single-phase three-winding converter transformer. An interesting feature, technically and practically, is that the valves are suspended from the hall ceiling.

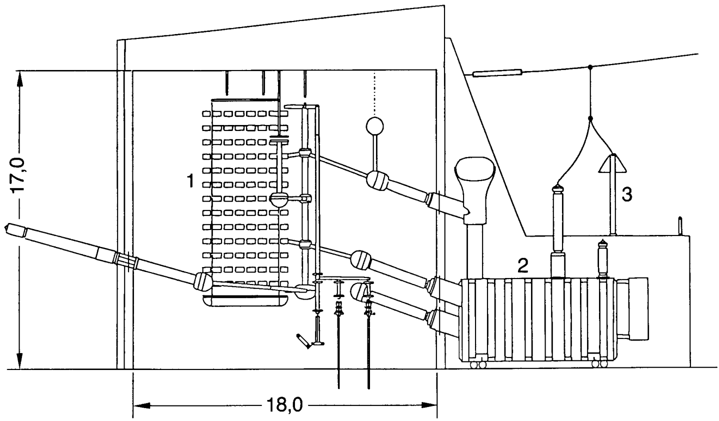


Fig. 11-44

Section through the valve hall of a 500 MW HVDC converter station (400 kV):
1 Converter valves, 2 Converter transformer, 3 Surge arrester.

11

11.6 Static var (reactive power) compensation (SVC)

11.6.1 Applications

In recent years, the control of reactive power has gained importance alongside active-power control. The use of mechanically switched choke and capacitor banks (see also Section 12.3.2 for the latter) has improved the reactive current balance in the networks. This has reduced transmission losses and kept stationary voltage deviations within the preset limits. In addition to this equipment, thyristor-controlled reactive-power compensators (SVC = Static Var Compensator) have also been implemented. They react virtually instantly and also offer the following advantages:

– very quick and infinitely variable reactive power conditioning,
– improvement of voltage stability in weak networks,
– increase of static and dynamic transmission stability and attenuation of power swings,
– enhancement of transmission capacity of lines,
– quick balancing of variable non-symmetrical loads,

– lower transmission losses,
– increased static and dynamic stability and reduced power fluctuations,
– increased transmission capacity,
– balancing of unsymmetrical loads,
– continuous regulation of power factor.

Equipped with electronic components, SVC systems respond almost instantaneously.

Unlike the reactive-power compensation considered in Section 12.3.2, SVC systems allow infinitely variable control across a whole band of reactive power. Also, the stability of networks can be improved.

11.6. 2 Types of compensator

Thyristor-Controlled Reactor (TCR)

An inductance (reactor bank) is controlled by thyristors as shown in Fig. 11-45. The reactive power in this case is continuously changed between zero and the maximum value by conduction angle control of the thyristors. In many cases, this configuration is operated together with a parallel-switched capacitor bank. This occurs when the entire reactive power correcting range also includes a capacitive component.

Features of this type are:
– continuous correcting range,
– no transient influence,
– generation of harmonics.

To avoid harmonic overload of the network, the parallel capacitor banks must be upgraded to filter circuits.

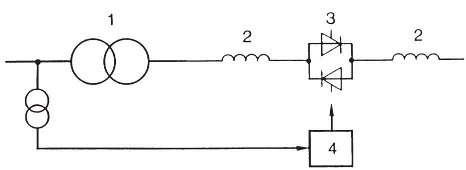


Fig. 11-45

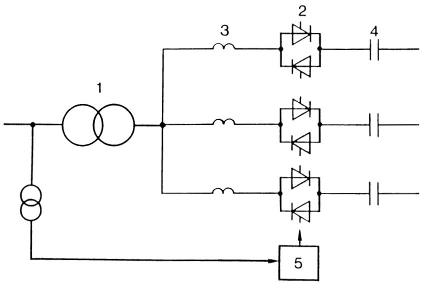
Thyristor-Controlled Reactor (TCR):
1 Transformer, 2 Reactor coil, 3 Thyristor valve, 4 Control system

Thyristor-Switched Capacitor (TSC)

In this case, thyristor-switched capacitors (capacitor banks) are switched on or off, path by path as shown in Fig. 11-46. To avoid transients, the thyristors are fired when the thyristor voltage is zero.

Fig. 11-46

Thyristor-Switched Capacitor (TSC):
1 Transformer, 2 Thyristor valve, 3 Damping coil, 4 Capacitor, 5 Control system



Features of this method are:

- stepwise control,
- no transient interference,
- no harmonics,
- low losses.

Applying reactors instead of capacitors, again arranged as in Fig. 11-46, creates the Thyristor-Switched Reactor method (TSR), which provides similar features to those above.

Thyristor-Switched Capacitor/Thyristor-Controlled Reactor (TSC/TCR)

Often a combination of the two above methods provides the best solution.

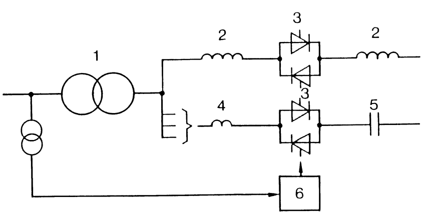
A compensator as shown in Fig. 11-47 allows low-loss thyristor control of the entire capacitive and inductive reactive-power correcting range. A smoothly varied output of reactive power is obtained by altering the TCR's firing angle. As soon as the TSC range has been compensated by the TCR, the capacitive path is disconnected and the compensator functions as a reactor.

Features of this method are:

- continuous adjustment,
- no transient interference,
- slight generation of harmonics,
- low losses.

Fig. 11-47

Thyristor-Switched Capacitor/Thyristor-Controlled Reactor (TSC/ TCR)
1 Transformer, 2 Reactor coil, 3 Thyristor valve,
4 Damping coil,
5 Capacitor,
6 Control system



11.6.3 Systems in operation

SVC systems in routine network service are generally highly reliable and very effective. The first static compensator for a high-voltage network was installed in 1972. Advances in thyristor technology led to the first water-cooled thyristor valve in operation in 1975. A system with a total power rating of 445 Mvar has been operating since 1985 in the 765 kV network of EDELCA (Venezuela). The largest system supplied to date by ABB has a total power of 1066 Mvar, of which 600 Mvar are thyristor-controlled. The installation is located in Mexico in the 400 kV network of CFE (Comision Federal de Electricidad). Fig. 11-48 shows a typical layout of a static compensator installation for a long-distance transmission system.

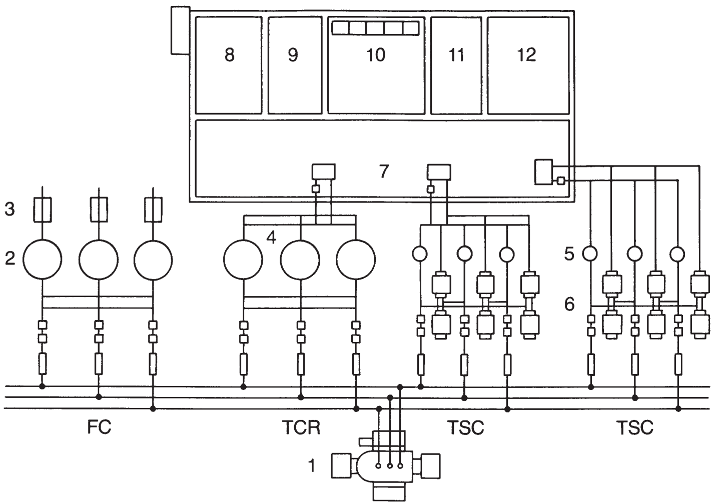


Fig. 11-48

Plan view of a static compensator installation for a long-distance transmission line: 1 Transformer, 2 Filter circuits, 3 Capacitor bank, 4 TCR reactor coil, 5 Damping coil, 6 TSC capacitor, 7 Thyristor valves, 8 Cooling plant, 9 Auxiliary power, 10 Control room, 11 Storage, 12 Workshop