TRANSFORMER SUBSTATIONS

The purpose of transformer substations is to transmit electrical energy between networks of different voltage levels. Among the essential parts of such substations are the power transformers. Further essentials are the switchgear installations of different types, voltages, and short-circuit ratings.

The circuit arrangement (the configuration and type of switchgear) depends on its required function:

- Quantity of power to be transformed
- Mechanical and thermal short-circuit strength
- Security (reliability) of supply
- Conditions of site and environment

As required by International Electrotechnical Commission (IEC) and other national standards, the clearances, lightning protection, grounding system, thermal and mechanical short-circuit strength, and insulation ratings must be observed during the installation and connection of switchgear and transformers.

Distribution substations are used for distributing power from a high-voltage network (e.g., 110 kV up to 170 kV system) to regional centers (cities and industries) with a medium-voltage network (usually up to 38 kV). The high voltage is fed by overhead lines or cables.

DESIGN CRITERIA

Depending on the system requirements, the substation primary parameters and the scope of its equipment must be specified. When a substation is being planned, the various alternatives should be examined and the total costs of each option calculated. The following should be considered:

- Losses of power transmission and transformation
- Reliability and operational flexibility of different busbar arrangements
- Fault current and load flow calculations

Busbar Arrangements

The selection of the busbar scheme and its possible extension is an important initial step of the substation design. Among the factors that affect the decision are operational flexibility; system safety, reliability, and availability.

Today there are many basic substation designs, and it is not possible to describe and illustrate them completely. For that reason only the most common concepts are described, which are:

- Single busbar
- Double busbar
- $1\frac{1}{2}$-circuit-breaker arrangement
- 2-circuit-breaker arrangement
- Ring-bus arrangement
- H arrangement
- Mesh arrangement

The medium-voltage side is usually realized by single or double busbar arrangements.

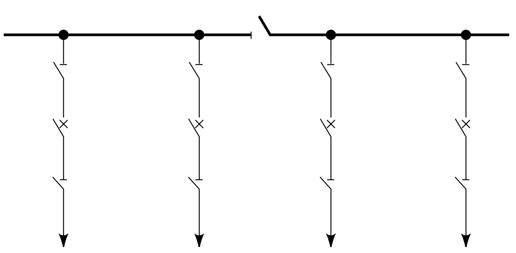


Figure 1. Single-busbar arrangement.

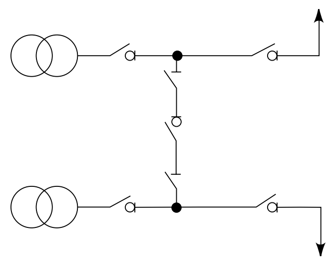


Figure 3. H arrangement.

Single Busbar. Because of its low cost, the single-busbar design is mainly suited for small substations (see Fig. 1). Variants with transfer busbars are also possible.

A partition into two different busbar sections is possible by a sectional switch. This can be an advantage for maintenance work. However, a short circuit on the busbar causes a complete outage of the substation. Therefore this configuration should be used only where consumers can be disconnected or supplied by another electrical path.

Double and Multiple Busbars. Two independent busbars used instead of a single busbar (Fig. 2), are called a *double busbar*. Double busbars are preferred in large substations because maintenance or modification is possible without interruption. Each feeder can be connected to each busbar by means of a bus coupler and busbar isolator without interrupting the energy flow. Substations provided with double busbars have a higher availability than single busbar substations. A short blackout of the complete substation, however, cannot be excluded even in double-busbar substations. Such a failure can be caused, for example, by a defect on the bus coupler that leads to a disconnection of all feeders by the busbar protection.

Variants with transfer busbars are possible as well. The transfer bus is an auxiliary busbar system that is connected through the bypass feeder. Its advantage is that each feeder in the installation can be isolated for overhaul without interrupting the supply. But only one breaker can be bypassed at a time.

Triple (or multiple) busbars are used for vital installations, such as large power plants or junction points in large networks, when operational considerations or the limited short-circuit capacity make it necessary to separate sections of networks and to operate them with galvanic separation. This arrangement is very often provided with a transfer bus.

H Arrangement with Looping in Existing Lines. H arrangements are increasingly used in many countries in installations of limited-extent where there are reduced demands on the flexibility of the feeders. In most cases there are circuit configurations based on fixed allocation of the transformers to the lines.

Such an H arrangement with looping in an existing transmission line can be seen in Fig. 3. Different H arrangements can be used for the connection of substations to the high-voltage network. The type shown in Fig. 3 is a very cost effective one, in that it is realized with load break switches and without circuit breakers.

H arrangements can be connected with two single feeders to a double-line system or looped in a single-line system. They are realized with two to five circuit breakers.

1½-Circuit-Breaker Arrangement. The advantages of the so-called 1½-circuit-breaker arrangement, as shown in Fig. 4, are above all its high switching flexibility and high availability.

During normal operation all feeders are closed. In that way, in contrast to single-, double-, and multiple-busbar arrangements, the affected feeder need not be disconnected if a busbar failure occurs. The necessity of three circuit breakers for two feeders is a disadvantage that raises the cost of this kind of substation design. Furthermore, the circuit breaker in the middle must react selectively in the direction of either feeder. That requires a higher expenditure for protection and for automatic reclosure.

Ring-Bus Arrangement (Classic). The classic ring arrangement needs only one circuit breaker per feeder and is therefore cost-effective (see Fig. 5). This arrangement is used in smaller substations.

Very often substations are initially realized as ring-bus arrangements and later enlarged to a 1½-circuit-breaker arrangement. All switching operations can be executed by circuit breakers. Extraction of each circuit breaker can be done without interruption. The main disadvantage of this type is its low switching flexibility—the lowest of any arrangement. Furthermore, there are disadvantages when maintenance or

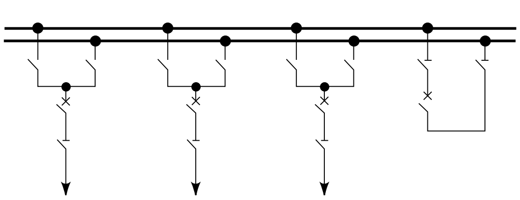


Figure 2. Double-busbar arrangement (one circuit breaker per feeder).

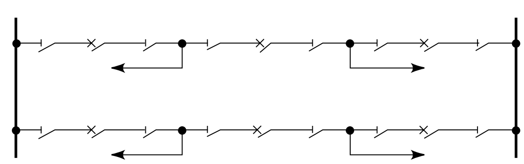


Figure 4. 1½-circuit-breaker arrangement.

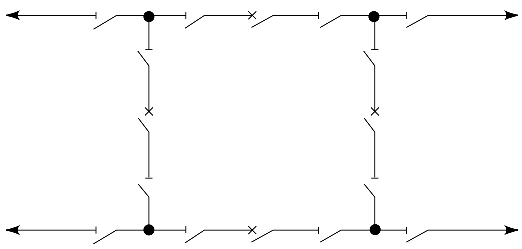


Figure 5. Ring-bus arrangement.

modification must be performed, because the ring must be opened. The ring arrangement is suitable for four to six feeders. Other arrangements are more useful if more feeders are needed.

2-Circuit-Breaker Arrangement (Duplex). For this type, two circuit breakers are needed for each feeder (see Fig. 6), resulting in considerable flexibility for switching operations as well as high reliability of the substation. The fact that this design uses two circuit breakers per feeder makes it one of the most expensive designs; nevertheless, often it is used in connection with power plants. It is very seldom found in medium-voltage networks.

Table 1 gives a comparison of some important busbar configurations of high-voltage substations concerning cost ratio, operational flexibility, and space.

Switchyard Layouts for the High-Voltage Side

Factors determining the choice of the switchyard layout are transformer rating and voltage levels (influencing the amount of floor space needed), site conditions, civil construction requirements, and environmental conditions. These affect the choice of substation (conventional air-insulated, gas-insulated, or hybrid) and the total cost of the installation.

General. Criteria for the choice of an appropriate type of substation are shown in Table 2.

Air-Insulated Switchgear (AIS). The design of outdoor substations is influenced by economic considerations, especially adaptation to the space available and the operational requirements of reliability and ease of supervision. To meet these conditions various layouts have evolved for the basic circuit configurations dealt with in the preceding subsection. They are governed by the equipment and its arrangement.

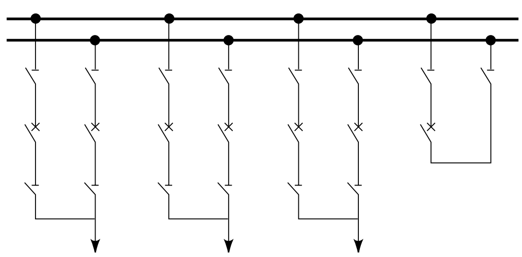


Figure 6. 2-circuit-breaker arrangement.

Low-Rise (Classical) Layout. With the low-rise (classical) layout the busbar disconnectors are arranged side by side in line with the feeder. The busbars are strung above these on a second level, and on a third level 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 their 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; see Fig. 7.

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

In-Line Layout. The layout of an in-line bay with tubular busbars is used for substations with busbar currents from 3150 A upwards. The poles of the busbar disconnectors are in line, parallel to the busbars. Supporting portals are only needed for the outgoing overhead lines. Consequently, this arrangement involves the least outlay for steelwork and makes the station very easy to supervise; see Fig. 8.

Transverse Layout. In a transverse arrangement the portals of the busbar disconnectors are in line, but perpendicular to the busbars. With this arrangement the busbars may also be either of wires or tubes. The feeders are above them and supported by portals. However, although the bays are narrow, the overall width of the installation is large; see Fig. 9.

High-Profile Layout. The high-rise, or T-mast, layout requires the least floor space, because the busbar disconnectors are on the third level above the breakers. The high frame with a crossbar for the busbars and possibly an inspection walkway for the busbar disconnectors necessitates correspondingly expensive steelwork and foundations, but the disposition is simple and clear. The use of this layout is confined to locations where a minimum of floor space is available; see Fig. 10.

Load-Center Layout. Load-center stations, such as industrial or network stations with one or two main transformers, are generally constructed as simple transformer substations. The basic layout is the H connection, which is easily extended to form a single busbar installation. Two incoming lines are connected to a pair of transformers. Thus two busbar sections are produced, which are interconnected by double sectionalizers (two disconnectors in series). Thus either section can be isolated for overhaul. Separate teed operation of the busbar sections or crossover operation is possible and ensures high reliability of operation and of the supply with relatively modest demands for space and equipment; see Fig. 11.

Diagonal Layout. In this layout the busbar disconnectors (pantograph type) are situated diagonally beneath the busbars; see Fig. 12. It is often chosen for 245 kV and 420 kV installations. There are two versions, depending on the level of the busbars.

$1\frac{1}{2}$-Breaker Layout. Substations using the $1\frac{1}{2}$-breaker layout are mainly found in countries outside Europe. They are employed for all voltage levels above 110 kV, but predominantly in the extremely high voltage (EHV) range.

The double busbars of these stations are arranged above, both outside and inside, being constructed of either wires or tubes; see Fig. 13.

2-Breaker Layout. Substations employing the 2-breaker layout are mainly found in the EHV range. The double busbars

Table 1. Comparison of Busbar Configurations

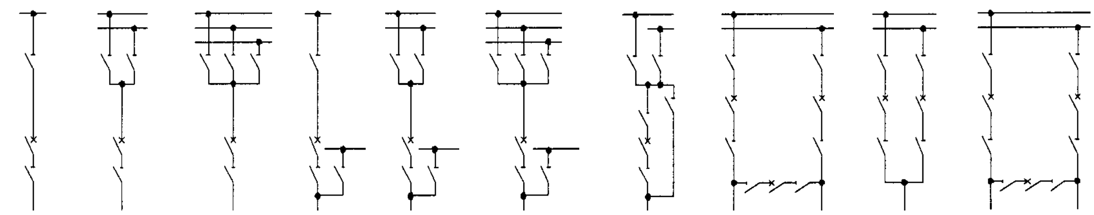
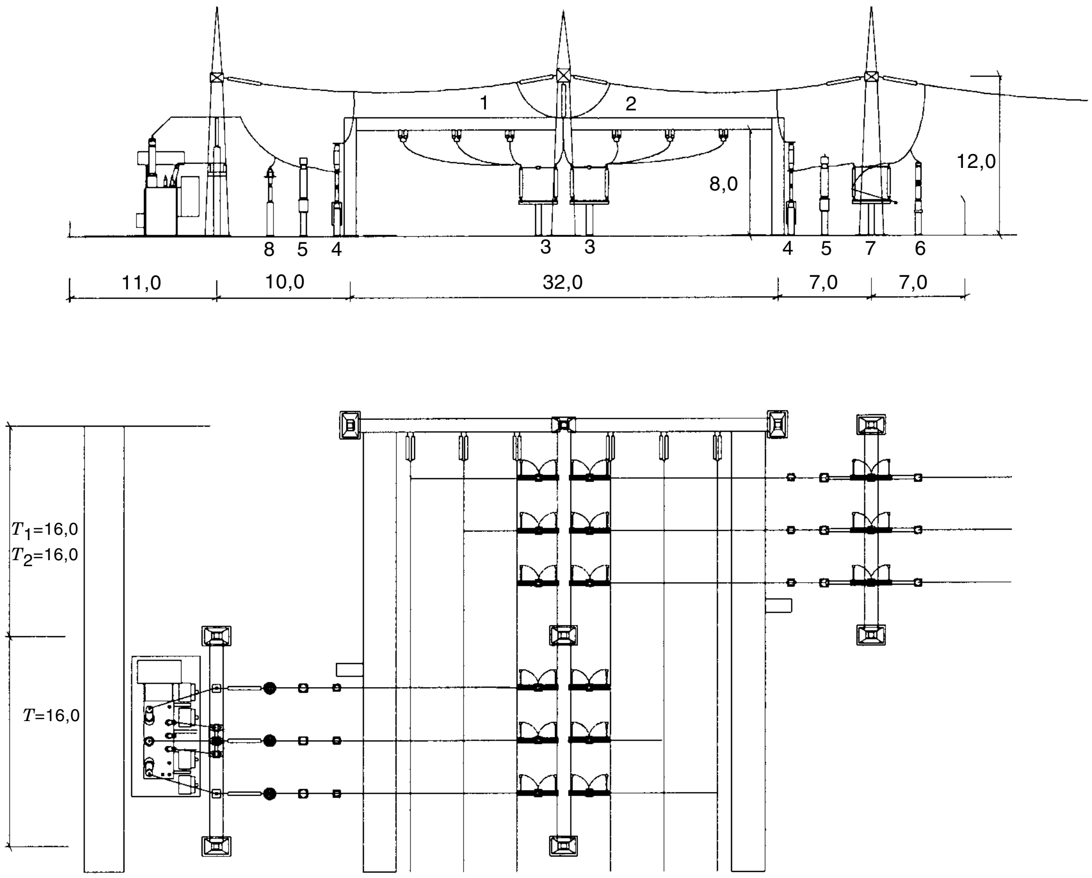
Main features	Busbar Configurations							Breaker Configurations		
	Without Transfer Bus			With Transfer Bus (tb)			With Shunting Switch	With $1\frac{1}{2}$ Breakers	With 2 Breakers	Ring System
Basic circuit:										
Number of busbar systems	1	2	3	1+tb	2+tb	3+tb	2	2	2	—
Number of										
• breakers	1	1	1	1	1	1	1	$1\frac{1}{2}$	2	1
• disconnectors per feeder, (%)	2	3	4	3	4	5	5	3	4	2
Cost ratio between different circuit configs. at 245 kV per feeder, (%)	91	100	110	100	112	118	103	111	144	88
Network splitting possible?	No	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	No
Operational										
• flexibility	Rigid	Flexible	Very flexible	Rigid	Flexible	Very flexible	Flexible	Very flexible	Very flexible	Rigid
• changeover without interrupting supply										
• from busbar	No	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
• from outgoing feeders	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Approximate relative space occupied in 245 kV substations per feeder, (%)	85	100	115	100	115	130	105	65	95	50

Table 2. Criteria for the Choice of an Appropriate Type of Substation

Criteria	For Type of Substation: AIS	GIS	Hybrid
Floor space required	Large (100%)	Small (20–40%)	Medium (50–70%)
Cost, including civil work	Generally low (100%)	Generally higher than AIS (110–140%)	Generally higher than AIS (120–130%)
Ambient condition pollution class[a]	Preferred for classes[a] 1, 2, 3, (4)	Preferred for classes (3), 4	Preferred for classes[a] 1, 2, 3, (4)
Susceptibility to external factors	Higher than GIS	Low	Comparable with AIS or lower
Effects of disturbances	Generally slight	Greater than AIS, particularly with busbar faults	Comparable with AIS (depending on AIS or GIS proportion)
Effect on environment	Large	Slight	Medium
Ease of repair	Very good	Good	Good
Maintenance outlay	Slight	Less than AIS	Comparable with AIS or lower
Preferred voltages (kV)	52–765	52–765	245–525

[a] As per IEC 71-2, IEC 815 and DIN VDE 0111, pt. 3.



1 Busbar system I
2 Busbar system II
3 Busbar isolating switch
4 Power breaker
5 Current transformer
6 Voltage transformer
7 Outgoing feeder isolating switch
8 Surge arrester

T Bay division
T_1 Division of starting bay of busbar stay-pole straining
T_2 Division of final bay of busbar stay-pole straining

Figure 7. 245 kV outdoor substation with double busbars: low-rise (classic) construction.

mounted above can be of wires or tubes. The arrangement is similar to the traditional version described under “Low-Rise (Classical) Layout.”

Sulfur-Hexafluoride (SF_6) Gas-Insulated Switchgear (GIS). SF_6 gas-insulated switchgear occupies only a fraction of the area and space required by conventional air-insulated switchgear. For applications in areas of high electrical load density, especially in cities and industrial centers, GIS is an economic solution. The range of high-voltage (HV) SF_6 GIS extends from 72.5 kV to 765 kV, with short-circuit ratings up to 63 kA. In all installations, the equipment complies with the IEC rules currently in force, thereby meeting nearly all national standards.

The distinctive advantages of SF_6 GIS are: compact size, low weight, high reliability, safety against touch contact, low maintenance, and long life. The on-site erection time is short, owing to extensive prefabrication and factory testing of large assemblies or complete bays.

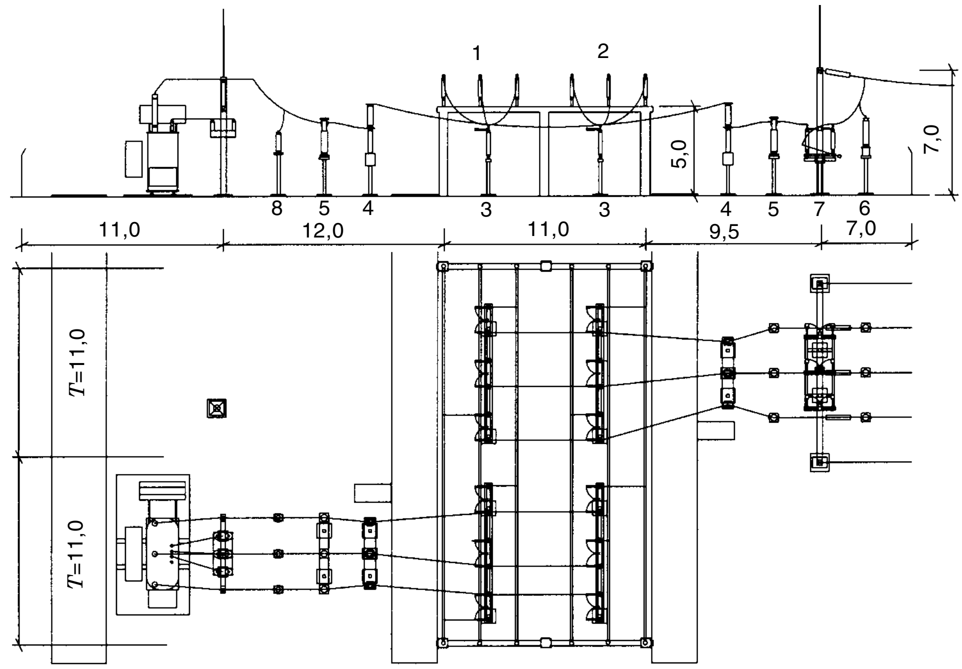
GIS equipment is usually of modular construction. All components such as busbars, disconnectors, circuit breakers, instrument transformers, cable terminations, and joints are contained in grounded enclosures filled with SF_6 gas.

The three phases of GIS are usually in a common enclosure up to 170 kV; the phases are segregated at higher voltages.

The modular construction of SF_6 switchgear means that switchyard layouts of all busbar arrangements previously described are possible.

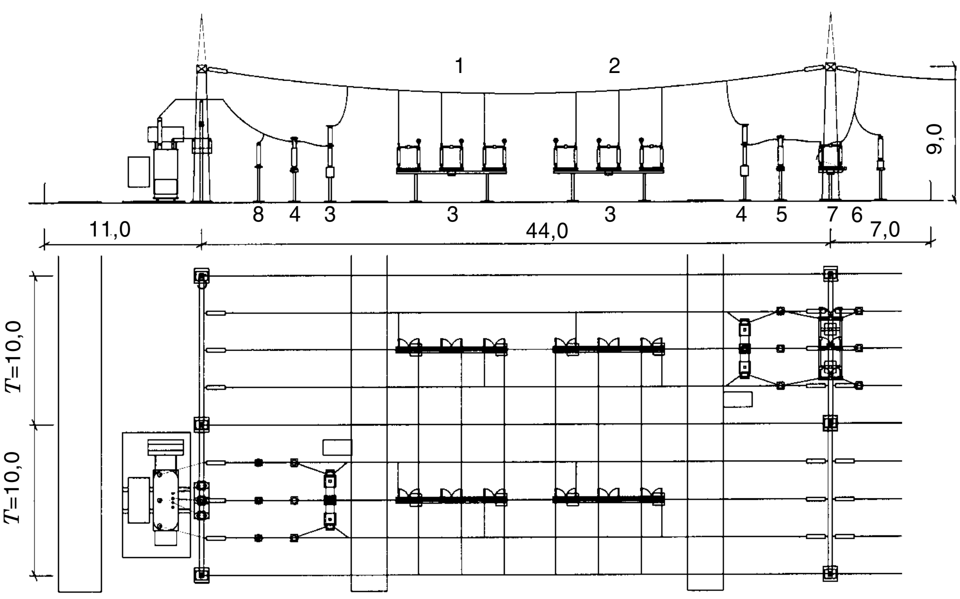
Figures 14 to 16 show a selection of three station layouts of SF_6 switchgear for 123 kV to 170 kV:

Fig. 14 Double busbar arrangement
Fig. 15 H-arrangement
Fig. 16 $1\frac{1}{2}$-circuit-breaker arrangement



1 Busbar system I
2 Busbar system II
3 Busbar isolating switch
4 Power breaker
5 Current transformer
6 Voltage transformer
7 Outgoing feeder isolating switch
8 Surge arrester

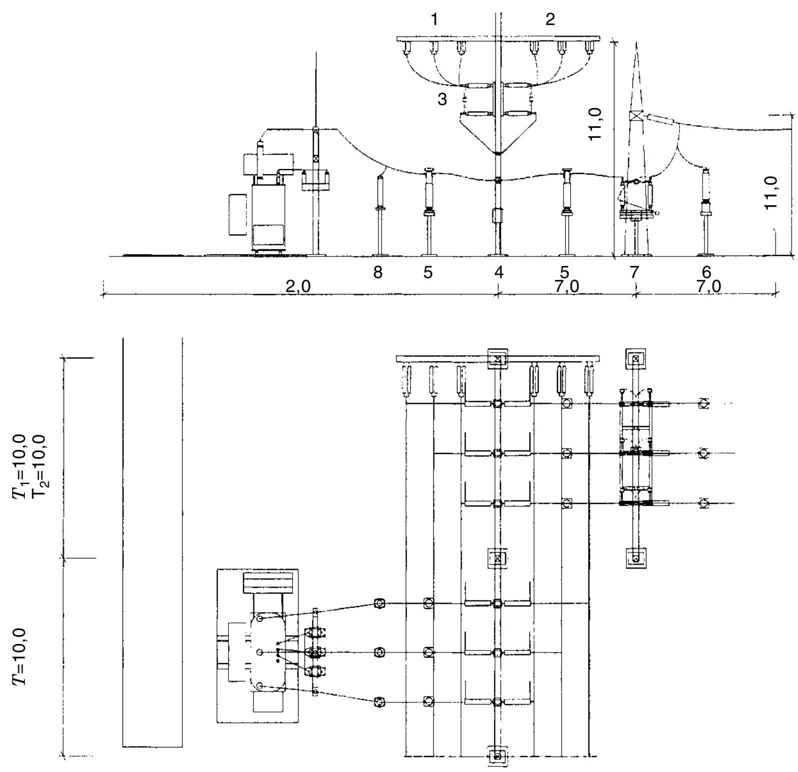
Figure 8. 123 kV outdoor substation with double busbars: in-line layout with longitudinal series construction and tube-type busbars.



1 Busbar system I
2 Busbar system II
3 Busbar isolating switch
4 Power breaker
5 Current transformer
6 Voltage transformer
7 Outgoing feeder isolating switch
8 Surge arrester

T Bay division

Figure 9. 123 kV outdoor substation with double busbars: transverse series construction.



1 Busbar system I
2 Busbar system II
Busbar isolating switch
3 Power breaker
4 Current transformer
5 Voltage transformer
6 Outgoing feeder isolating switch
7 Surge arrester

T Bay division
T1 Division of starting bay of busbar strained support
T2 Division of final bay of busbar strained support

Figure 10. 123 kV outdoor substation with double busbars: high-profile or T-pole construction.

MEDIUM-VOLTAGE SWITCHGEAR

Modern medium-voltage (MV) switchgear consists of cubicles completely enclosed in steel sheets. Such cubicles provide greater protection against contact than open cubicles. Metal-enclosed and metal-clad switchgear have compartments for the busbars, the circuit breaker, and the instrument transformer and cable connection (see Fig. 17). They are also classified by the way the switchgear is mounted in the cubicles: with fixed-mounted apparatus, or with truck-mounted apparatus, where the circuit breaker is of drawout design and can be transported by means of a separate auxiliary truck.

Nowadays the MV circuit-breakers are mainly oil free. Vacuum (or SF_6) circuit breakers have the important advantage of being largely maintenance-free and having a high long-term breaking capacity.

Constant refinement and technical improvements have over the past years significantly reduced the volume of switchgear. A further phase of development began with the introduction of gas insulation. This new generation of switchgear meets the users demands for maximum safety, small size, high reliability, low maintenance, and outstanding availability—even in rough surroundings and operating conditions.

Modern gas-insulated MV switchgear has compartments with gastight partitions between them, each with a pressure vent for the extremely unlikely event of an arcing fault. The insulating medium is nitrogene or SF_6 (for voltages of 20 kV and more). This gas also serves as a protective medium. In contrast to conventional air-insulated switchgear—where contamination can cause a deterioration in insulation level—failures due to corrosion, dust, and condensation, as well as vermin are unknown with gas-insulated switchgear. The modular structure of the switchgear panels permits variable circuit technology, with the result that nearly all requirements can be implemented in a simple and space-saving manner.

The newest developments in gas-insulated MV switchgear have a computer-controlled switchgear management system, which uses the diverse resources of microprocessor technol-

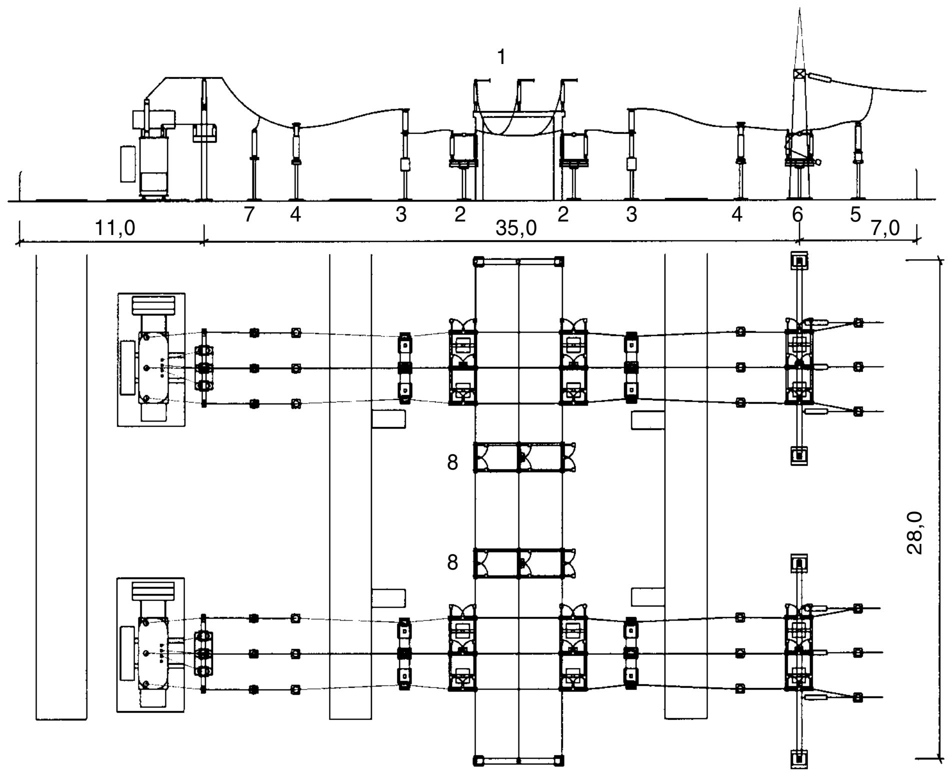


Figure 11. 123 kV main substation: load center substation (industrial or network substation, nonstandard construction).

1 Busbar system
2 Busbar isolating switches
3 Power breakers
4 Current transformers
5 Voltage transformer
6 Outgoing feeder isolating switch
7 Surge arrester
8 Busbar longitudinal isolating switch

ogy. Integrating the many secondary control and protection functions into software greatly reduces the wiring in the cubicle. The use of sensors (for measuring voltage and current) instead of conventional instrument transformers allows the method of data collection to be matched to an electronic bay control and protection unit. Sensors offer greater reliability than other measurement acquisition systems. They are also used for temperature-compensated pressure detectors and inductive proximity switches for identifying switching position.

DIGITAL SWITCHGEAR CONTROL AND MONITORING

Over the past ten years digital substation control systems have been increasingly installed in electrical systems worldwide. These computer-aided technologies offer high flexibility and operational reliability, and an excellent user–machine interface. Permanent self-supervision and early fault detection are further important features of modern secondary technology.

The new generation of electronic control systems has benefited from many innovative changes for sensors and actuators and from the computer-compatible data formatting and handling. The result is a decentralized system of microprocessor-based electronic devices, located as close as possible to the process. This includes the application of sensors for current and voltage measurement, replacing the heavy current and voltage transformers. In addition to functional such as advantages absolute linearity and lack of saturation, a more compact and space-saving substation layout is achieved.

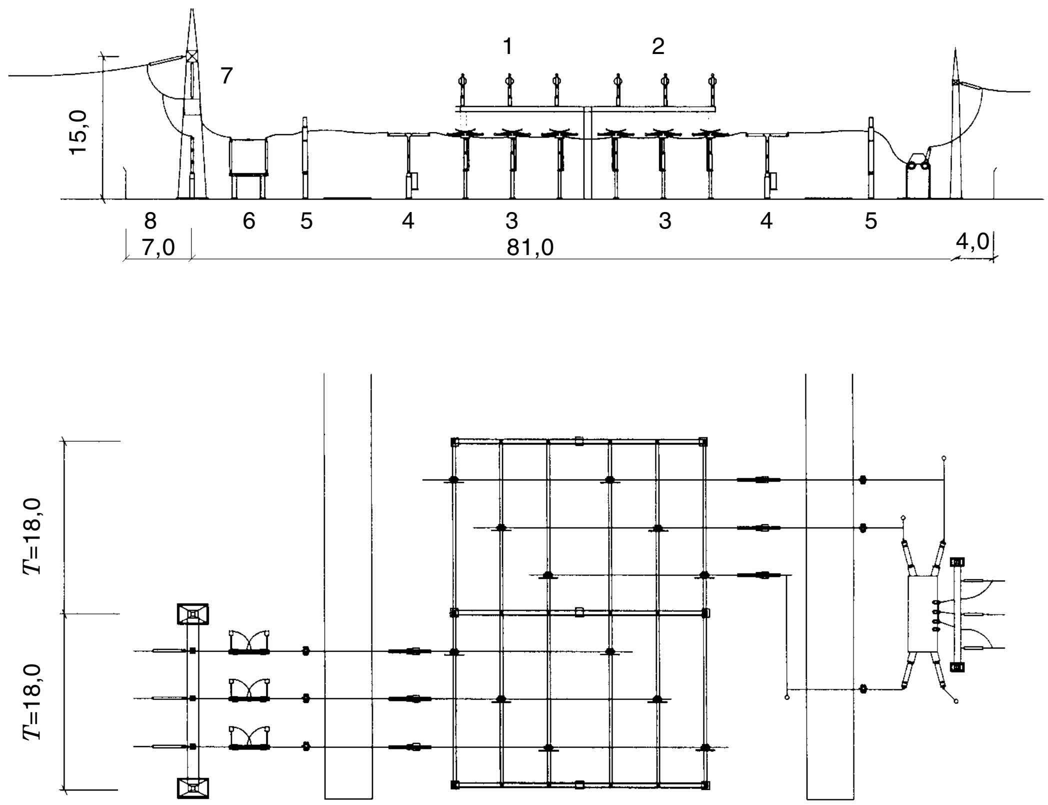
Most performance failures today are caused by failures in auxiliary and control circuits and accessory devices. The decentralized location of microprocessor-based units allows permanent supervision down to the sensors and actuators. Compared with passive devices, these provide very fast failure identification in the complete secondary technology.

Application of Novel Sensor Technology

As shown for MV switchgear in the preceding section for GIS HV installations, a basic set of sensors is required for monitoring purposes:

- Switchgear contact positions
- Stored energy of operating mechanisms
- Gas density
- Current and potential at main circuits

The switchbay of today is an integrating solution, with sensors and actuators on the process side and highly developed computer technology on the assessment, control, and opera-



1 Busbar system I
2 Busbar system II
3 Busbar isolating switches
4 Power breaker
5 Current transformer
6 Outgoing feeder isolating switches
7 HF stopper
8 Capacitive voltage transformer

T Bay division

Figure 12. 420 kV outdoor substation with double busbars (tubular): diagonal construction, busbars above.

tion side. Such a system allows maintenance to become condition-dependent rather than periodic.

The condition-monitoring concept includes following functions:

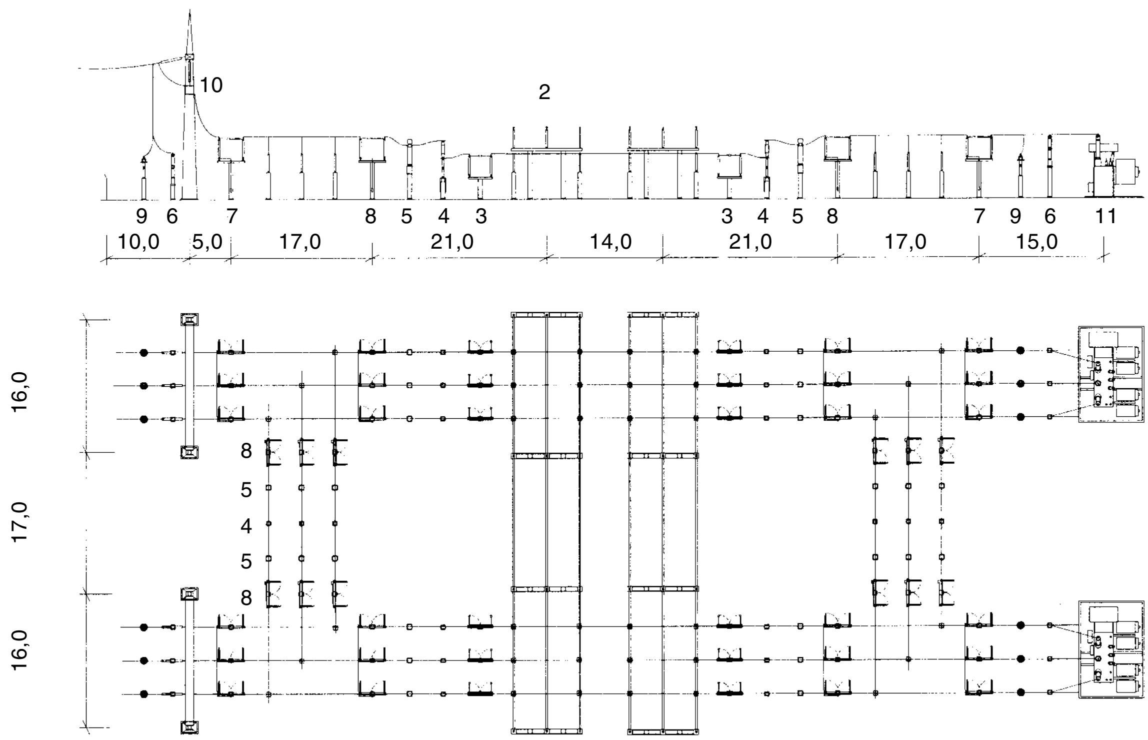
- *Switching Times, Operation Counting.* All operating mechanisms are equipped with touchless position sensors. By means of a very simple software module the switching times for opening and closing are determined and compared with specified values. Critical deviations trigger an immediate alarm. The number of operations is counted and considered in the maintenance program.
- *Gas Density.* The conventional density relay has only two or three microswitches, adjusted to given limit values. Electronic density sensors permanently give an output, representing the actual density. Thus trend analysis is easy. Necessary gas replenishment can be planned in advance.
- *Stored Driving Energy in the Circuit Breaker Operating Mechanism.*
- *Circuit Breaker Contact Wear.* The contact condition is deduced from previous short-circuit interruptions by integration of individual arcing times and squared short-circuit currents.

Effects of the Intelligent-Bay Concept on Substation Technology and Operation

The homogeneous technology of intelligent bays and the advantages of modern substation control technology will lead to increased reliability and availability of operation.

Substation quality is improved by reducing the number of components, which is equivalent to a minimization of opportunities for defects (OFDs). Multiuse of identical modules increases the production rate and ensures a wide basis of experience. This applies chiefly to software modules. Since a type-tested and accepted software module is guaranteed to be free of defects—in contrast to conventional wiring—quality will be automatically enhanced.

A further availability improvement is derived from permanent self-supervision. Sensors are required to supply a continuous signal with defined limit values. Even an obscure deviation will immediately trigger an alarm. Actuators are subjected to periodical check impulses; short circuits or defects thus detected lead to an alarm as well.



1 Busbar system I
2 Busbar system II
3 Busbar isolating switch
4 Power breaker
5 Current transformer
6 Voltage transformer
7 Outgoing feeder isolating switch
8 Subcircuit isolating switch
9 Surge arrester
10 HF stopper
11 Transformer

Figure 13. 245 kV outdoor substation: $1\frac{1}{2}$-circuit-breaker construction.

INNER-CITY SUBSTATIONS (E.G., UNDERGROUND SUBSTATIONS)

Design

Underground substations are often called for in quickly growing cities. Urban substation options include (see Fig. 18)

- Substations above ground (conventional)
- Substations within buildings, at the base of higher levels
- Substations below ground
- Substations within buildings, below ground

Substations close to the public, close to streets, in parks, or within buildings must be designed to prevent accidents and to be protected from adverse outside influences (e.g., fire). Likewise, fires inside the substation have to be limited to it. The same is true for other emissions (e.g., noise).

The main challenges for the planner are the space available, logistic access to the substation (e.g. to large transformers), and other environment restrictions (laws, regulations, etc.). Substations planning must take the following into account:

1. Overall costs (electrical and auxiliary equipment, civil engineering, space/volume)
2. Space and volume of the substation
3. Disaster prevention (e.g., fire protection)
4. Logistics (e.g., easy access)
5. Standard layout

The overall costs are usually the variable of optimization for decisions concerning substation layout. In areas with extremely high costs for space and volume (e.g. large cities), point 2 may be the most important one. This is especially true if a substation is being installed in an existing building with special boundaries imposed.

If offices or living areas are within the building, the substation must be designed with special measures for disaster prevention and fire protection, often regardless of costs. For operational reasons simple logistics and easy access to the substation may be a reason for one or another utility. Standard layout of substations is important for reasons of easy operation, maintenance, and storekeeping.

One of the main goals of underground development is reducing the building height and downsizing the necessary corridors and machine hatches. For this purpose the transformer

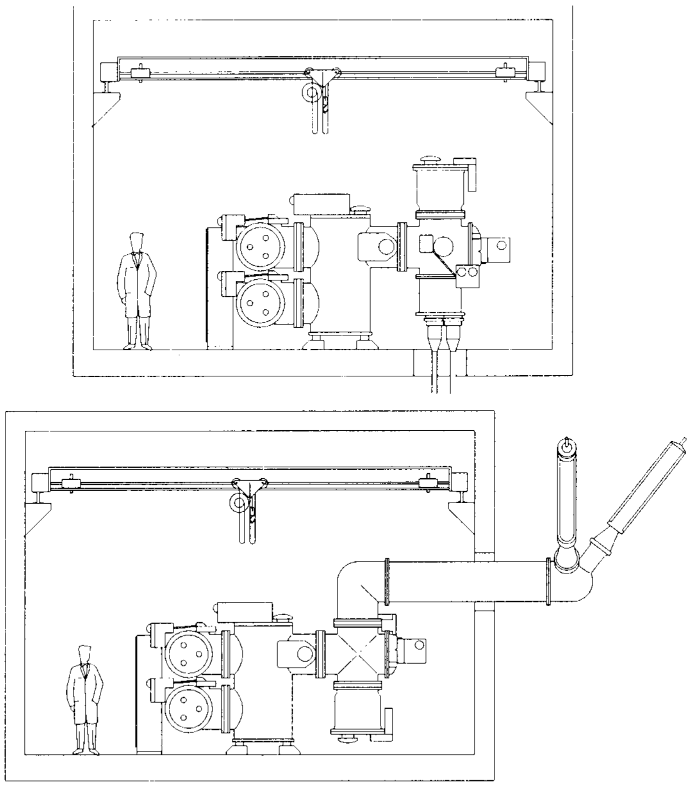


Figure 14. GIS-Substation layout in double busbar arrangement (side view).

height must be reduced, because the power transformer is the dominating component of the substation. This effort is ultimately limited by the physics of transformers.

Civil Construction Requirements. For constructing switchgear installations the civil engineering consultant requires a great deal of detail from the layout drawings. The layout drawings are the basis for preparing the construction drawings (plans for foundations, framework and reinforcement, and services).

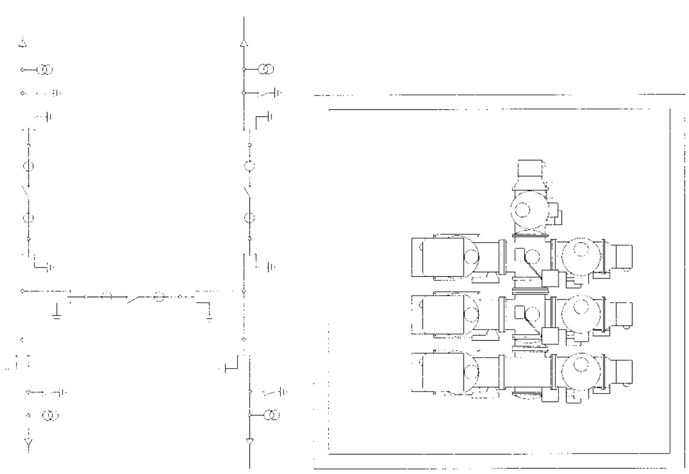


Figure 15. GIS-Substation layout in H arrangement (single-line and top view).

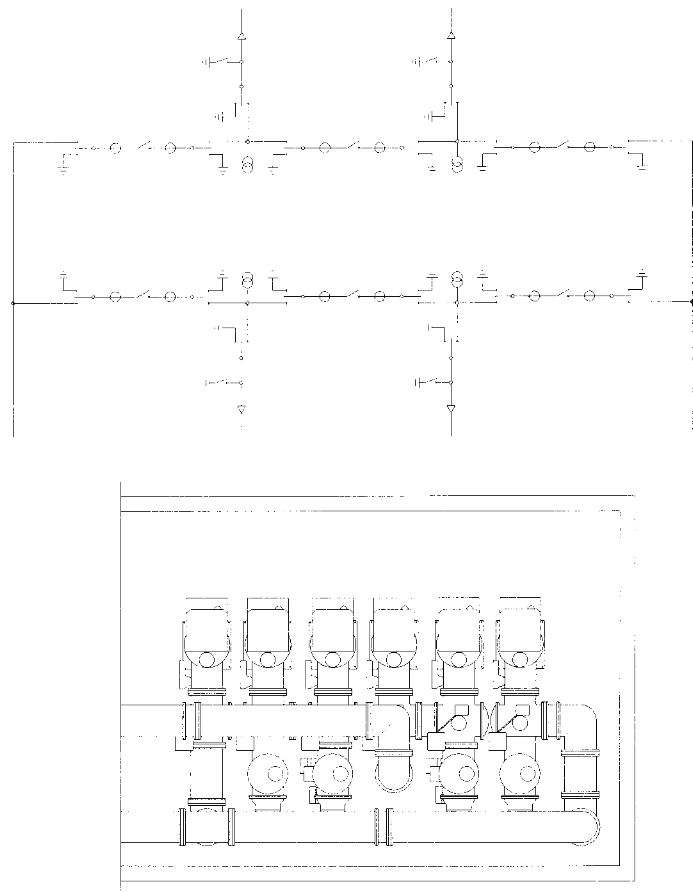


Figure 16. GIS-Substation layout in $1\frac{1}{2}$-circuit-breaker arrangement (single-line and top view).

The information required includes the following:

- Physical arrangement of the equipment
- Gangways for operation, transport, and servicing
- Principal dimensions of equipment parts
- Loading
- Gates, doors, and windows, how they open, whether fire-resistant or fireproof
- Ceiling and wall penetrations for cables, piping, or ducting
- Details on rooms with specialized services
- Normal building services
- Ventilation and air conditioning
- Floor, including steelwork
- Grounding for foundations and buildings
- Lightning protection
- Drainage

SF_6 Installations. For erection and servicing purposes it is advisable to extend the length of buildings for SF_6 switchgear by one bay and install a crane with a capacity suitable for the heaviest components.

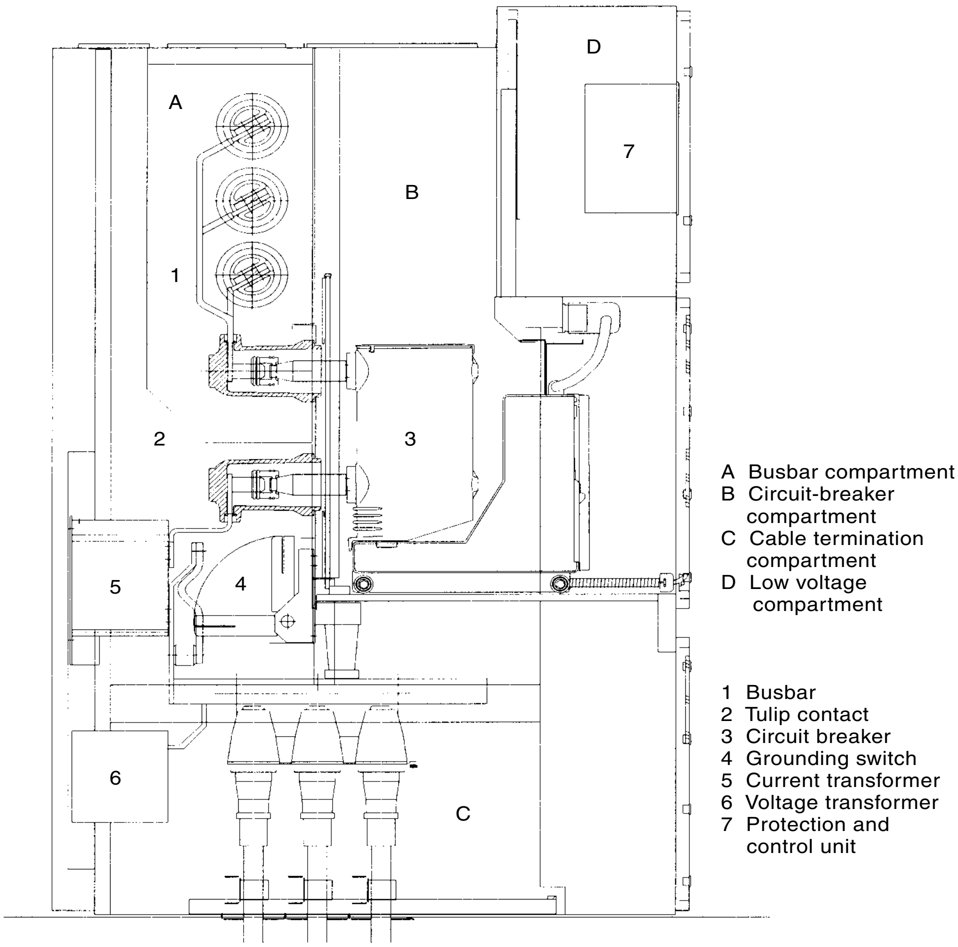


Figure 17. Switchgear panel for 24 kV, 25 kA (cross section).

SF_6 installations must also include provision for disposal of SF_6 gas in the event of leakage or defects. For this purpose special SF_6 detectors are installed, which are connected to an alarm system to warn personnel or to prevent them from entering the switchgear installation in case of leakage.

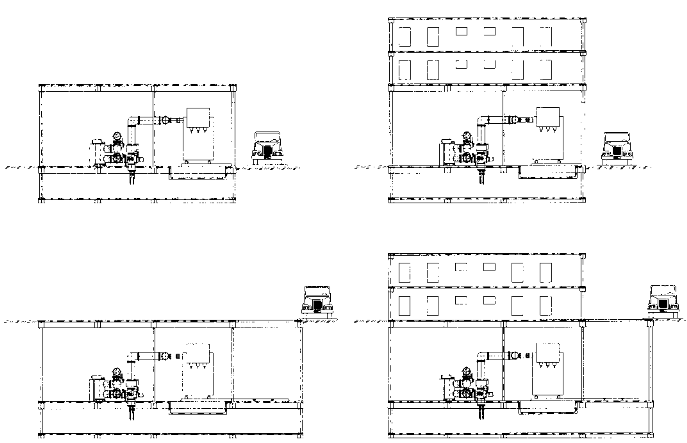


Figure 18. Four possible variants of subtransmission substations within buildings.

In proximity to SF_6 switchgear there are often offices containing electronic equipment. Therefore electromagnetic compatibility (EMC) requirements for electronic equipment as well as the public must be considered. System grounding of such substations exceeds the usual specifications. Special wiring concepts, screening, and EMC testing are becoming more important (IEC 694 Amendment 3, 1995). In modern substation design technology it is no longer possible to separate power-frequency grounding from high-frequency grounding.

Power Transformer Installation

Transformer and switchgear rooms must be arranged so that they are easily accessible.

The room dimensions must take into account temperature rise, noise, fire hazards, and the ability to replace equipment. If transformers intended for self-cooling are installed indoors, suitably large ventilation openings must be provided above and below the transformers to maintain the required temperature. If natural ventilation is not sufficient, forced-flow ventilation must be provided. A disadvantage of forced-flow ventilation for indoor applications is the resulting noise.

Attention must be paid to the following requirements when transformers are installed:

- Clearances
- Safety distances

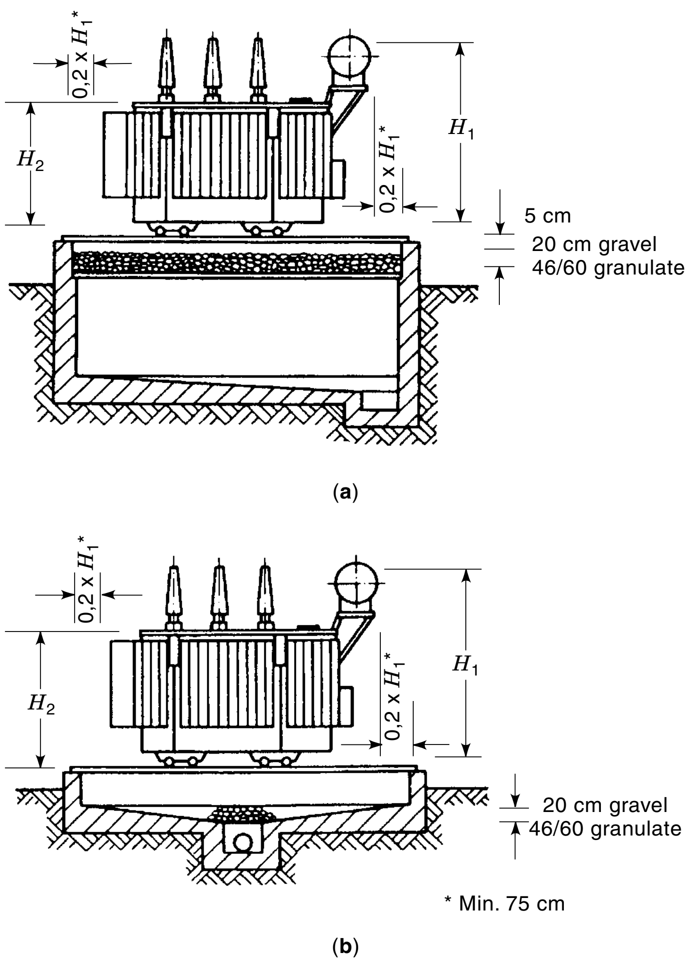


Figure 19. Transformer installation with gullies, pits and sumps.

- Execution of high-voltage links
- Access for operation and maintenance
- Access for transport
- Cooling and ventilation
- Preventive fire protection
- Auxiliary equipment
- Erection
- Provision of exit for subsequent transformer replacement

Gullies, pits, and sumps must be provided under transformers containing insulation liquids to protect against fire and water pollution. They must be built so that the insulating fluid cannot escape to the soil (see Fig. 19).

From the technical point of view, different types of transformers are available for indoor applications, but they are not available for all voltage levels or for the entire power range.

Immersed Transformers. The active part is placed in a tank filled with a dielectric belonging to one of the following groups:

- Mineral oils
- Silicone oils
- Halogenated insulating liquid [nontoxic, and thus now replacing the askarels (pyralene), whose use is forbidden in numerous countries; the use of this liquid involves no restrictions or special precautions]

The liquid dielectric also serves as a means of conveying heat to the cooling system. The dielectric varies in temperature, and it expands and contracts as the transformer load increases and decreases. The transformer must be designed therefore to absorb the volume variations of the dielectric. Two principles are used:

1. *Breathing Transformers.* The expansion of the dielectric takes place in an expansion tank placed above the tank.
2. *Sealed Transformers.* For power transformers of less than 16 MVA in which the dielectric quantity is low, it is possible to avoid any contact with air.

Dry Transformers. These are transformers with dry insulation in which the cooling is effected by ambient air without an intermediate liquid. They belong to one of the following groups:

Class H Impregnated. Transformers in which the windings are impregnated and polymerized with varnish. The insulation and varnish are selected to avoid the propagation of fire and the discharge of smoke and toxic fumes.

Cast-Resin (Encapsulated). Transformers in which windings are encapsulated in epoxy resin. This resin can be reinforced with glass fiber and is specially designed to avoid propagation of fire.

Environmental Impact

One of the most important points in building design is to reduce noise and vibration.

Noise. Noise control should be conducted to keep the substation-generated noises within the limits of local laws and regulations. Local regulations usually depend on how the building is used (besides the substation) and what kind of installations and buildings surround it.

The main noise sources are listed in Table 3. In addition, the most common measures for the reduction of noise are listed in Table 4 and for noise control in Table 5.

Table 3. Noise Sources

Components	Origin of Noise
Power transformer	Iron core of the transformer
Shunt reactor	Iron core
Auxiliary transformer	Iron core of the transformer; noise level is low
Forced-air cooler	Fan rotation and motor
Water-cooling tower	Fan rotation and motor; falling water
Fans	Fan rotation and motor; air flow
Louvers	Air flow through slots
Circuit breaker	Switching operation

Table 4. Methods of Noise Reduction

- Equipment: Soundproof covers; choice of fan sizes and speeds.
- Place of installation: Distance (difficult to achieve for wind tunnels, ducts, and other such structures)
- Structural insulation:
  - Shelters: Soundproof (concrete) walls, ceilings, and floors
  - Sound insulators
- Absorption:
  - Noise channels and bends with abrupt changes in width
  - Noise absorbers (frequency characteristics checked for effective installation)
  - Silencers (porous absorbers providing absorption, reflection, and interference)

Table 6. Vibration Sources

Component	Source of Vibration
Power transformer	Iron core
Shunt reactor	Iron core
Circuit breaker	Switching operation
Forced-air cooler	Fan and motor
Air compressor	Compressor
Pumps	Cooling pump
Piping	Depends on installation
Ducts	Air vibrates the duct
Fan	Fan

Vibration. Vibration, in contrast to noise, passes through the building framework and requires as much attention as noise (see Table 6). The most common measures for the reduction of vibration are listed in Table 7.

One very effective measure of vibration reduction is to install rubber dampers at supports or underneath the electrical equipment (e.g., transformers, gas-insulated switchgear).

Ventilation

The dimensions of the ducts for air intake and exhaust must be designed carefully and take the loads and the resistance of the air path into consideration.

The rooms must be sufficiently ventilated to prevent condensation. To avoid corrosion and other damage due to high relative humidity and condensation, it is advisable to follow the figures given in national standards for atmospheric influences in rooms containing switchgear. The ranges recommended here are:

- Maximum relative humidity: 95% (24 hour mean value)
- Maximum and minimum ambient temperature averaged over 24 h: 35°C and −5°C, respectively

In areas with heavily polluted air the rooms should be kept at slight positive pressure, using filtered air. The necessary air vents must be protected against rain, water splashes, and small animals. Below heights of about 2.5 m above ground level, the vents must also have prod-proof plates mounted behind.

The same considerations apply for the cooling equipment. If ventilation is not sufficient, cooling equipment must be installed. Here, especially, the power transformers must be considered. Power transformers have load-dependent losses up to 0.5% of their nominal rating. This leads to enormous heat loads in underground substations, which must be extracted.

Power transformers can be cooled through:

- Direct oil cooling with an outside oil cooler
- Oil–water heat exchanger with outside cooling water tower
- Air cooling (ventilation)

Ventilation of Transformer Cells. If transformers intended for natural cooling are installed indoors (e.g., in cells), sufficiently large ventilation openings must be provided above and below the transformer so that natural air movement is sure to remove the heat losses.

If natural ventilation is inadequate or the required flow area would be too large or the shaft too high, a fan must be provided that can accommodate the required flow rate and head. The fan must provide not only the static pressure needed to overcome resistance in the air path, but also the dynamic or discharge pressure. Static and dynamic pressure together amount to ≈0.2 mbar to 0.4 mbar (20 Pa to 40 Pa).

Table 5. Noise Controls

Equipment	Main Considerations
Transformer	Low-noise transformers and coolers Sound absorbers at walls and ceilings Concrete walls as noise insulation
Outdoor cooling tower	Soundproof walls
Fan room	Sound absorbers at walls and ceilings
Louver	Dimensioning according to air flow, wind velocity, and rain-preventive requirements
Ventilation ducts	For cooling transformers or ventilation of buildings Provision of bends Installation of sound absorbers
Breaker room	Sound absorbers at walls and ceilings

MAINTENANCE

The operational reliability of the fully enclosed GIS is not influenced by external elements such as pollution or moisture. Consequently, the GIS requires extremely little maintenance. Under normal operating conditions it can be considered maintenance-free. Inspections are recommended at intervals of five years. They do not require access the primary enclosures, and the switchgear can therefore remain in operation.

Table 7. Methods of Vibration Reduction

- Separate equipment from its foundation by means of suspended foundation structure
- Support vibrating machinery on springs; rubber dampers are commonly used
- Fasten the equipment adequately

The circuit breaker and disconnectors require maintenance only after many thousand mechanical operations. Scheduled maintenance of HV circuit breakers also depends on the number of short-circuit interruptions, at the earliest following 30 interruptions of fault current. Medium-voltage vacuum circuit breakers are maintenance-free. Maintenance of the fast-acting grounding switch is required after closing twice onto a fault.

Recommended scheduled maintenance of the load break switch and fast-acting grounding switch is every 2000 operations. These limits are far more stringent than the requirements of practical operation. This means that overhaul work generally need not be taken into account for power system planning.

For power transformers the examination of the insulating fluid (e.g., the oil) is very important. Changes of its electrical properties (as loss factor, breakdown voltage) and an analysis of the gases dissolved in the oil give indications for oil and transformer aging. Therefore it is recommended that oil samples be taken every two to three years. Further inspections (every six months or once a year) check oil-tightness, oil level, protection devices, pumps, and vents. Tap changers should be inspected after a specified number of operations.

Reading List

Asea Brown Boveri, *Switchgear Manual,* 9th rev. ed., Berlin: Cornelsen Verlag, 1993.

CIGRE WG 23-10, Task Force 03, User guide for the application of gas-insulated switchgear (GIS) for rated voltages of 72.5 kV and above, Draft 11, 1997.

V. Rees and M. Schumacher, Innovative gas-insulated switchgear (GIS) with modern control and sensor technology, presented at IEEE Seminar, Acapulco, Mexico, July 1997.

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TRANSFORMS. See HADAMARD TRANSFORMS; HARTLEY TRANSFORMS; HILBERT TRANSFORMS; LAPLACE TRANSFORMS; MULTIRATE FILTERBANKS.

TRANSFORM, WAVELET. See WAVELETS.