Chapter 9

Transmission substations

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9.1 Introduction

The function of a substation in a transmission system is to provide a switching node through which circuits, generating units and step-down transformers can be interconnected. Substations are critical to the safety, reliability and availability of the network and should be carefully planned with both current and future system requirements in mind [1, 2].

9.1.1 System requirements

The need for a new substation will be identified by system planners who will define the key design parameters. Examples of such system requirements are:

- general location
- extent of the substation
- required availability of circuits
- switching arrangement
- transformer ratings and impedances
- normal current rating
- fault current levels
- neutral point earthing
- fault clearance time with respect to system stability
- need for future extensions
- control facilities
- equipment characteristics.

Where applicable, it is generally advisable to select system requirements to align with IEC or EN Standards. Many utilities also find it beneficial to specify technical requirements so as to allow the use of standardised HV equipment with identical characteristics (e.g. short-time current level, maximum current carrying capacity, characteristics of transformers, insulation level).

9.1.2 *Choice of switching arrangement*

Some of the more common switching arrangements used in UK practice [1] are as follows.

9.1.2.1 *Double busbar*

This arrangement has been widely used in the UK at both transmission and distribution voltages for larger substations where security of supply is critical (see Figure 9.1). Each circuit is provided with a dedicated circuit-breaker (1) and can be selected to either of the two independent busbars by means of busbar selector disconnectors (2). The busbars can be coupled by means of a bus coupler circuit-breaker (3). The line disconnectors (4) are normally provided at transmission voltages to facilitate maintenance but may be omitted in many cases without loss of operational functionality.

Service continuity can be maintained with a busbar out of service; however, a single circuit outage is necessary for fault repair or maintenance in the circuit-breaker area.

9.1.2.2 *Multi-section double busbar*

This arrangement (see Figure 9.2) adds bus section circuit-breakers (A) to the standard double busbar configuration. The ability to segregate circuits across a number of sections of busbar separated by circuit-breakers is used to limit system disruption under worst-case fault conditions.

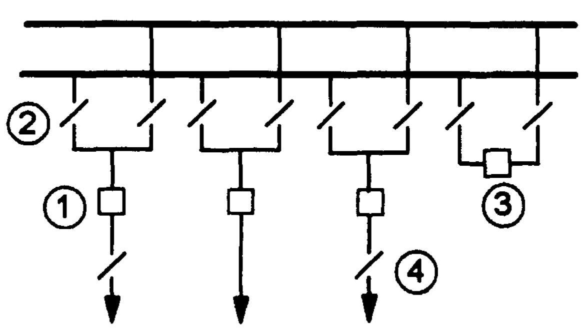

Figure 9.1 Double busbar switching arrangement

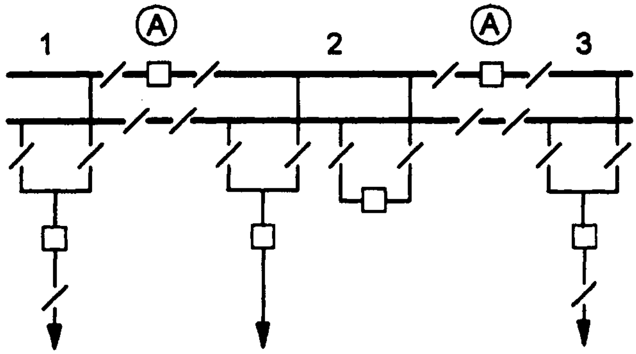

Figure 9.2 *Multi section: double busbar switching arrangement*

An example of the use of this configuration is the connection of large generating units to a system. If each unit is arranged so as to feed a separate section of busbar (1, 2 and 3 in the diagram above), then normally only one unit will be tripped for a busbar fault, leaving the remainder in service. Under worst-case fault conditions (a bus section or bus coupler circuit-breaker fault) a maximum of two generating units will trip. The system can thus be operated with reserve generating capacity sufficient only to cater for the loss of these two units.

9.1.2.3 One and a half switch

This arrangement (see Figure 9.3) has two busbars (1) interconnected by chains of three circuit-breakers (2), often referred to as a diameter. Outgoing circuits are taken off from between pairs of circuit-breakers (3). Although not common in the UK, arrangements of this type are widely used internationally at transmission voltages.

This arrangement when intact offers a high level of service continuity of the outgoing circuits and is therefore beneficial where line availability is critical. However, during busbar or circuit-breaker maintenance outages the substation can be vulnerable to single fault outages.

9.2 Site selection

The first step is to locate potential sites within the general location required, which should be:

- reasonably level
- of sufficient area to accommodate the planned equipment
- available at reasonable cost
- easily accessible
- of low environmental impact
- accessible by existing or available line corridors.

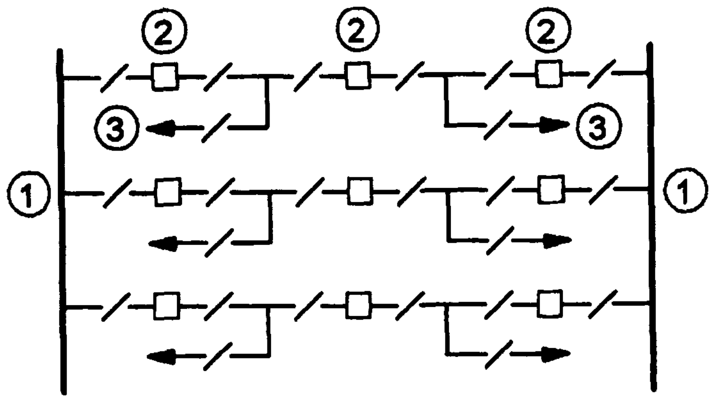

Figure 9.3 One and a half switch: double busbar switching arrangement

In many cases the choice of site will be limited by the need to locate the substation adjacent to or in close proximity to an existing line corridor. It may therefore be impossible to find sites meeting all of the above requirements.

Once possible locations have been identified, an analysis is made of the environmental impact, technical characteristics and costs of each site. It is also worthwhile assessing the social acceptance of the project at this stage.

9.2.1 Environmental impact

The following guidelines on siting of substations have been developed by The National Grid Company plc (NGC) to assist designers in minimising the environmental impact of substations.

9.2.1.1 Overall system options and site selection

In the development of system options including new substations, consideration must be given to environmental issues from the earliest stage to balance the technical benefits and capital cost requirements for new developments against the consequential environmental effects to keep their adverse impact to a reasonably practicable minimum.

9.2.1.2 Local context, land use and site planning

(a) The siting of substations, extensions and associated proposals should take advantage of the screening provided by land form and existing features and the potential use of site layout and levels to keep intrusion into surrounding areas to a reasonably practicable minimum.

Notes:

1. A preliminary study should be undertaken to identify the extent of land required to meet both operational and environmental needs.
2. In some instances it may be possible to site a substation partially or fully enclosed by existing woodlands.
3. Topographical information should be obtained at an early stage. In some cases a geotechnical survey may be required.

(b) The proposals should keep the visual, noise and other environmental effects to a reasonably practicable minimum.

Notes:

1. Allow sufficient space for screening of views by mounding or planting.
2. Consider appropriate noise attention measures where necessary.
3. Use security measures which minimise visual intrusion from lighting.
4. Consider appropriate on-site water pollution prevention measures.
5. Consider adjoining uses and the amenity of local inhabitants.

(c) The land use effects of the proposal should be considered when planning the siting of substations or extensions.

Notes:

1. Issues for consideration include potential sterilisation of nationally important land, e.g. Grade 1 agricultural land and sites of nationally scarce minerals.
2. Effects on land drainage.

9.2.2 Technical characteristics

9.2.2.1 Substation type

One of the fundamental decisions to be made at the planning stage is to select the type of substation. At transmission voltages the choice generally lies between a conventional outdoor air insulated substation (AIS) and an indoor or outdoor metal-enclosed SF_6 gas insulated substation (GIS). (See also Figures 3.12; 3.13; 8.8a, b; 8.9a, b.)

In GIS switchgear the primary conductors are installed in metallic enclosures filled with sulphur hexafluoride gas (SF_6) at a pressure, typically, of 3–5 bar. At the higher transmission voltages the enclosures are generally phase-segregated and only accommodate a single conductor.

At lower voltages ($\leq$170 kV) many GIS designs have three phases in a single enclosure. Conductors are supported inside the enclosure by cast resin insulating spacers. The gas filled enclosures also house all the main substation components, e.g. circuit-breakers, disconnectors, current transformers and voltage transformers. A cross-section through a typical GIS switchgear installation is shown in Figure 9.4.

The first costs of AIS will generally be lower than for GIS; however, GIS offers a number of advantages which allow a greater range of sites to be considered. Some of these can be summarised as follows:

(i) A smaller site area is required.

- Substations can be located closer to load centres, reducing transmission costs.
- Site purchase costs may be reduced.
- Site preparation costs may be reduced.

(ii) GIS has a high level of immunity from the effects of atmospheric pollution.

- The use of sites adjacent to the coast or sources of industrial pollution can be considered without an adverse impact on reliability.

(iii) Reduced environmental impact is compared with an equivalent AIS.

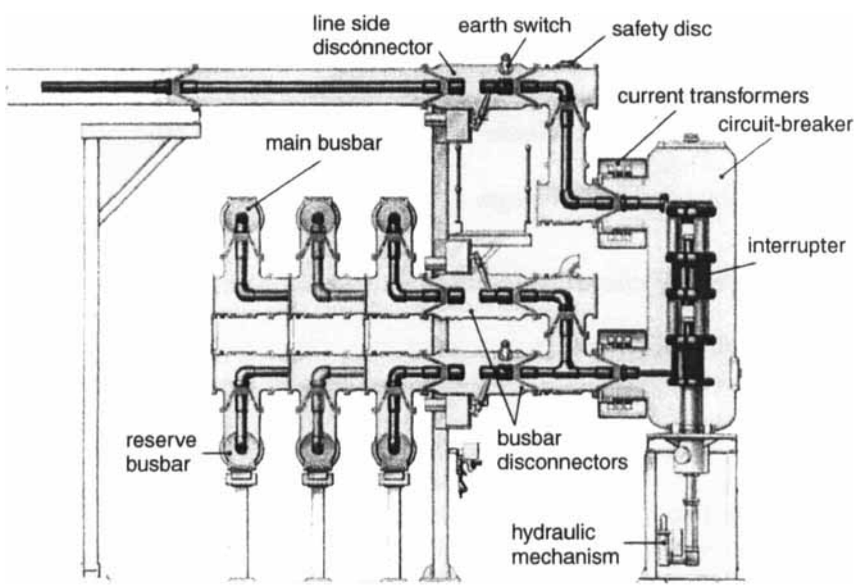

Figure 9.4 Sectional view through a typical 420/550 kV GIS duplicate busbar circuit (courtesy VATECH Reyrolle)

- Lower height reduces visual impact and permits more effective screening.
- The building used to house GIS can be designed to match or complement local architectural styles.

(iv) Reduced lifetime maintenance costs are compared with an equivalent AIS.

- Modern GIS switchgear, particularly where housed in a building, requires little maintenance.

Some of the disadvantages of GIS are as follows:

(i) There is limited flexibility to modify or extend (except as originally intended).

- The compact design of GIS generally precludes modifications to the original substation configuration.
- Since GIS equipment and layouts are manufacturer-specific users are normally tied to the original supplier for any additional work.

(ii) Uprating may be impractical.

- Due to the integrated construction of GIS, replacement of individual components (such as circuit-breakers) with others of higher rating may be difficult or impossible.

(iii) There are long post-fault downtimes.

- Whilst GIS has an excellent reliability record, if faults do occur then repair times can be long in comparison with equivalent AIS installations.

The characteristics of GIS make it particularly suitable for applications in urban areas, in mountainous terrain (where large level sites are often not available), in environmentally sensitive areas and in areas with high levels of atmospheric pollution. It should also be considered for sites at altitudes > 1000 m, where the insulating properties of air are reduced. GIS may also be of benefit where asset replacement of an existing AIS must be carried out within existing site boundaries.

9.2.2.2 Topography

It is preferable to construct a substation on level ground and flat sites should be selected where available. Care should be taken, however, that the area is not vulnerable to flooding.

It may be feasible to level a site with poor topography but such preparatory works can significantly increase costs and should be avoided. Terracing the site may be more economic (this usually increases the total levelled area but reduces the volume of soil displaced); however, terraced substations require special design solutions and may cause operational problems.

9.2.2.3 Geological and geotechnical characteristics

The soil must be suitable to allow the construction of roads and foundations. The minimum bearing load required is usually ~50 kN/m^2. If piling is required then this will increase costs.

The following should also be considered:

- Sites located on geological faults should be avoided.
- Sites in areas where there are disused mines can suffer from severe problems due to ground subsidence.
- In earthquake zones a careful study is essential, as earthquake intensity may vary dramatically in places located only a few kilometers apart.
- A high water table may require the construction of drainage facilities, increasing costs and causing construction delays.
- A low value of soil resistivity is desirable so as to simplify earthing system design.

9.2.2.4 Access

Access must be provided for delivery of power transformers and large reactors. To confirm this it may be necessary to study the complete route between the supplier's factory (or port of delivery) and the proposed substation. In the most difficult cases, single phase transformers may need to be specified instead of three phase units, transformers of lower rated power may need to be substituted (thus increasing the total number) or the transportation route may need to be improved. Access to the site for operators and maintenance teams should also be considered.

9.2.2.5 Pollution

High levels of coastal (saline) or industrial pollution may sometimes cause insulator flashover in an AIS installation (e.g. see Figures 8.8a and b for typical disposition of insulation). GIS is preferable in these cases as it greatly reduces the number of exposed insulators (illustrations are shown in Figures 8.9a and b).

9.3 Substation design

Once the site has been selected then work can start on the detailed design of the substation. At this stage consideration must be given to the arrangement of main plant within the substation, the mechanical and electrical design of the busbar system interconnecting these components and the overall impact of the substation on the locality.

9.3.1 GIS substations

Where the substation is to be of the GIS type then the switchgear arrangement and the interconnecting busbar system will generally be proposed by the switchgear supplier to best suit his standard equipment configuration. The substation designer need only consider the disposition of other equipment (e.g. transformers, power cables and line entries) and the architectural treatment to be applied. GIS is often housed in a building (e.g. see Figure 3.13), which can be designed so as to harmonise with other structures in the vicinity or with local architectural styles.

9.3.2 AIS substations

Some of the design issues that must be considered at this stage are as follows.

9.3.2.1 Selection of conductor system

Whilst copper conductors were once widely used, aluminium alloy is now commonly chosen as a conductor material in transmission substations. Both rigid tubes and stranded flexible cables are available in a range of sizes to suit the required current rating.

Rigid tubes facilitate the construction of compact, low profile substation layouts, but span lengths are limited, requiring many supports. Where used in long spans, flexible cables require high strain structures but the number of low level structures is reduced.

9.3.2.2 Operational clearances

AIS substations must be designed so as to ensure the integrity of the air space between live parts and other conductors (whether earthed or at different potential) for the rated voltage conditions. This is generally achieved by adopting design clearances from recognised Standards such as BS 7354. These clearances assume a worst case conductor configuration and are intended to ensure an adequate level of reliability in such circumstances. Reduced clearances are permissible if a specific conductor arrangement has been tested in accordance with BS EN 60694; however, this is generally not practical for high voltage substations.

Some clearances used in UK substation design are listed in Table 9.1 based on the specified switching impulse level (SIL) and basic impulse level (BIL).

Table 9.1 Substation electrical clearances

Nominal system voltage	BIL/SIL	Basic electrical clearance (phase to earth)	Phase-to-phase clearance
kV (RMS)	kV (p)	M	M
33	170/**	0.5	0.43
66	325/**	0.7	0.78
132	650/**	1.1	1.4
275	1050/850	2.1	2.4
400	1425/1050	2.8	3.6

** No SIL value specified

The specified electrical clearances must be maintained under all normal conditions. Exceptionally reduced electrical clearances may be allowed, for example, in the case of conductor movement caused by short-circuit current or by extremely strong wind.

9.3.2.3 Safety clearances

Safety clearances are distances in air which must be applied in the design of substations so as to allow personnel safe access to install, operate, maintain, repair and demolish equipment in the vicinity of live conductors. These clearances are normally based on national legislation, utility Safety Rules and/or utility operating procedures.

In Europe, work within substations is generally based on the concept of a live working zone that should not be entered by any part of a person's body or by any object unless live working procedures are adopted. This concept is defined in European Standard BS EN 50110.

In the UK the live working zone is defined by measuring a Safety Distance from high voltage conductors and support insulators. This is illustrated in Figure 9.5.

It is difficult for a substation designer to assess an equipment configuration by considering only Safety Distances. It is therefore common practice to consider a design clearance for safety. This is interpreted in the same way as section clearances, which were for many years the basis of HV safety rules in the UK. The use of section clearances is illustrated in Figure 9.6.

The work section defines where personnel may stand whilst performing work activities and provides for appropriate clearances from live conductors. Design clearances are based on a basic dimension of 2.4 m which is widely accepted as the vertical distance from a person's feet to the top of the fingers of an upwards upstretched hand, this may under some circumstances be reduced to 1.5 m where the reach is horizontal.

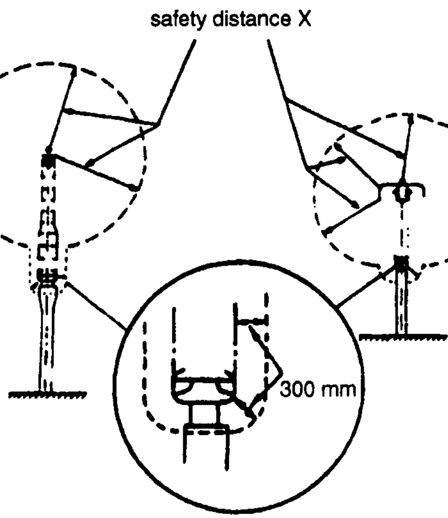

Figure 9.5 *Typical 400 and 132 kV post insulators illustrating safety distances from live high voltage conductors*

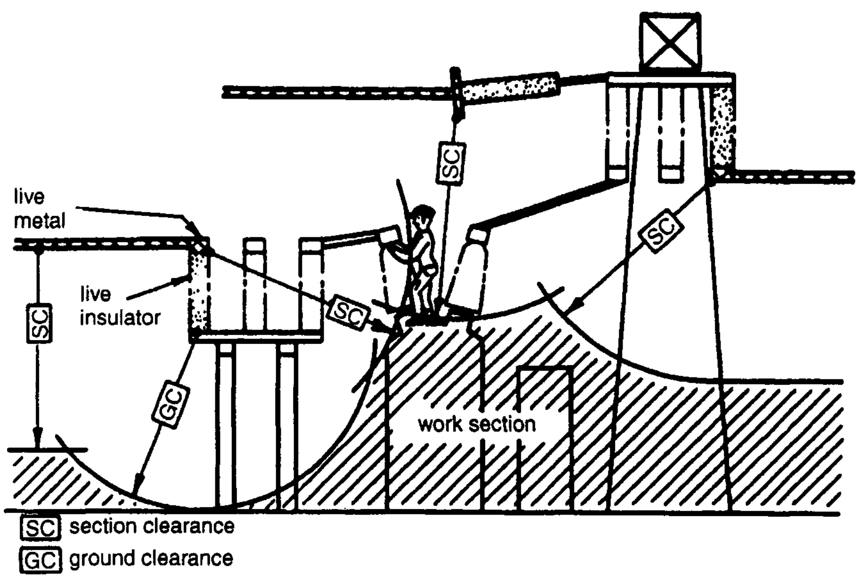

Figure 9.6 *Illustration of work section boundaries*

Safety Distances and design clearances used by the National Grid are listed in Table 9.2.

Where adequate safety clearances cannot be provided then personnel access should be limited by a fence or other barrier. Access gates to such a segregated area should generally be interlocked so as to ensure that

Table 9.2 Substation safety clearances/distances

Nominal system voltage	Safety Distance (from NGC Safety Rules)	Design clearance for safety (vertical)	Design clearance for safety (horizontal)	Insulation height (pedestrian access)
kV	m (Note 1)	m (Note 2)	M (Note 3)	M (Note 4)
11/22/33	0.8	3.2	2.3	2.4
66	1.0	3.4	2.5	2.4
132	1.4	3.8	2.9	2.4
275	2.4	4.8	3.9	2.4
400	3.1	5.5	4.6	2.4

Note 1. Persons shall not allow any part of their body or any object to infringe this distance to exposed conductors operated at high voltage.
Note 2. The minimum clearance from a live conductor to ground level at a point to which pedestrian access is permitted. [These figures are derived by adding the 'personal reach' (the vertical reach of a person with upstretched hand), which is taken to be 2.4 m, to the appropriate Safety Distance].
Note 3. These figures may be used by agreement. In general the vertical design clearance should be applied in all directions.
Note 4. The minimum clearance from the lowest insulation part of a support insulator to a point to which pedestrian access is permitted.

exposed conductors are isolated and earthed before personnel access is permitted.

9.3.2.4 Mechanical design

The design of the conductor system should take into account foreseeable loads and loading combinations to which it may be exposed.

The probability of the simultaneous occurrence of various mechanical forces will be dependent on local conditions. Consideration should be given to forces resulting from:

(a) wind loading on conductors and equipment
(b) ice covering (where appropriate)
(c) short-circuit current
(d) seismic forces (where appropriate)
(e) dead-weight of equipment and reaction forces
(f) static conductor tension.

There are two common approaches to substation mechanical design. One is to assess 'working' loads on the equipment and then to apply safety factors in order to estimate design loads. The second is to establish maximum forces that can be anticipated during the working life of the equipment and to use this as a design load without application of any additional safety factors. The latter approach is commonly used in the UK and is recommended by IEC.

(a) Wind loading

The wind load on conductors, equipment and support structures must be considered and maximum values should be determined from meteorological data. Standard values are given by some IEC publications (i.e. IEC 60694) but local conditions must always be considered.

Methods of calculating wind pressure on busbars, equipment and structures are given in BS 6399 Part 2.

(b) Ice covering

Where applicable, the effect of an even thickness of ice covering conductors, insulators and structures should be considered. This will add to the dead weight of equipment and increase the cross-sectional area exposed to wind pressure.

UK practice is to allow for a 10 mm radial ice coating with a mass per unit volume of 912 kg/m^3 in substation design. Other standard values are defined in BS EN 60694.

(c) Short circuit current

It is impractical to demonstrate the withstand capability of every busbar configuration by a short-circuit test. Instead, the short-circuit strength of the busbars is generally only calculated, the calculation methods being verified by testing of typical busbar arrangements.

Simplified calculation methods for both rigid and flexible conductors are defined in BS EN 60865–1. The background and verification of these calculation methods is detailed in CIGRE Brochure 105, SC23, 1996.

Advanced calculation methods using finite element techniques can be used to optimise specific arrangements, to validate calculated results or to establish loads in complex conductor configurations. Advanced techniques give access to more comprehensive data than simple methods (for example, dynamic effects, supporting structure stress and strain, spacer compression, connection to apparatus, insulator and supporting structure flexibility).

(d) Seismic forces

Substation planners should consider the probability and the expected severity of a possible earthquake. Because the horizontal acceleration is ~0.3 . . . 0.5 g (the vertical acceleration is less than 50% of the horizontal) and the frequency of the earthquake is 0.5–10 Hz, 275–500 kV equipment and conductor systems that resonate in this frequency band may be damaged. Bus support insulators are particularly vulnerable. Tubular aluminium conductors are also thought to resonate during earthquakes and, if required, 'dampers' or 'slide supports' may be fitted. Equipment in the substation is liable to suffer from damage where the ground conditions are not stable; particular attention should therefore be paid to site preparation to ensure 'solidity' of the ground.

(e) Dead weight and static conductor tension

In addition to the normal weight of apparatus, conductors, structures, etc. and the static conductor tensions, temporary loads must be considered. These may include the loads imposed by maintenance staff access and erection loads (lifting of structures, asymmetric conductor tensions, etc).

9.3.2.5 Loading combinations

It is UK practice to design equipment to meet the maximum values of the following load combinations:

- wind loads on apparatus without ice covering plus short circuit forces
- wind loads on ice covered apparatus.

Since these forces are known maxima, then the resultant stresses can be up to the maximum allowable, e.g.

- guaranteed cantilever breaking strength of porcelain
- guaranteed minimum proof stress of drawn or extruded metals.

9.3.2.6 Other mechanical design considerations

Tubular busbar systems with long spans of low natural frequency are susceptible to wind induced (aeolian) vibration. This may be damped either by external mechanical dampers or by fixing a length of flexible conductor inside the tube. Stresses resulting from aeolian vibration are not generally considered during the conductor system design process and so prolonged exposure should be avoided.

9.4 Concluding remarks

It has only been possible in this chapter to provide brief general guidelines for the design of substations. Further source material is available from CIGRE [2] and IEE and IEEE publications.

9.5 References

1 CIGRE Working Group 23–04 paper: 'General guidelines for the design of outdoor AC substations'. CIGRE, SC23, August 2000 (Brochure 161)
2 CIGRE Information Sources: see http://www.cigre.org and Study Committee 23 Activities (http://www.cigre-sc23.org/) CIGRE, SC23, 1996 (Brochure 105)