69

GENERAL GUIDELINES FOR THE DESIGN OF OUTDOOR A.C. SUBSTATIONS USING FACTS CONTROLLERS

Working Group 04
(Design, construction and maintenance of substations
(GIS excluded)
of
Study Committee 23 (Substations)

cigré

GENERAL GUIDELINES FOR THE DESIGN OF OUTDOOR A.C. SUBSTATIONS

Working Group 04 of Study Committee 23 (Substations)

H.G. SCHÜTTE

L. DEMOULIN P.L. FLETCHER J.M. RANGEL D.F. STEVENS

O. DETER A. KETOLA H. RÖHSLER V. VACHEK

GENERAL GUIDELINES FOR THE DESIGN OF OUTDOOR A.C. SUBSTATIONS

by

H G SCHÜTTE

L DEMOULIN
P L FLETCHER
J M RANGEL
D F STEVENS
O DETER
A KETOLA
H RÖHSLER
V VACHEK

ACKNOWLEDGEMENTS

The authors of this document wish to acknowledge the assistance of many colleagues throughout CIGRE, especially the members of WG 23-04, who have helped in its publication.

CONTENTS

CHAPTER 1

INTRODUCTION

The purpose of this document is to provide a simple guide to the design of an outdoor, AC Substation, from the System requirements, through the selection of the most suitable site, to the design of the equipment to be installed. It gives advice on the general principles, refers to relevant IEC standards and CIGRE reports, as appropriate, and gives an indication of the economic factors involved.

In general the guidelines cover a substation within a transmission network although some sections such as those covering site selection and plant will be applicable to other situations such as DC/AC convertor stations.

The scope is limited to Air Insulated Switchgear although mention is made of Gas Insulated Switchgear as an option, in the appropriate sections.

The document is divided into three main chapters.

The first covers system requirements and basic concepts, including network considerations and the particular needs of a substation.

The second chapter covers the selection of the most suitable site and considers the physical features of the area and environmental factors.

The final chapter details the criteria which are applied to select substation layout and determine the primary and secondary equipment required.

Figure 1 shows the various stages necessary in the establishment of a new substation.

Once the decision has been made a course of action can be determined. The flow chart gives a typical example where a "step by step" approach to the planning and design process whereas in practice iterative actions may often be involved. It must be emphasised that the decision on whether or not to build a substation may depend on different conditions in different countries.

Questions and remarks about this Paper are welcome. Please send these in writing to:

CIGRE Central Office
(for the attention of the Secretary of Study Committee 23 (Substations))
3-5 Rue de Metz
75010 Paris

The secretary of SC23 will pass any correspondence to the relevant Working Group or Experts within SC23.

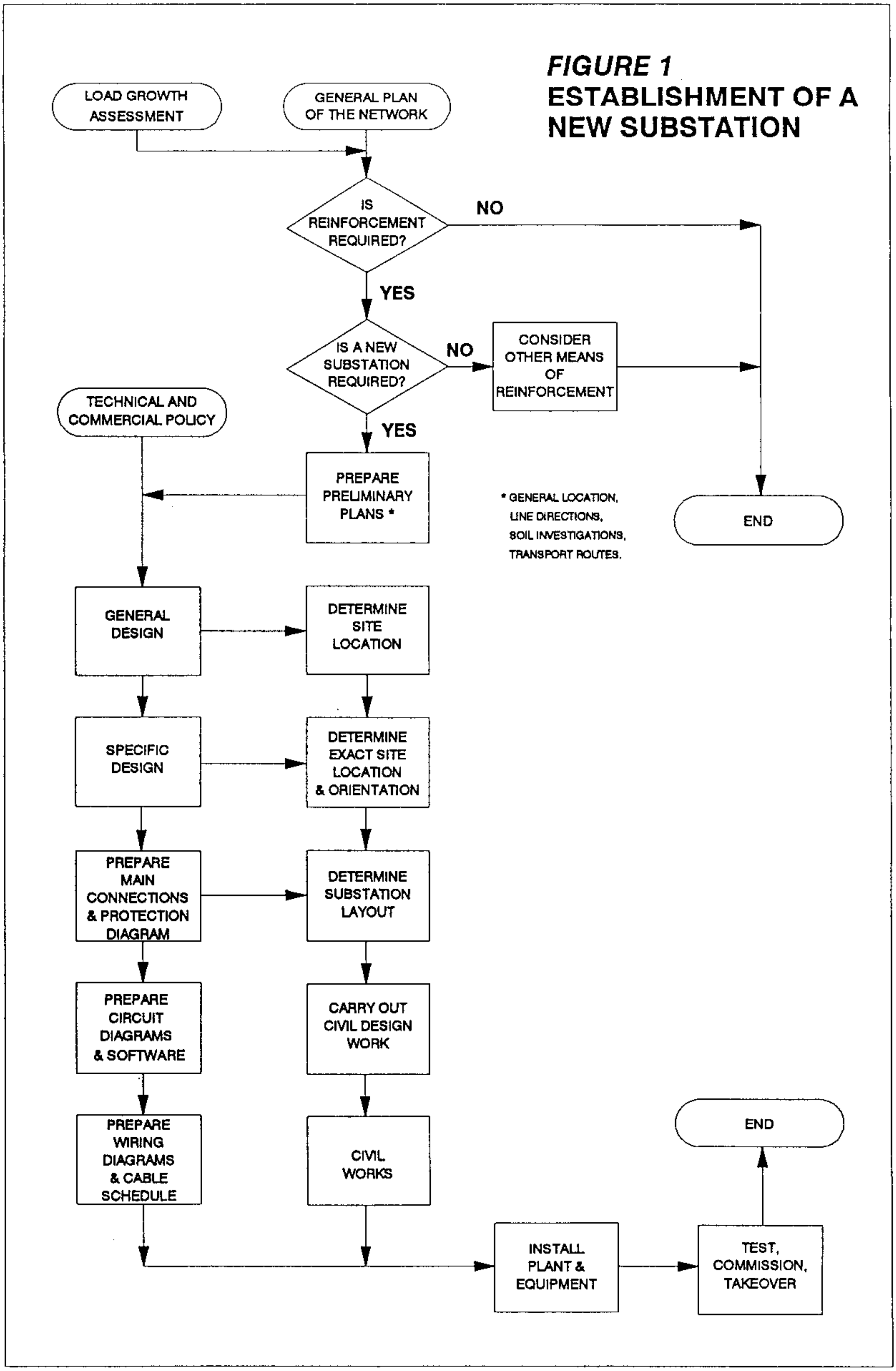


FIGURE 1
ESTABLISHMENT OF A NEW SUBSTATION
LOAD GROWTH ASSESSMENT
GENERAL PLAN OF THE NETWORK
IS REINFORCEMENT REQUIRED?
NO
YES
IS A NEW SUBSTATION REQUIRED?
NO
CONSIDER OTHER MEANS OF REINFORCEMENT
YES
TECHNICAL AND COMMERCIAL POLICY
PREPARE PRELIMINARY PLANS *
* GENERAL LOCATION, LINE DIRECTIONS, SOIL INVESTIGATIONS, TRANSPORT ROUTES.
END
GENERAL DESIGN
DETERMINE SITE LOCATION
SPECIFIC DESIGN
DETERMINE EXACT SITE LOCATION & ORIENTATION
PREPARE MAIN CONNECTIONS & PROTECTION DIAGRAM
DETERMINE SUBSTATION LAYOUT
PREPARE CIRCUIT DIAGRAMS & SOFTWARE
CARRY OUT CIVIL DESIGN WORK
PREPARE WIRING DIAGRAMS & CABLE SCHEDULE
CIVIL WORKS
END
INSTALL PLANT & EQUIPMENT
TEST, COMMISSION, TAKEOVER

CHAPTER 2

SYSTEM REQUIREMENTS AND BASIC CONCEPTS

2.1 INTRODUCTION

The transmission network has two main constituent elements:

(a) Circuits that enable power transmission.

(b) Substations that enable the interconnection of these circuits and the transformation between networks of different voltages.

2.1.1 Functions of the Network

The transmission network performs three different functions:

(a) The transmission of electric power from generating stations (or other networks) to load centres.

(b) The interconnection function which improves security of supply and allows a reduction in generation costs.

(c) The supply function which consists of supplying the electric power to sub-transmission or distribution transformers and in some cases to customers direcly connected to the transmission network.

2.1.2 Types of Substation

These three functions of the transmission network are fulfilled through different types of substations listed below:

(a) Substations attached to Power Stations.

(b) Interconnection substations

(c) Step-down (EHV/HV, EHV/MV HV/MV) substations.

A single substation may perform more than one of these functions.

2.1.3 Structure of a Substation

Substations generally comprise the following:-

(a) Switchgear.

(b) Power Transformers.

(c) Control Protection and Monitoring Equipment.

Substations usually include busbars and are divided into bays. In special cases other plant such as reactive power compensators, harmonic filters, fault current limiting devices and load-management equipment are included.

2.1.4 System Requirements

The design of a substation depends on the functions it has to fulfill. The system planning requirements define these functions and enable the parameters that have to be complied with, to be determined.

Some of these parameters are common for all the substations which perform the same function whereas others are specific to each substation.

Standardised parameters are established jointly by system planners and transmission departments by means of system studies, and economic considerations. Particular economic benefits are derived from specifying the technical requirements to allow the use of standardised HV equipment with identical characteristics (such as short-time current level, maximum current carrying capacity, characteristics of transformers, insulation level and compensating devices).

The location of a substation at a particular site will give rise to specific system requirements, some will however be standardised within the network of the Utility. Examples of system requirements are:-

(a) General location requirement.

(b) Extent of the substation.

(c) Required availabilty of circuits.

(d) Busbar schemes.

(e) Current rating.

(f) Fault current levels.

(g) Neutral point earthing.

(h) Fault clearance time with respect to system stability.

(i) Future extensions.

(j) Control and needs of personnel

(k) Equipment characteristics.

2.2 PARAMETERS DETERMINED BY THE NETWORK

System planners seek to optimise the parameters which apply to the complete transmission system. They proceed to network studies that involve mainly, insulation coordination, transient stability, short-circuit level and load flow.

2.2.1 Main Equipment Parameters

When a utility determines a standardisation policy and the development of technical requirements, the main characteristics of the primary equipment have to be specified in close consultation with system planners. The following parameters may be defined:-

(a) The short circuit current ratings of the substations' equipment (busbars, disconnectors, circuit breakers current transformers), including its supporting structures.

(b) The maximum load current passing through the components of a substation (which is related to the maximum current carrying capacity of the lines and underground cables)

(c) The transformer numbers, ratings and impedances as well as the mode of voltage control required ie operating mode of tap changing, regulation range, phase shifting characteristics and number of taps [IEC 76].

2.2.2 Fault Clearing Time with Respect to System Requirements

Transient stability characterises the dynamic behaviour of a generator in the case of large oscillations following a major disturbance. In order to comply with the requirements of the Network (system stability), or the specifications of particular utilities, specified fault clearance times must not be exceeded.

Fault clearance time limits and the reclosing conditions may influence the choice of circuit-breakers and other switchgear, and also the dimensioning of the earthing grid and the mechanical strength of the equipment.

2.3 PLANNING OF A SUBSTATION

This section will give information helpful for dimensioning the substation primary parameters and for defining the general scope of the substation equipment, depending on the system requirements. The options of extending or uprating existing substations and/or lines should have already been evaluated.

The starting point for a substation design procedure is as follows:-

(a) The need for a new substation has been approved.

(b) The range of its duties, loadings and general location have been determined.

2.3.1 General Location

For the location of a new substation in the network several alternatives often exist, the total costs of each option should be calculated. The cost of building new transmission lines and the reinforcement of existing circuits are often of the same order as that of the substation. It is thus worth examining various alternatives with system planners to limit transmission line costs.

The following should be considered when estimating the substation cost:-

(a) The losses in power transmission and transformation.

(b) Telecontrol and communications.

(c) Reliability and busbar schemes.

(d) Fault current and load flow calculations.

Nowadays it is not easy to get new line corridors, and their availability alone may determine the location of the substation.

Along with the automation of substations the costs of telecontrol and telecommunication grow, but they do not have a decisive effect from the point of view of location.

2.3.2 Extent of the Substation

The area available for the substation, the number of outgoing feeders of different voltage levels, the number of main transformers, the busbar schemes and the possibility of extension as well as compensating equipment options should be selected for the needs of the future. It should be noted that the lifetime of the substation may be between 30 and 50 years.

It is very important to allow sufficient space for extension. Sophisticated network planning is needed to estimate the necessary reserve space, if no better prognosis exists 100% reserve of outgoing feeders may be used as an estimate. The space required depends essentially on the function of the substation.

Extension work such as building of new bays, reconstruction of existing bays or extension of the set of busbars may be rather difficult and expensive if there has been no previous planning for them.

It is important to define the number and the size of the main transformers at the final stage of development. The initial peak load of a power transformer is dependent upon a number of factors such as the network configuration, standby philosophy and rate of load growth.

In the case of GIS it is usual to reserve space for a number of spare bays and also to make allowance for the future extension of the control building.

The outgoing line corridors should be planned so that there is a minimum number of crossings between different circuits.

2.3.3 Busbar Scheme

The selection of a busbar scheme and its possibile extensions for a particular substation is an important initial step of the design. Among the matters that affect this decision are operational flexibility, system safety, reliability and availability, ability to facilitate system control and costs.

2.3.3.1 Operational Flexibility

In order to reduce the risk of disconnection of generators or consumers due to faults in system components the circuits between two substations are often doubled, so that power transfer is shared, for instance between two separate overhead line circuits.

In some instances it is also necessary to limit short-circuit levels. This requirement can result in the installation of a proportionally greater number of busbar sections in the substation when the number of outgoing feeders is large.

2.3.3.2 System Security

Faults occuring on feeders or within the substation itself, must be cleared rapidly by as small a number of circuit-breakers as possible in order to limit disturbances in the network and to maintain non-faulted circuits in service.

Careful selection of the electrical schematic arrangement - primary connections and protection scheme - and the detailed construction layout should enable these criteria to be optimized.

2.3.3.3 Reliability and Availability

The evaluation of how the availability of substation elements influences the over-all performance of the substation is a complicated task in a meshed transmission network. The failure rates of the equipment and the choice of the substation scheme have a considerable effect on reliability and availability ie forced outages and planned shut-downs. Calculations can give only approximate results, because available failure statistics are always based on an older generation of apparatus and the likelihood of a severe outage occuring during the life-time of the substation is quite small [IEC 271].

However, for a comparison of different schemes, reliability calculation is a valuable instrument for the substation engineer which can assist in the choice of scheme and lay-out.

Many papers have been written with the aim of evaluating the performance of different substation schemes with respect to reliability [1, 2, 3, 4, 5].

Recent publications have indicated that not only the primary equipment but also the secondary equipment, eg the location and number of instrument transformers and the arrangement of the secondary circuits can have a great influence on the over-all reliability performance. For the 1 1/2 breaker schemes and looped substation schemes in particular, special attention has to be paid to the secondary wiring and cabling [6].

2.3.3.4 Substation Control

The proposed scheme and layout must allow simple and efficient performance of normal operational switching, changes of busbar selection and planned outage for maintenance or extension.

2.3.4 Fault Current Levels

Fault current dimensioning depends on the neighbouring network and the size and short-circuit impedance of the main transformers. System planning usually defines the following fault current ratings for a new substation:-

(a) Maximum three-phase effective short-circuit current for the lines and the substation for the forseeable future.

(b) Duration of the effective short-circuit current.

(c) Peak short-circuit current.

(d) Maximum earth fault current and corresponding time.

(e) Maximum current through the neutral point of the main transformer [IEC 909].

(f) Minimum short-circuit current (for protection).

(g) Minimum earth fault current (for protection).

2.3.5 Neutral Point Earthing

The electrical networks may be:-

(a) Effectively earthed (earth fault factor up to 1.4).

(b) Non-effectively earthed (earth fault factor eg 1.7). eg resistance earthed or resonant earthed.

(c) Isolated.

In the first case earth current may be 60 ... 120% of the short-circuit current. If the conductivity of the soil is poor (resistivity of 2000 ohm-m or greater), special attention has to be paid to the magnitude of station potential during an earth-fault. In this case it is possible to limit the earth-fault current and dimension the insulation level of the three-phase transformer neutral point correspondingly. Alternatively the potential rise of the earthing grid may be limited by ensuring that the earth wires of outgoing overhead lines are of good conductivity and, in extreme cases, have cross sectional areas equivalent to those of the phase cables.

2.3.6 Control in General

Control includes actions to be taken under normal conditions such as energising and de-energising a feeder, earthing of a section of busbar, etc. The way of carrying out this control can be dependant on the following factors:-

(a) Whether disconnectors are operated manually or by motor.

(b) Presence of earthing switches.

(c) Whether control is via a local control board or a local computer terminal.

(d) Degree of substation automation, sequence control.

(e) Remote control from Grid Control centre.

(f) Regulations.

(g) Whether the station is manned or unmanned.

The need for telecontrol and telecommunication links depends on the needs of the automation, remote control, data transmission and operation of the network. A substation is often also a nodal point of a data transmission network.

Remote control and automation of substations is increasing. In the future substations will be designed to be unmanned with operation and maintenance managed from control centres. Whether a station is manned or unmanned will depend on the importance of that substation in the transmission network.

In accordance with system planning requirements load shedding, network sectioning, voltage regulation and load distribution regulation devices may be placed on the substation.

2.3.7 Protection in General

The substation has to be constructed so that all possible faults can be eliminated:-

(a) Selectively.

(b) So that the fault current rating of the lines and equipment is not exceeded.

(c) So that no danger is caused to personnel and the requirements of safety codes are fulfilled.

(d) Within such a time that stability of the network is maintained.

(e) In such a way that load and production are held in balance.

For every protection item back-up protection is usually provided and important main protection is duplicated.

Protection systems can be divided into the following groups according to the protected item:-

(a) Line protection.

(b) Transformer protection.

(c) Busbar protection.

(d) Breaker failure protection.

(e) Compensating equipment protection.

or according to the type of the protection:-

(a) Short-circuit protection.

(b) Earth-fault protection.

(c) Sub-harmonic protection.

(d) Overload protection.

(e) Overvoltage protection.

(f) Automatic switching schemes (Load shedding, auto-reclosing, network sectionalisation and splitting of the network).

2.4 TYPICAL SWITCHING ARRANGEMENTS

2.4.1 General

The guidance given in this section cannot be exhaustive but gives a choice between a number of the more commonly encountered arrangments. The continuity of service under fault and maintenance conditions for switching arrangements is categorized.

Figure 2 shows some commonly used switching arrangements. In a substation, flexibility can be achieved by the introduction of sectionalization of the busbars or by using different arrangements.

More than one of the examples shown in figure 2 may be used on the same site but at different voltage levels.

It should also be noted that the choice of disconnector used (see section 4.5.4) may influence the switching arrangement chosen.

In figure 2 earthing switches (to meet the requirements specified in 4.4.1) and instrument transformers have been omitted for clarity.

Considering the above influences on choice, the following gives suggestions regarding the application of the individual switching arrangements shown in figure 2.

(1) Arrangements A, B and F

Single busbar arrangements are more commonly used for HV/MV substations.

Single busbar with transfer busbar, and single busbar installations connected as a ring of stations, offer improved flexibility but limited system security.

These arrangements have little security against busbar faults, little switching flexibility, and involve fairly extensive outages for busbar and busbar disconnector maintenance.

(2) Arrangements C and D

The double or triple busbar arrangement is recommended for large substations where security of supply is important. These are particularly suitable for highly inter-connected power networks in which switching flexibility is important and multiple supply routes are available. They are also used for splitting networks which are only connected in emergency cases.

Circuits are lost during circuit breaker and instrument transformer maintenance and repairs in arrangement D. When a by-pass facility is used as in arrangement C, permanent interconnection of the circuit can be maintained during most maintenance work. It may also be possible to use the by-pass connection after a failure but the possible coincidence of failure during maintenance should be considered.

(3) Arrangements E and G

The double circuit breaker and 1½ circuit breaker arrangements are particularly suitable for substations handling large amounts of power, such as those associated with generating stations, and for networks which comprise mainly radial circuits with few mesh connections.

It should be noted that to cover all contingencies of switching, the circuit breakers and associated equipment in arrangement G should be capable of handling the combined load current of two circuits.

(4) Arrangements H1 and H2

The mesh arrangements are particularly suited to applications where maximum security against busbar faults and minimum outage for maintenance is required.

It should be noted that equipment in the ring connections of the mesh must be capable of carrying the maximum load current that may occur due to any switching contingency.

Additionally mesh arrangements are not readily extensible.

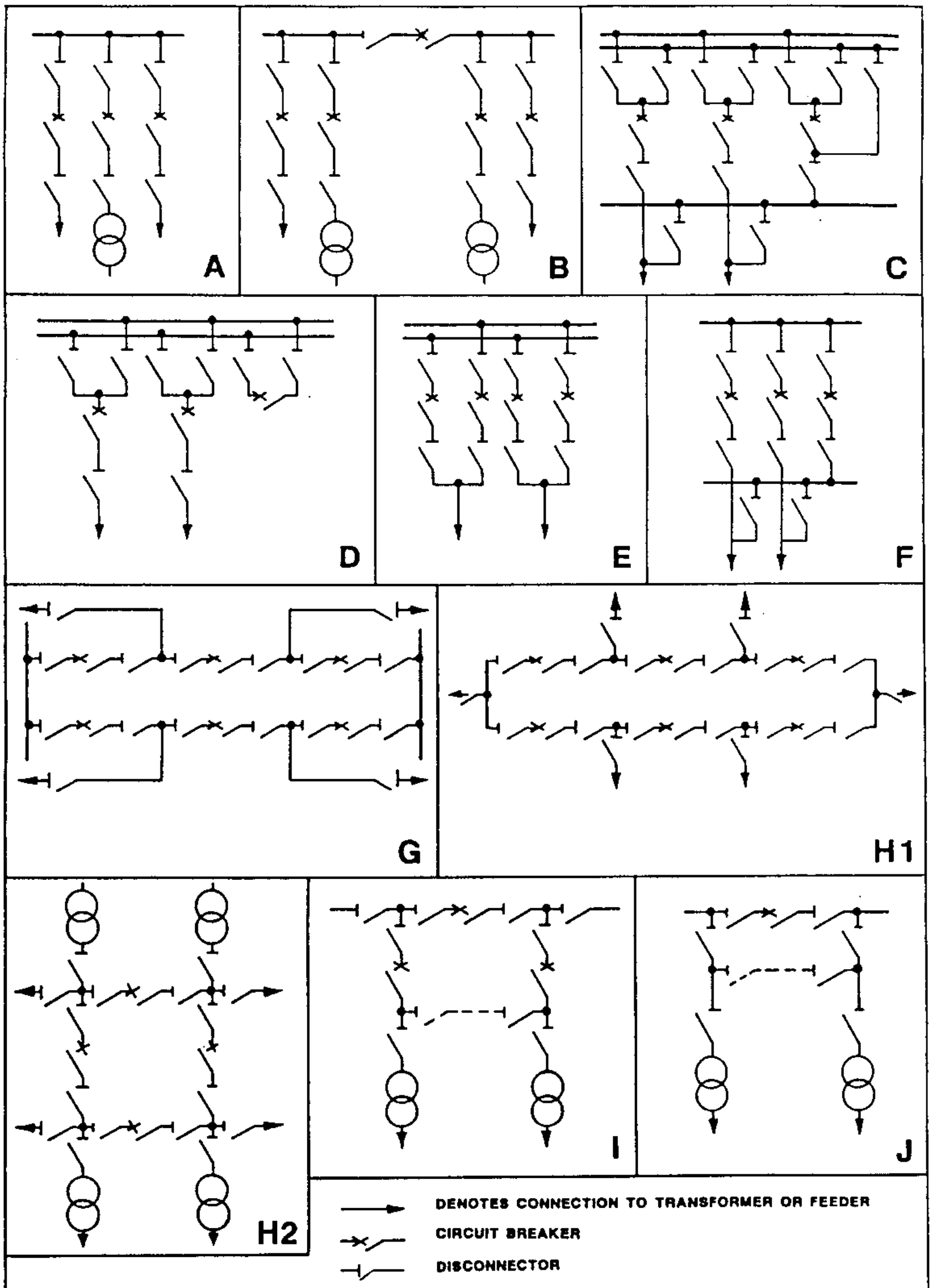


Figure 2 Main Connection Diagrams

(5) Arrangements I and J

The single and 3 switch arrangements have limited application and are mainly suited to a ring system of supply feeding bulk supply points consisting of duplicate transformers or banks of transformers.

2.4.2 Service Continuity

When choosing a specific switching arrangement one of the prime considerations should be the effect of the loss of plant due to fault conditions or for maintenance. Such effects may include loss of Generating Plant, loss of transmission and loss of supply to customers.

In all the examples given, if line or transformer faults or maintenance (of eg line disconnector, instrument transformers or line traps) are considered continuity cannot be maintained on the affected circuits. Apart from these limitations a measure of service continuity can be maintained.

Reliability calculations for schemes are complex and the following information is given to allow a quantitative assessment of the effects of repair or maintenance outages.

An assessment of the continuity that can be obtained from any example in figure 2 has been categorized as follows and shown in table 1.

Category 1: No outage necessary within the substation for either maintenance or fault.

NOTE. Category 1 necessitates no system outage but does not necessarily provide a secure supply (ie continuity of supply) for single faults even if these are limited to busbar and circuit breaker faults.

Category 2: Short outage (maximum approximately 4 hours) necessary to transfer the load to an alternative circuit for maintenance or fault.

TABLE 1. ANALYSIS OF SERVICE CONTINUITY

Ref	Type of arrangement	Service continuity category	
		CB area	Busbar area
A	Single busbar	3	4
B	Single busbar with bus section CB	3	3
C	Double busbar with by-pass facilities	2	2 (see note 1)
D	Double busbar without by-pass facilities	3 (see note 2)	2 (see note 1)
E	Double busbar with double CB	1 or 2	1
F	Single busbar with transfer bar	2 (see note 1)	4
G	Double busbar with 1½ CB	1 or 2 (see note 3)	1
H	Mesh	1 or 2	Not applicable
I	3 switch with by-pass	1 or 2	Not applicable
J	1 switch with by-pass	1 or 2	Not applicable

NOTE 1 To achieve these stated categories a bus coupler switch must be included.

NOTE 2 Category 2 applies when facilities are provided to transfer the protection of a feeder bay to the bus-coupler bay.

NOTE 3 Category 1 applies for maintenance conditions. Category 2 applies for fault conditions.

Category 3: Loss of circuit or section until the repair is completed.

Category 4: Loss of substation.

In situations where a fault occurs when maintenance is in progress on other equipment the above categories do not apply. Under these conditions the probability of a split in the network can increase rapidly especially in the polygonal arrangements.

2.4.3 Choice of Switching Arrangements

In addition to the functions of a substation previously considered in this section choice of switching arrangements may be influenced by:

(a) The level of skill and experience of operating staff;

(b) The future growth and development of the supply system;

(c) Economy in the early stages of development;

(d) The ease of facilitating future extensions;

(e) Duplication of circuits to give alternative supply routes;

(f) Amount of power to be transmitted;

(g) Strategic importance of the circuits;

(h) The service continuity of other significant parts of the network.

(j) The reliability, both of the substation as a whole, and the individual components within the substation [3, 4, 6].

(k) The standardization policy of the organisation.

(l) Maintenance requirements and techniques.

(m) National regulations (for example whether or not it is permissible to operate a disconnector remotely to change a particular switching arrangement without personal verification).

CHAPTER 3

SITE SELECTION

3.1 GENERAL

The choice of a site for a susbtation is a compromise between technical, economic, environmental and administrative factors.

A flow-chart covering site selection for a substation is shown in Fig 3.

In simple terms the problem is to find one place within a fairly large geographic region, where the substation can be built, given the total number of circuits, the destination of the lines and the rated nominal power of the transformers.

Typically, in the whole region, climate and altitude are almost the same, but earthquake hazard and pollution may vary.

The first step is to locate possible sites which are as level as possible, with enough available area, at reasonable costs, with easy access and without important restrictions on line corridors where the substation can be erected. It is advantageous to locate sites near to existing line corridors or even at crossing points. Sometimes such places simply do not exist and the choice will be confined to places that have only some of the above characteristics.

The influence of the most important site characteristics on substation design and their consequences are shown in Table 2.

Table 2

Site characteristics	Influence on substation design	Main associated consequences
Available area	Layout	Land cost
Topography	Number of Terraces	Volume of soil displacement
Geological and Geo-technical charac-teristics of soil	Foundations and earth grid	Levelling costs per m^3 and foundation
Hydrology	Usually small	Drainage costs
Access	Usually small (in some cases geogra-phical orientation)	Construction and improvement costs
Line corridors	Layout and geogra-phical orientation	Cost of Inter-connections and influence on reliability
Pollution [IEC 815]	Creepage distances insulator cleaning techniques and period	Equipment costs and influence on reliability
Environmental concerns	From landscaping measures to change of substation type	Site preparation costs HV equipment costs, buildings costs
Seismic Level	Special design required	Equipment, structures and foundations costs
Altitude	Increase electrical clearances. Additional cooling required	Equipment costs

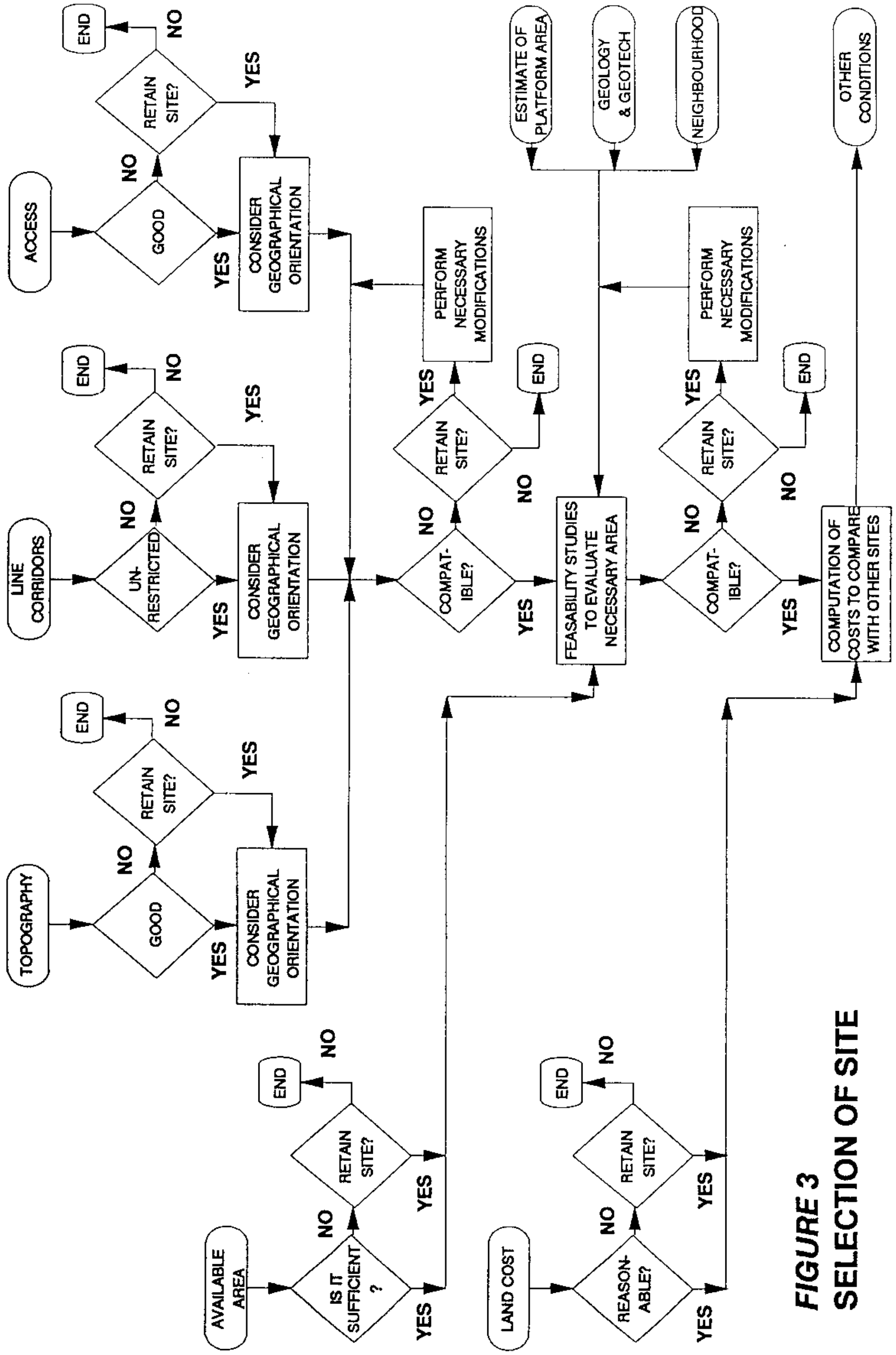


FIGURE 3
SELECTION OF SITE

3.2 Available Area

A first estimate of the area required to install the substation can readily be made by taking into account the previous practice of the utility and the main connections arrangement chosen.

This estimate has to be reviewed and adapted to the particular site conditions, for instance, possible line corridors and access constraints.

3.3 Topography

It is convenient, for reasons of standardization of supporting structures, economy of space, access to equipment, even distribution of stresses between equipment terminals and easy connection of equipment, to level the ground where the substation is to be built. (Small slopes, to allow necessary drainage, must, of course, be provided).

To level the area required by a substation may be a costly and time consuming task, so it is better to choose a site as flat as possible but not subject to flash floods.

Taking into account orographic characteristics it is convenient to evaluate the consequences, concerning levelling works, of small displacements and changes of geographic orientation.

In mountainous regions, where the substation must be placed as far as possible from avalanche corridors, levelling costs may force the reduction of the dimensions of the substation.

Another way of reducing levelling costs is to divide the substation into various terraces usually increasing the total levelled area but reducing the volume of soil displacements. A significant distance between terraces may create difficulties with regard to operation and interconnection, but usually, allows line entries from various directions, and can help to solve problems related to line corridors.

3.4 Geological and Geotechnical Characteristics of Soil

The soil must allow the construction of roads and foundations. The minimum bearing load is usually about 50 kN/m^2. The existence of geological faults is usually sufficient reason to reject a particular location.

Siting a substation in areas where there are disused mines can lead to severe problems due to ground subsidence and such locations are best avoided.

In zones subject to earthquake hazards a careful study is essential, as earthquake intensity may vary dramatically in places located only some kilometers apart.

A high water level may require the construction of drainage facilities, increasing costs and causing construction delays. Terracing costs and maximum possible inclination of the talus are a consequence of geological and geotechnical characteristics of soil and a comparison of costs is given in Table 3.

A low value of soil resistivity is desirable and this should be measured before erection of the substation. Additional actions such as increasing the site area and inputing earthing facilities will be necessary.

Table 3 – Terracing costs per m^3 and gradient of slope on various types of soil

Type of soil	Handling	Terracing costs (relative)	Gradient of slope
Sandy	Bulldozer	1	1:2
Clay	Bulldozer	1.5 - 2	1:1.5
Rock (half-disaggregated)	Bulldozer	2 - 2.5	1:1
Hard rock	Explosives	4 - 5	1:0,5

3.5 Access

The most difficult equipment, as far as access is concerned, are power transformers and large reactors, the other equipment being of a shape compatible with any common transportation network.

Power transformers, on the contrary, have large irregular shapes and very heavy weights thus making it necessary to study the complete route between factory and substation.

The transport procedure must be checked both ways (to and from substation site) and measures taken to maintain it during the substation lifetime.

Small difficulties may be solved by changing the type of transformers; by the use of a different low loader; or by the temporary reinforcement of bridges.

In the most difficult cases, single phase instead of three phase transformers, the use of transformers with less rated power (thus increasing the total number), or even improvements in the transport network may be necessary.

Another aspect to be considered is the daily access of operators (for manned substations) and maintenance and emergency teams (for unmanned substations).

3.6 Line Corridors

The substation will be connected to the network through overhead lines making it necessary to study the vegetation of line corridors in the vicinity of the substation. The cost of modifications to existing lines to allow their connection to the substation must also be evaluated. In extreme cases it may not be possible to make the connection to the substation directly by overhead line, and a cabled entry must be considered.

The consideration of future extensions with additional line entries may have different consequences upon the various sites being analysed.

Line corridors have great influence on the geographical orientation of the substation and may impose the choice of a substation layout.

Difficulties in the establishment of line corridors may be overcome by the use of multi-circuit pylons or, in extreme cases, changing from overhead line to underground cables.

3.7 Pollution

Pollution causes the deposition of small particles on the insulators. The relationship between creepage distances and pollution level is indicated in IEC Standard 71-2. As pollution levels may change (increase) with time a small overdimensioning is usual. In extreme cases, in heavily polluted or dry zones, cleaning facilities or the use of protective products may be necessary [IEC 71-2, 507, 529, 815].

GIS is prefereable in these cases as it greatly reduces the number of insulators exposed to pollution.

Saline and some types of industrial pollution can cause corrosion in supporting structures, and protective coating may therefore be needed.

Pollution can also affect equipment installed indoors as the protection offered by buildings, cubicles and cabinets is not 100% effective. A careful choice of equipment and, in extreme cases, the use of filters or an overpressure ventilation system will reduce the consequences. It is also necessary to take measures to avoid condensation so that pollution problems are not exacerbated, eg by heating.

Nevertheless, whatever measures are taken, the risk of failure and the equipment and maintenance costs will always increase with the pollution level. Such risks are however minimised with GIS.

Whenever possible the prevailing winds should flow through the substation towards the origin of the pollution (sea, industrial zones, highways ...) or, the substation should be protected by some natural barrier (eg hills or trees).

3.8 Environmental Aspects

Substation landscaping may be covered by local regulations and should be considered in detail when siting the substation [8].

The best site, as far as landscaping is concerned, is such that the substation is not visible from the most common viewpoints.

The use of conductors on only two levels, with equipment spread over a large surface, the choice of the right colour for insulators, and some thought given to the material and finish of supporting structures, can contribute to making the substation less intrusive [9].

Screens of trees, bushes along the enclosure, and the use of natural soil instead of gravel (if allowable step and touch potentials are obtained) may help to disguise the substation.

If the substation is in a residential area it may be necessary to adopt low noise transformers, enclosed by walls, and to pay special attention to the corona effect that causes interference on radio and TV transmissions.

Substations are better located far away from:

- airports and aeronautic corridors, as there are usually restrictions on the maximum height of structures and due to possible disturbances on navigation equipment.

- installations with special risk such as fire or explosion.

- pipelines, telephone cables and water pipes should also be avoided where possible, however this is often not practical.

CHAPTER 4

DESIGN

4.1 INTRODUCTION

This chapter covers the selection of substation type (GIS or Open Terminal) and the detailed design of Open Terminal Substation.

Many nations have their own safety rules and, because of their important and legally binding nature, these are considered in the early part of the chapter.

The three component parts of the substation are defined as follows:-

(a) Primary System

The primary system comprises all equipment which, in whole or in part, is in service at the nominal voltage of the system.

(b) Secondary System

The secondary system comprises all equipment which is used for the control, protection, monitoring and measurement of the primary system.

(c) Auxiliary System

Auxiliary systems are those which are required to enable the primary equipment to operate.

4.2 SELECTION OF SUBSTATION TYPE

The selection of substation type is, in most cases, dependent upon economic factors.

As far as HV equipment is concerned an air-insulated substation generally costs less than an equivalent in GIS, but, as GIS allows a much wider choice of site, the distance to the load centre, site preparation costs and reduced maintenance costs may balance the difference.

In recent years reduction of the HV equipment price gap and increasing pollution and environmental concerns have made GIS more attractive. As a consequence, air-insulated, indoor, HV substations are not often installed at voltages above 200 kV.

The main advantage of GIS substations is that they need only a fraction of the area occupied by an air-insulated substation(remember however that power transformers have the same dimensions in all types of substations), making them a good solution in cases of:

(a) Urban areas (high land cost and unavailability of required area for an air-insulated substation).

(b) Mountainous zones (high site preparation costs).

(c) Environmental concerns. GIS can be easily disguised and indoor (or, exceptionally, underground) installed if necessary. It should be noted, however, that it is not always possible for incoming feeders to be overhead lines.

(d) Very high pollution levels. GIS phase-to-phase and phase-to-ground insulations is not affected by pollution, but the metallic envelopes may suffer from corrosion problems in harsh environments.

(e) Altitude above 1000 m. The internal GIS insulation is independent of atmospheric pressure, so need for special insulators is limited to the bushings.

(f) Uprating, refurbishment or replacement of air insulated substations in restricted areas.

The disadvantages of GIS substations are that the small area occupied can lead to difficulties concerning maximum step and touch voltages, so earth conductors may have to be extended beyond the substation limits. [IEEE 80].

As all HV equipment in a GIS must be compatible, extensions and replacements for the next 20 or 30 years must, if possible, be considered at the time the initial order is placed.

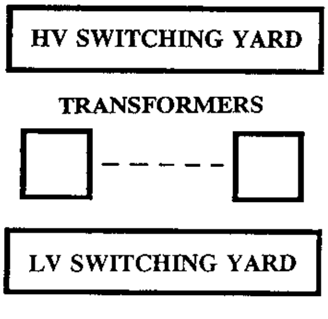
4.3 SUBSTATION LAYOUT

It is not possible to give a great deal of detail on the subject of substation layout in this document but the following guidance should be followed:-

(a) The layout of equipment on a substation should be simple and easy to understand.

(b) Generally it should be standardized within a utility.

Complicated or non-standard layouts may lead to errors and, consequently, danger to the operators, or loss of supplies due to misoperation. A simplified layout is shown in the following diagram:-



4.4 GENERAL CRITERIA AND RULES

4.4.1 Safety Rules [10]

Definitions:

Step Voltage - The difference in surface potential experienced by a person bridging the distance of a human step without contacting any other conductive part [IEEE 80].

Touch Voltage - The maximum potential difference between the accessible earth surface and dead part which can be touched by a hand of person standing on the surface [IEEE 81].

Safe Current - The current which can flow through the human body without threat to the life and health of exposed person [IEC 479].

Maximum step and touch voltages are set to levels which will limit the current flowing through an exposed person to the safe current level.

The proposed methods of service and repair work must be considered in the design of a substation.

In most countries the minimum distance between live parts and personnel is standardized. The following parameters are ususally defined:-

(a) Minimum height of live parts above the accessible surface.

(b) Minimum horizontal distance between a live part and protective rails, fences, etc.

(c) Minimum distance between a live part and a human body (or conductive tools) during the work in the substation.

(d) Minimum distance between a live part and the operating mechanism or any moving conductive part.

The main circuit, once isolated, must be considered a live part until it is earthed. It is generally required to check for voltage on the conductor before applying the earthing device. As it is not easy to test voltage by an independent device in EHV and UHV substations, a remotely controlled earthing switch is used to earth the circuit after visually checking the disconnectors are in the open position. It is also dangerous to handle a long rod with a portable earthing conductor in the vicinity of live parts. Therefore earthing switches are preferable in substations above 245 kV. Portable earthing devices are only used for additional earthing eg protection against induced voltage on long busbars [11].

4.4.2 Overvoltage and Insulation Levels

All equipment installed in a substation must be designed to take account of the rated power frequency voltage of the network; temporary overvoltages at power frequency caused by eg sudden loss of load or earth faults; switching overvoltages and lightning overvoltages. In order to determine its capability it is subject to voltage tests as follows:-

(a) Lightning Impulse Withstand Voltage. (1.2/50)

(b) Switching Impulse withstand voltage (250/2500).

(c) Power frequency (50 or 60 Hz) (wet and/or dry).

Additionally an oscillating voltage or chopped wave test may be required.

The set of test voltage values determines the insulating level. Standard insulating levels are defined in IEC Standard 71 although the Network parameters may dictate other values [IEC 71].

The necessary insulation level depends on the insulation co-ordination, ie on the properties of different parts of the network (mainly lines), the protection used against overvoltages and also on the required reliability of the substation (permissible probability of flashover) and may vary in different parts of the same substation.

4.4.3 Current Rating and Overcurrents

The instantaneous load flow within a substation depends on the state of the entire electrical network.

Usually a complete network analysis is required to determine the nominal values of currents flowing in an individual substation circuit. It is theoretically possible for maximum current flow to occur with a relatively low total production of electricity in the network. eg the supply to a pumped storage power station or when utilising the by-pass facility within a substation.

In designing a substation it is necessary to consider two aspects of the effect of current:-

(a) The thermal effect (including induced currents).

(b) The mechanical effect on conductive items of plant and their support structures.

Precise thermal modelling of equipment is very difficult as many factors influence the resultant temperatures of conductive parts eg previous loading, ambient temperature, wind speed, and solar conditions.

Thermal design is therefore empirical and is proven by type test covering nominal current rating and short-circuit current rating.

Standard procedures have been devised to predict the thermal behaviour of conductors, particularly with respect to sag.

It may be possible to assign a short-term current rating in excess of the nominal but the analysis leading to this must be exceedingly thorough to ensure that no "hot spots" (transformers, terminals, busbar support points) are overlooked.

Methods of calculating short-circuit current values are given in IEC Standard 909 and the effects of short circuit current can be evaluated in accordance with IEC Standard 865.

4.4.4 Electrical Clearances

It is not possible to test the whole HV installation by corresponding test voltages. Therefore minimum clearances in air between live parts or between live and dead parts in the air are stated, to obtain the required insulation level in arrangements which have not been tested. As the clearances are stated universally, they must assume the insulation in the worst supposed case of spark-gap with sufficient reliability. Smaller clearances are permissible if the particular arrangement has been tested by the prescribed insulation test [IEC 71].

The values of minimum distances to live parts in the air also depend upon practical experience and therefore, some differences can be found when comparing rules in different countries.

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.

4.4.5 Mechanical Forces

4.4.5.1 Weight

Together with the normal weight of apparatus, conductors, structures etc the additional and temporary loads must be considered, especially the weight of frost and ice (depends on local climate) and maintenance staff. The strain during erection must also be considered (lifting of structures, asymmetric pull of conductor etc).

4.4.5.2 Wind Loading

The wind pressure may substantially influence the strain of structures and footings and also reduce the clearances between flexible conductors. Standard values are given by IEC but local conditions must always be considered. The twist of flexible conductors which can impose extreme strains on the structures may be caused by turbulent air flow if the substation is located in an area with a rough landscape (IEC 68-1).

4.4.5.3 Short-Circuit Forces

Generally equipment is type tested in a short-circuit laboratory. However, the short-circuit strength of the busbars is usually only calculated and the calculation methods are verified by testing some typical busbar arrangements.

In simplified methods the peak value of short-circuit current is used to evaluate mechanical stresses.

The force caused by short-circuit current excites the strain of the movement of conductors. Rigid conductors may amplify the strain of supports by resonance. The reduction of clearances between flexible conductors has to be considered. The analysis and computation methods of short-circuit current influences and guidelines for design are described in CIGRE Technical Brochure 23-19 [12 13].

4.4.5.4 Combination of Forces

The probability of the simultaneous occurence of various mechanical forces will be dependent upon local conditions [14].

Calculations should normally include specified combinations of:-

Wind loads
Ice loads
Short circuit loads
Earthquake loads whenever necessary
Maintenance and/or erection loads

Additionally mechanical loads due to low ambient temperatures and circuit-breaker operations have to be taken into account.

4.4.6 Corona and Radio Interference

All devices must satisfy the specified level of radio noise. The limits of radio noise are stated by national standards.

International rules are IEC-CISPR Publication 1 and IEC-CISPR Recommendation No 30.

4.4.7 Acoustic Noise

The permissible acoustic noise level is generally given by national regulations or standards. Recommended noise levels are contained in the ISO Recommendation R 1996 "Acoustics" [15].

An acoustic study for the planned substation should be carried out to determine the acoustic conditions of the various items of equipment, chiefly the transformers and their working equipment and, if necessary, the circuit-breaker.

Within the framework of this study, the nature, distribution and number of sources of noise for the final installation and at intermediate stages has also to be considered.

If the acoustic study shows that the natural attenuation of the sound level is not enough to meet the permissible agreed noise criterion, three courses of action are open:

(a) Use of a low-noise transformer.

(b) Modifying the installation plan of the substation, eg position of transformers, direction of oil-cooler fans.

(c) Provision of one or more noise attenuation devices. The attenuation that was obtained for different types of them is shown in Table 4.

Table 4

Type of Acoustic Insulation	Attenuation
Steel plates (4 mm thickness) with sound-absorbing glass fibre or rockwool, mounted on the transformer tank	8 - 10 db(A)
Screens (concrete, plain metal)	10 - 15 dB(A)
Carefully erected metal enclosure incorporating sound absorbent material	15 - 25 dB(A)
Brick built or concrete enclosure	20 - 35 dB(A)
Double absorbent metal or double concrete enclosure	30 - 40 dB(A)

Additionally the propagation of acoustic frequencies into supporting structures may be limited by spring, rubber or hydraulic dampers.

4.4.8 Water Contamination

All noxious materials in the substation must be used and handled without leakage. The vessels of power and measuring transformers, capacitors, coils etc must be, where possible, leakproof.

In most countries additional measures against detrimental materials are required. Oil pits are designed to catch some proportion of the oil (or other liquid) and to prevent oil from burning. If a central underground tank is used, it must be large enough to contain the volume of the largest oil-filled equipment and any rain water which has fallen in the period between emptying. When no oil leakage occurs, the rain water may be drained off. Otherwise decontamination is necessary by such means as mechanical separation, filtering or chemical cleaning.

4.4.9 Civil Design

Civil design includes supporting structures, foundations, facilities (internal roads, rails, site surface, ...) fencing and buildings.

4.4.9.1 Supporting Structures

Supporting structures include terminal gantries and structures for circuit-breakers, disconnectors, instrument transformers and post insulators. Whereas reinforced concrete may be used for HV substations, supporting structures of UHV substations are commonly made from welded or bolted steel lattice, of open profile or of tubes. In some cases aluminium structures are used for their low weight and resistance to corrosion but it must be noted that the buried portion must be made of steel in order to avoid electro-chemical corrosion.

Calculation of loads is usually covered by national standards and regulations which specify safety factors and load combinations.

4.4.9.2 Foundations

Calculation methods are given by national or company standards. Dimensioning is carried out according to the loads on the structures and additional forces such as the dynamic stresses imposed by circuit-breaker operation.

Depending upon the type of soil and the loads, foundation types can be:

- poured concrete with or without steel reinforcement
- prefabricated reinforced concrete
- concrete slab (mostly used in indoor substations or for GIS)
- drilled (suitable in hard soil)
- auger bored piles

Steel stubs or anchor bolts to which the structures are attached, are usually cast into the foundation. Often a template is used to locate such fixings prior to the concrete being poured. GIS support structures can be fixed to rails or bolted directly to the floor.

4.4.9.3 Transformer Civil Works

Civil works for transformers or reactors have four main purposes:

(a) To support the transformer during service and enable its transport (rails may be needed depending upon transformer type).

(b) To retain any leakage of transformer oil and help to extinguish burning oil under the transformer: the oil containment area may be filled with gravel covered by an upper layer of broken stones or connected to an underground tank.

(c) To prevent the risk of fire propagation: fire walls and fire stops in trenches are appropriate.

(d) To reduce the level of acoustic noise.

4.4.9.4 Site Facilities

Facilities for maintenance and operational needs must be taken into account in substation design. Where access by crane or trucks has to be provided for maintenance or replacement operations, roads or tracks have to be constructed.

The surface of the site will also influence access. Usually stone chippings or grass are used.

4.4.9.5 Fencing

External fencing reduces the possibility of unauthorised persons entering. Special measures are usually given in national standards. Special attention must be paid to touch voltage when metallic fencing is used.

Internal fencing is mostly protective and rails or wire fencing can be used for this purpose.

4.4.9.6 Buildings

The design of buildings has to conform to national and utilities standards. Their main role is to contain and give shelter to protection relays, SCADA equipment, auxiliaries, batteries, fire protection pumps etc.

Whether a substation is manned or unmanned will determine the extent of the facilities required locally for the operators.

Access conditions to the substations and the maintenance practices of the utility will determine whether or not to install a transformer untanking hall.

For economic reasons (reduction of the wires lengths and sections, lowering voltage of auxiliary supply, minimizing first investment) several dispersed buildings rather than one central building can be built in a substation.

4.4.10 Fire Protection

The use of fire protection systems and/or measures is mainly based on [16]:

(a) Minimizing the hazard for the operators and the public and protecting the environment.

(b) Limiting the damage to power transformers and to adjacent apparatus, equipment and buildings.

(c) Minimizing the loss of customer's service.

A water spray protection is generally preferred for outdoor installations, predominantly to protect the power transformers, CO_2 for indoor installations.

Halon is now being phased out of use in many countries because of its negative effect on the atmosphere.

Smoke detectors (indoor), bimetal detectors and quartzoid bulbs with a detecting pipe system pressurised with compressed air at 0.25 - 0.8 MPa are the most common fire detecting elements. To prevent inadvertent operation of the fire protection system, the use of two detection systems is recommended. For starting the fire fighting system of power transformers the use of the transformer protection relays is also common.

To minimize the risk of fire damage, passive protection measures should also be taken to prevent a propagation of fire or to limit damage, eg fire barriers between or around transformers, fire resistant material etc.

Provision may be made to aid the extinguishing of burning oil under the transformer, such as

(a) A 200 - 300 mm layer of broken stones on the grid above the oil-containing pit.

(b) A stone filled pit.

(c) A steel or concrete chamber connected to the oil retaining area by pipe(s). eg 5 m long by 200 mm diameter.

Fire protection of cables in indoor and outdoor HV substations is usually only by passive measures to reduce the fire propagation - fire stops (concrete, steel, mineral wool, sand, silicone) and/or fire resistant painting. In installing fire barriers care must be taken to ensure that hot spots are not induced. Power and control cables should be installed along separate routes eg separate cable racks or separate trenches.

4.5 SPECIFICATION AND SELECTION OF MAIN COMPONENTS

4.5.1 Introduction

When the maximum load currents (see 2.2.1) have been determined the rated current of the switching equipment should be selected from the IEC series. Nowadays we can say that the lowest current rating available on the market may be overdimensioned for most purposes especially in the networks of the developing countries [IEC 56, 129, 694].

The current rating of busbars depends on the scheme. The rated current of the main busbar is normally chosen to be 1.5 to 3 times higher than that of the line bays. The physical grouping of the feeders may affect this choice. Busbars are often overdimensioned during the first stage of a substation's life, because their reinforcement later on may be difficult and expensive and the additional cost of overdimensioning is relatively small.The rating of meshed scheme configurations can be difficult (eg 1 1/2 circuit breaker) and it is necessary to define which switching conditions and network contingencies have to be governed, making allowance for maintenance outages. The nominal current of the by-pass busbar and coupling bay is at least the same as the highest rating of any of the circuits which may be connected. The sectionalizing bay is dimensioned for 50 ... 100% of the current rating of the corresponding busbar. Power companies usually standardize upon 3 or 4 current ratings. Flexible or rigid conductors and connectors have several standard sizes.

Power transformers have a considerable short-time and continuous overload capacity especially at low ambient temperatures. On the other hand switching equipment possesses very little overload capacity. Therefore, the current rating of the transformer bays should be some 20-30% higher than the rated current of the transformer.

System planning determine the numbers, capacities and future extension requirements of the compensating equipment. It is to be noted that according to IEC the current rating of the shunt capacitor bank switching equipment should be 1.5 times that of the capacitor. [IEC 56].

4.5.2 General

The common ratings of switchgear and controlgear including their operating devices and auxiliary equipment should be selected from the following [IEC 694]:

(a) Rated voltage.

(b) Rated insulation level.

(c) Rated frequency.

(d) Rated normal current.

(e) Rated short-time withstand current.

(f) Rated peak withstand current.

(g) Rated duration of short circuit.

(h) Rated supply voltage of closing and opening devices and of auxiliary circuits.

(i) Rated supply frequency of closing and opening devices and of auxiliary circuits.

(j) Rated pressure of compressed gas supply for closing and opening devices.

(k) Pollution Level [IEC 815].

(l) Corona and RIV requirements.

Equipment has to be type tested in order to verify its compliance with the specified ratings.

Note:- Other rated characteristics may be necessary and are specified in the relevant IEC standards.

4.5.3 Circuit Breaker

A circuit-breaker is a mechanical switching device, capable of making, carrying and breaking currents under normal circuit conditions and also making, carrying for a specified time and breaking currents under specified abnormal circuit conditions such as those of short-circuit.

The breaking capacity of a circuit-breaker is defined by a large number of parameters. The value of breaking/making current must be related to the transient recovery voltage (TRV) which depends mainly on the properties of circuit to be switched. The shape of TRV varies at the same point of the network depending upon switching state (the number, type and load of interconnected bays) and on the location of the short-circuiting point. These circumstances give different resonant circuits and the circuit-breaker must be able to break the current in all cases.

The shape of TRV is partially influenced by the circuit-breaker itself as it depends on the deformation of the current waveform immediately before the interruption. More beneficial conditions are given by minimum-oil and SF_6 "puffer" then by air-blast arc extinction chambers.

The switching process is considered to give rise to a steep fronted TRV when the short circuiting point is up to 3 km on the line side of a circuit-breaker. Switching of longer lines may lead to a lower steepness but higher peak value of TRV, which may threaten the insulation of switchgear (see 4.4.2).

The results of long-term investigations form the basis of type tests given by IEC Standard 56. However, in particular cases the switching conditions may be more severe then those given by IEC 56, in which cases an over-rated circuit-breaker may need to be used for lower current. Some methods of evaluation of breaking capacity under non-standard TRV conditions have been formulated but they are not included in IEC Standards.

The time period between receiving a trip command and current interrupting or making is very important for the setting of back-up protection relays. Therefore it influences the requirements of the current-carrying capacity of all the switchgear as well as the dynamic processes in the EHV network. A longer time can be expected when breaking current after auto-reclosing on to an uncleared fault.

Circuit breaker types are defined by their interrupting medium and their drive mechanism.

(a) Interrupting Medium

- Bulk oil.
- Small oil volume.
- Air blast.
- SF_6 (or a mixture of SF_6 and Nitrogen for very low ambient temperatures)
- Vacuum.

Although other types of circuit-breaker may be available, the present day choice at Transmission Voltages, is generally SF_6.

These are grouped in accordance with their arc extinction chambers as "dead tank" or "live tank".

The circuit-breakers of the 'live tank' type supplied for outdoor open-terminal substations have the interrupters housed in porcelain weather-shields on top of an insulated support column.

Circuit-breakers of the 'dead tank' type have interrupters housed in an earthed metal container with their connections taken out through porcelain bushings. In this arrangement the bushings may be used to house the current transformer windings.

(b) Drive Mechanism

There are three types of drive mechanism in common use for circuit-breakers at Transmission Voltages:-

- Pneumatic, using either a unit compressor or a compressed air system common to a complete substation.

- Hydraulic, using a high pressure oil system in conjunction with a nitrogen gas or spring accumulator.

- Spring, using a spring charged by an electric motor.

Any circuit-breaker drive must be fitted with an energy storage device which permits a complete standard sequence of operation without further input of energy. Rated operating sequences are defined in IEC 56. If the circuit-breaker is in the "Open" position its operation must be automatically inhibited if there is insufficient stored energy for a further "Close-Open" sequence [IEC 56].

IEC 56 clause 8 gives comprehensive details of the selection of circuit-breakers for service in terms of their electrical and mechanical performance.

4.5.4 Disconnectors and Earthing Switches

A disconnector is a mechanical switching device which provides, in the open position, an isolating distance in accordance with specified requirements.

A disconnector is capable of opening and closing a circuit when either negligible current is broken or made, or when no significant change in the voltage across the terminals of each of the poles of the disconnector occurs. It is also capable of carrying currents under normal circuit conditions and carrying for a specified time currents under abnormal conditions such as those of short-circuit [IEC 129].

An earthing switch is a mechanical switching device for earthing parts of a circuit, capable of withstanding for a specified time currents under abnormal conditions such as those of short-circuit, but not required to carry current under normal conditions of the circuit.

There are four types of disconnector in common use:-

- Rotating-End-Post (single arm or double arm).

- Rotating-Centre-Post.

- Pantograph (vertical or horizontal).

- Single Lifting Arm.

The way in which each of these types of disconnector operates has an important effect on the design of the substation. Three insulation conditions must be considered when selecting disconnectors:-

- phase to earth insulation level
- phase to phase insulation level
- pole to pole (open contact) insulation level

The pole to pole insulation level is particularly important in areas where surge overvoltages can occur across a disconnector.

With all these types of disconnectors except the rotating centre post, the contacts remain live whether the disconnector is open or closed. Thus, electrical clearances, have to take into account the volume swept by the blades of the disconnector. Use of rotating-end-posts disconnectors, for instance, requires greater phase to phase clearance than the use of rotating-centre-post disconnectors.

Another factor which has to be considered is that in the case of rotating end post and rotating centre post designs, earthing switches can usually be mounted on the same structure rather than having to be separately mounted.

At transmission voltages it is usual for disconnectors to be motorised. Earthing switches may be motorised or operated manually.

In the case of double circuit lines special consideration has to be given to the interruption of capacitive and inductive loads when the parallel circuit is energised. The disconnector must also be capable of interrupting and making parallel circuits when transferring load between main and reserve busbars.

4.5.5 Surge Protection Devices

The effectiveness of any surge protection device is very dependent upon the quality of the earthing system and the geometrical arrangement of the device. In particular the surge impedance, the length of the connection between hot line and earthing system and the earth resistance play an important role.

(a) Spark Gaps

The spark gap is a surge-protective device which consists of an open air gap between an energized electrode and an earth electrode and provides the simplest possible form of surge protection [IEC 71, 72].

There are several disadvantages to the use of co-ordinating gaps as a means of surge protection.

First if the gap operates a fault is caused on the system; secondly, if the gap is set for positive impulses the protection against negative switching impulses is poor at the higher voltages; thirdly a higher insulation is generally requires if gaps are installed; lastly the increasing threshold voltage causes inadequate protection against steep fronted surges.

(b) Surge Arresters

The use of a surge arrester provides superior protection compared to a co-ordinating gap, and it is not sensitive to polarity. A big advantage is that a system fault is not caused by the operation of a surge arrestor. The margins between the protective level and insulation levels of a system are covered in IEC standard 71.2 [17].

The two principal types of arrester are gapped silicon carbide and gapless zinc oxide, the latter are now most commonly used.

The silicon carbide arrester comprises a stack of silicon carbide blocks with series gaps. There is a some variation in the voltage at which "sparkover" occurs, especially for steep fronted surges the threshold voltage rises [IEC 99.1].

The zinc oxide arrestor is gapless and comprises a stack of zinc oxide blocks and is, therefore, very simple to construct. Its characteristic can be set very precisely and unless temporary overvoltages are relatively high (as non effective earth system) then it is usually possible to obtain lower protective levels compared with the gapped types of arrester.

(c) Lightning Protection

In most areas it is necessary to ensure protection against direct lightning stroke and this can be achieved by installing different types of effectively earthed conductors. Substation protection is provided by means of vertical rods on top of support structures or, specially erected masts or protective conductors may be suspended above the substation.

When interconnected overhead lines are not generally protected against direct lightning stroke it is necessary to take measures to protect the substation. An earthwire should be installed on each overhead line for a distance of approximately 1-2 km from the substation, in many cases this earthwire is extended over the total circuit length. This measure does depend, however, on the rated voltage of the system and is not normally applied to medium voltage distribution networks.

4.5.6 Instrument Transformers

4.5.6.1 General [18]

Instrument Transformers are the devices used to transform the values of current and voltage in the primary system to values which are suitable for measuring instruments, meters, protection relays and other similar apparatus. An essential property of an instrument transformer is that it isolates primary voltages from the accessible parts of the secondary system.

Internal insulation is oil-impregnated paper SF_6 or, cast resin.

Traditionally instrument transformers have been either of the electromagnetic or capacitive type although developments are taking place using optical fibres.

It is possible to combine the current and voltage transformers in one housing, but this becomes less practicable at higher voltages.

4.5.6.2 Voltage Transformer (VT)

Voltage transformers are either of the capacitor (CVT) or electromagnetic type [IEC 186, 358].

CVT's are used singly for metering purposes or in three-phase sets for protection.

Electromagnetic VT's are used when a higher degree of accuracy than can be provided by a CVT, is required - for example high accuracy metering, or when no other means of discharging an overhead line is available.

4.5.6.3 Current Transformer (CT)

Current transformers are specified by their primary rated current and their accuracy class which are selected according to their service requirement.

The rated current of the current transformers should be selected from the IEC series. Rated currents and ratios should be selected according to the requirements of continuous current rating, accuracy and protection. Current rating can also be extended (120%, 150% or 200%) [IEC 185].

When the characteristics of a network are liable to evolve, multiratio CTs are necessary to follow the network evolution. They require adequate nominal current rating and the ability to operate protection relays when short-circuit current is at its minimum.

Usually a number of multi-ratio current transformers are housed within a single unit to allow for future development and an increase in circuit loading.

Application of accuracy class is as follows:-

0.1)
0.2) Measurement and
0.5) metering
1.0)

5)
10) Protection

Measurement and metering require different core from protection with different accuracy class, secondary power rating and rated overcurrent factor.

4.5.7 Line Traps

A line trap is an apparatus intended for series insertion into a high-voltage line and, in conjunction with a coupling capacitor, it forms a parallel, resonant circuit. Its impedance shall be negligible at the power frequency so as not to disturb the power transmission, but must be relatively high over any frequency band appropriate to carrier transmission [IEC 353].

A line trap consists of a main coil with a protective device and, usually, a tuning device.

Line traps are used for power line carrier protection and may be mounted directly on post insulators or CVTs or supported by suspension insulator sets.

Note:- For operation of power line carrier protection equipment it is necessary to inject the signal through a capacitor. It is most economical to use the CVT's for this purpose rather than to provide a separate capacitor unit.

4.5.8 Busbars and Connectors

Busbars may be either flexible stranded conductor or of tubular construction. Aluminium (and its alloys) and copper are the most commonly used materials [IEC 105].

Connectors may be bolted, welded or crimped or any combination of these. Fittings should allow for expansion and contraction with temperature [IEC 114].

Mechanical strength must be considered in addition to the general ratings described in paragraph 3.1. Aeolian vibration of tubular conductor can cause fatigue failure and steps may need to be taken to limit this, for example, stranded conductor laid inside a tubular busbar is often a very effective damper or special clamps with built in dampers may be used. Bi-metallic joints require special construction and jointing techniques to prevent corrosion. All busbars, fittings and joints should be designed to mechanically avoid the ingress of moisture and electrically to avoid corona discharge [19].

4.5.9 Post Insulators

A post insulator consists of one post insulator unit or an assembly of such units and is intended to give rigid support to a live part which is to be insulated from earth or from another live part.

The dimensions of post insulators have been standardised and details are given in IEC standard 273. The testing requirements are given in IEC standard 168.

4.5.10 High Voltage Cables

In some circumstances it will be necessary that connections into, out of, and within a substation will be by means of underground cables. For example within an urban area where overhead line entries are not possible or in order to connect a particular circuit to a particular section of the substation [IEC 141, 183, 885].

Cables have to be terminated in sealing ends which provide a transition from the cable insulation to air or other insulating medium (eg SF_6).

4.5.11 Earthing Grid

The earthing grid comprises conductors which are buried in the ground in the substation and is complemented, in some cases, by conductors which are above ground.

The conductors in the ground are buried in the form of a grid at a depth of about 0.5 ... 0.8 metres and designed to limit conductor temperature and touch and step voltages to the maximum allowable values under specific fault conditions.

Earth rods may be driven into the ground around the perimeter of the earthing grid and are bonded to the grid. The quantity and length of the earth rods will depend upon the resistivity of the soil. Additional earth rods are sometimes required immediately below (or adjacent to) certain items of equipment such as capacitor voltage transformers and surge arrestors.

The buried grid is usually made of copper strip or stranded copper cable and the earth rods of copper-covered steel, although other materials such as galvanised steel and cast iron may be used. When copper conductors are used precautions should be taken to prevent electrochemical reactions with steel structures.

All main parts of structures and dead parts of equipment are bonded to the earthing grid as well as the neutral points of primary equipments.

Where there are conductive pipelines, railway lines or other similar items, special attention must be paid to earthing in order to prevent the transmission of earth current leading to a rise in ground potential outside the substation.

If there are telephone lines or a low-voltage network in the neighbourhood their protection against ground potential rise may cause considerable extra costs. The most effective way to limit the potential, would be to use shield wires with good conductivity.

The layout of the earthing grid also has an effect on transient ground potential rise phenomena. A CIGRE Report [7] details the inter-relationships which exist between these effects and details the measures necessary for their reduction.

4.5.12 Power Transformers and Compensating Equipment

4.5.12.1 General

Plant which is intended to alter voltage or influence the power factor of transmitted energy is considered to form part of a substation. The rating of such equipment however, is different from that which may apply to other switchgear in that the main parameter is the total power handling capacity of the unit [IEC 76, 214, 354, 606].

The specification of this power rating is dependent upon the total required power, the cyclic nature of this power requirement and the policy of the utility on reserve capacity.

It is usually economic to use units of the same rating within a substation but in certain individual cases this may be unnecessary for example if a utility has determined to use a particular standard rating or if individual circuits have differing requirements.

4.5.12.2 Power Transformers

Power transformers are usually of the two-winding type. However when both HV and MV systems have similar earthing factors, and it is not necessary to limit the earth-fault current at the MV side due to interference or potential rise problems, auto-transformers are often used. In some countries as a cost saving measure the insulation level of the main transformers is designed to be lower than that of other equipment, depending upon the effectness of the overvoltage protection.

The capacity of transformers is usually decided by system requirements and it is necessary to specify this together with the general ratings given in paragraph 4.4.3.

Transformers may be designed with all three phases in a common tank or as three, separate, single-phase units.

In general it is only economic to choose single phase unit if there are transport problems or if it is important to replace a failed transformer by a spare unit very quickly.

The single phase units are easier to transport and install but transformation losses will be greater than in the case of a three phase unit. Additionally, three separate foundations are necessary; more space will be required and, depending on the fire fighting philosophy, extra barrier walls are often installed between the single phase transformers.

4.5.12.3 Compensating Equipment

There are several forms of compensative equipment:-

- Synchronous compensators - Comprising a variably excited small synchronous machine.

- Shunt reactors - Comprising mechanically switched shunt reactors which may be installed on the tertiary winding of a system transformer or connected directly to the grid system [IEC 289].

- Mechanically switched capacitors (shunt connected) - May be installed on transformer tertiaries or connected directly to a grid system for local voltage control purposes [IEC 594, 871].

- Series capacitors - Used in conjunction with long transmission lines [IEC 143, 595].

- Static VAR Compensation (SVC) - Comprising thyristor controlled reactors (TCR), thyristor switched capacitors and harmonic filters. SVCs are usually connected directly to their own discrete transformer.

The type of compensation required will usually be determined by the system planners but it should be noted that switching compensative devices imposes an onerous duty on the circuit-breaker.

4.5.12.4 Shunt Reactors

There are two kinds of shunt reactors, oil immersed types and air-core dry types. Oil immersed reactors can be constructed at all voltage levels, but the use of dry type reactors is limited to the MV range.

Oil immersed reactors look like transformers and their protection devices and accessories are similar.

The installation arrangement of dry type single-phase reactors can be a triangular configuration in order to get good phase symmetry and rapidly diminishing magnetic field in the neighbourhood of the reactor. A side-by-side installation is also possible. Dry type reactors need a lot of free fenced space round them. Special attention has to be paid to the location of metallic parts and loops in the vicinity of the reactor to keep their temperature rise and losses at an acceptable level. The main materials of the coils are fibre-glass and epoxy. Single-phase reactors usually consist of several parallel-connected cylinders.

4.5.12.5 Shunt Capacitors

Shunt capacitor banks are composed of capacitor units mounted on the racks. The reactive power range of units is nowadays 200 - 350 kVar. A capacitor unit contains usually 40 - 60 elements. The rated voltage of a unit depends on the number of series-connected element groups. There are two protection philosophies, namely internal fuses for each single element or external fuses for each unit. Units can be provided with one or two bushings. The most important material of the elements are plastic film and impregnating liquid.

An unbalanced protection is the most important and sensitive relay protection of a capacitor bank. If two or more capacitor banks are parallel-connected to the same busbar then it is necessary to install coils in series to limit inrush currents between the banks.

4.6 SPECIFICATION AND SELECTION OF AUXILIARY EQUIPMENT

4.6.1 A.C. Supplies

A.C. supplies provide energy for drives, compressors, charging batteries lighting and heating. Usually two independent sources of supply are used with 100% redundancy and automatic emergency switching. It should be noted that external supplies tend to be less reliable than sources fed through a station transformer from the main substation circuit. If supplies are taken from the MV network it should be ascertained that there is a degree of independence from the HV substation itself.

A secure supply of upto 20 kVA eg for a transformer tap-changer, can be provided by D.C. - A.C. invertors from the batteries.

4.6.2 Diesel Generation

Diesel Generators are used to provide a back-up LV supply in important substations for loads up to about 800 kVA and are activated automatically in the event of failure of the main LVAC supply (or supplies).

A diesel generator would be designed to provide energy for the essential components of the substation for a specified period of time (usually the estimated time it will take to restore the main supply). The components considered to be essential may vary from substation to substation and may include circuit-breaker drives (or charging of their energy source), charging of batteries, operation of disconnectors, cooling of transformers and emergency lighting.

4.6.3 D.C. Supplies

Batteries providing energy for a minimum specified period of time (usually 2-3 hours - based upon the time it will take for an engineer to reach the site and the time it may take to remedy the fault) connected in parallel to the load, are fed by chargers. In case of failure of the AC charge voltage, the batteries take over the load. DC voltage up to 60 V is provided for remote control and communication, up to 220 V for emergency light, operation of switchgear, etc. Traditionally batteries were kept in separate room(s) with proper ventilation; heated if necessary as the capacity falls by 1%/K below $20^{o}C$.

Batteries can be of the lead acid or nickel cadmium type. Nowadays leakproof cells are available and these may be placed indoors adjacent to LV equipment without taking any special precautions.

The servicing and maintenance schedules for batteries should be closely adhered to in order that full capacity under emergency conditions is retained.

4.6.4 Compressed Air Systems

Compressed air systems provide pneumatic power for circuit breaker drives and supply the extinguishing medium for air blast circuit breakers. In the case of small plant, air is compressed on demand at service pressure, but more commonly is compressed and stored at a level much higher than service pressure. Reduction can be directly at the device supplied or at a central facility.

To avoid humidity problems at service pressure level, a ratio of at least 5:1 for storage pressure to service pressure is recommended; this is designed to cover temperature falls of 20 K within a temperature range of $-35^{o}C$ - $+50^{o}C$.

4.6.5 Telecommunications and Telecontrol

4.6.5.1 Telecommunications

External telecommunication from the substation utilises both the private network of the utility and, in many cases, the public telecommunication network. The most important telecommunication services applied in the private network are telecontrol, operational telephony and teleprotection. New services (eg telefax and video transmission) are coming into use. Normal connection to the public network is a telephone subscriber line.

The connections to the private telecommunication network normally demand construction of a telecommunication transmission system. The type of transmission system varies with the needs, distance geography etc. Remote terminal units (RTUs) require a connection to the relevant control centre. Teleprotection requires a connection to the remote end of a power line. A telephony service is provided either by installing an exchange of the private operational telephone network into the substation or connecting some remote subscriber lines from the nearest exchange into the substation. Depending on the importance of the substation, alternate telecommunication routes may be needed.

Transmission systems may be power-line carrier (PLC), microwave, fibre or pilot cable. PLC is applied in the areas where distances are long and capacity needs are very low. Pilot cables are applied only in short distances. Their application is limited by the earthing difficulties of the substation.

Microwave and fibre are the modern systems. Microwaves are more economical in long routes when the terrain is suitable, capacity needs are moderate and the telecommunion authorities allow the use of microwave frequencies in private networks. Fibre systems are excellent due to the quality and capacity. They are future-proof, dealing with new teleprotection and network automation methods.

4.6.5.2 Telecontrol

Telecontrol systems provide for remote monitoring and control of processes which are geographically widespread.

Telecontrol equipment is needed for monitoring and control of the primary equipment from the remote locations such as regional or district control centres.

The telecontrol functions are accomplished by a remote terminal unit (RTU). The RTU is a unit which converts the information received from the substation system into information, which can be transmitted to the Regional Control centre.

Type and number of functions required to accomplish the telecontrol depend on the type and configuration of the substation. The following functions are usually used:

- telecommands
- teleindications
- telemeterings
- telecountings

The telecontrol system and remote terminal units are specified in IEC-870. This standard is divided into several parts:

Part 1 deals with general considerations in section 1 and section 2 is a guide to specification. The rest of part 1 deals with more specific items.

Part 2 is concerned with standardizing operation conditions such asenvironmental conditions, mechanical influences and power supplies.

Part 3 is concerned with standardizing various RTU interfaces and characteristics of them such as nominal voltages, current classes and signal levels. It also standardizes an interface with the communication system.

Part 4 standardizes various performance requirements such as operational parameters, expandability and influence of telecontrol equipment on the environment.

Transmission protocols are standardized in part 5. Requirements for data transmission and protocol specifications are dealt with.

It is very valuable to consider the requirement for telecontrol when planning the substation equipment, even though the utility may not have a telecontrol system. Readiness for telecontrol includes installation of all measuring tranducers, interposing relays, status contacts, etc needed for telecontrol and wiring there to a marshalling cabinet.

4.7 SPECIFICATION AND SELECTION OF SECONDARY EQUIPMENT

The term "secondary equipment" covers protection-, control- and measuring circuits. These items are described in detail in a guideline that is currently being prepared by Working Group 05 of study committee 23.

4.8 COMPUTER AIDED DESIGN

Computer Aided Design (CAD) is a tool used to create and manipulate graphic segments. Such segments can be built up to create a complete drawing in software from which a 'hard copy' print can be made.

One of its greatest assets is that objects which are frequently used on drawings can be stored in a library and recalled when required: thus saving time at the creation stage.

This tool lends itself quite readily to substation design as this is a matter of repetition of structures and modules. Thus elements and also the grouping of elements to form bays may readily be stored in the library.

5. COMMISSIONING

Commissioning covers all the measures which need to be taken on-site in order to assure the correct functioning of both single components of equipment and the substation as a whole. Beside the type test, routine test, and sample tests in the factory additional tests on-site may be necessary; these tests ensure the specifications of the equipment are met and serve to detect any damage caused by transportation, shipping, or erection which may modify the characteristics.

In general all installations that have to be erected on site are subject to commissioning tests. This involves both proving the wiring which provides remote control, signaling and measurement and also testing the HV equipment. One example is the gas-insulated substation; which, after erection is subject to various commissioning tests the most important of which is the high voltage test.

Typical examples of commissioning tests are:-

Checking of wiring, contact travel diagram of breaker and switches.

Duty cycle and hot spot checking for each bay, test of proper operation of remote control, signaling and measurement.

Checking of electrical clearances and conductor sag.

Insulation tests if required, (especially for GIS).

Commissioning tests are the most important quality assurance instrument when an installation is transferred to the user after erection. The extent of tests, the responsibilities, and the procedure of repair or correction in case of detected defects is subject to agreement between the companies concerned.

REFERENCES AND BIBLOGRAPHY

CIGRE Documents

The documents listed are those considered to be the most relevant to this paper.

[1] R J Cakebread, K Reichert, H G Schutte. Reliability in the design of EHV substations. Availability as a function of component failure rate, repair and maintenance times. Electra No 65, July 1979.

[2] P Kulik, H Rohsler, K Reichert, H G Schutte. Reliability in the design of substations; influence of the location within the grid and the kind of connections to the grid. CIGRE 23-01, 1980.

[3] J C Declercq, P van Miegroet, H Rohsler, H G Schutte. Substation reliability - Comparison of two methods and suitable presentation of results. Electra 99 (1985).

[4] R J Cakebread, K Reichert, H-G Schutte: Substation Design Criteria for Simple, Reliable and Safe Service. CIGRE 23-05, 1974.

[5] Power System Reliability analysis application guide. CIGRE WG 38-93, 1987.

[6] B G Andersson, J C Declercq, P van Miegroet, H Rohsler, H G Schutte. The reliability of HV substations with special regard to the secondary equipment. Electra No 111.

[7] H Aanestad et al. Substation earthing with special regard to transient ground potential rise. Design aims to reduce associated effects. CIGRE 23-06 1988.

[8] R J Cakebread, M Delis, N Tomatis, W Kiwit+ Adaption of Substations, their Environment both in Urban and Rural Areas, including Noise Problems and Oil Pollution of Subsoil. CIGRE 23-07, 1972.

[9] R J Cakebread, A W van Hamel+ Toward a Better EHV Substations' Environment. CIGRE 23-07, 1976.

[10] Parizy, Allodi, Blokker, Delis, Homberger, Kulik: The Effect of Safety Regulations on the Design of Substations. Electra No 19.

[11] A Arhomaa, K D Benneman: Earthing of high Voltage parts in outdoor substations by short-circuit proof devices. CIGRE Brussels Symposium 1985. Report 430-01

[12] Technical Brochure - The Mechanical effects of short-circuit currents in open air substations. CIGRE 23-02 1987.

[13] R J Cakebread, H J Brown: Integrated Mechanical Design Loadings for Open-Type EHV Substation Structures and Equipment. Electra No 60, 1977.

[14] A Arhomaa: Mechanical Design Criteria of Outdoor Substations. CIGRE Brussels Symposium 1985, Report 310-01.

[15] M Delis, O Deter, J A Kiupers, R R Rogers: Transformer Noise Attenuation in Substations. CIGRE 23-10, 1980.

[16] H Aanestad, G Benistan, O Deter, J A Kiupers: Fire Protection Systems and Measures in Substations. CIGRE 23-01, 1984.

[17] Metal oxide surge arresters in A.C. systems

Part I General Properties Electra No 128 January 1990

Part II Performance under operating voltage Electra No 128 January 1990

Part III Temporary over voltages Electra No 128 January 1990

Part IV Stresses due to temporary harmonic over voltages Electra No 130 May 1990

Part V Protection performance Electra No 133 December 1990

Part VI Selection of characteristics from standards Electra No 133 December 1990

[18] CIGRE Technical Brochure - The paper-oil insulated measurement transformer. Electra No 133, 1990.

[19] H Seljeseth, A Campling, K H Feist, M Kuussaari: Station earthing. Safety and Interface Aspects. Electra No 71, 1977.

[20] Design and Maintenance Practice of Substation Secondary Systems. CIGRE Technical Brochure. Draft December 1990.

IEC Standards and Reports

IEC Standards are given brief references throughout this paper. A full list of these and other IEC Standards is published in the 'Catalogue of IEC Publications'.

Publié par le CIGRÉ
21, rue d'Artois
FR-75 008 PARIS
Tél. : +33 1 53 89 12 90
Fax : +33 1 53 89 12 99

Published by CIGRE
21, rue d'Artois
FR-75 008 PARIS
Tel : +33 1 53 89 12 90
Fax : +33 1 53 89 12 99