DESIGN GUIDELINES FOR POWER STATION AUXILIARIES AND DISTRIBUTION SYSTEMS

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1. Objective

The objective of this report is to present an overview of the current practice and state of the art of auxiliaries power supplies for electric power stations. It is intended to be a support for design engineers. This overview considers the basic design of auxiliaries power supplies particularly regarding the process of developing the main electrical scheme and selection of rated voltages, as required in the development of specifications.

2. Scope

The scope includes discussion of alternatives for the main electrical distribution system and the basic electrical data used in the design process. This report uses a simple scheme as a starting point and develops arguments for additions and extensions for particular applications based on current knowledge within the Working Group. The results of a questionnaire are used to support the conclusions of the report.

Furthermore, the scope includes a discussion of the principal components applied in the electrical scheme.

For this report, the main electrical scheme includes all electrical supply systems, including power transformers, generator busbar systems, generator circuit breaker, and standby power supplies. The generator itself is not included in the scope of this report.

Figure 2 gives an example of the scope of the distribution system whose design is considered in this report.

Finally, maintenance aspects are considered.

3. Introduction

3.1. History

In 1978, Cigré Working Group 23-06 a predecessor of today’s Working Group 04, undertook the task of studying the basic technical concept of electrical power systems in power stations. The subject has been analysed and reported on at that time on the basis of responses to questionnaires circulated among Cigré SC 23 member countries (ref. 1, ref. 2).
3.2. **Current situation**

The requirement for reliable electrical power supply systems worldwide remains unaltered. The energy consumption of the industrialised nations may have reached saturation, but on the other hand the developing countries and the countries, which are at the stage of becoming highly developed, face rather high growth rates in the use of electricity. Also, new requirements for generating stations have had to be considered in recent years and an example is given below:

The permanent increase of the pollution of the environment has determined the need for desulphurization and denoxation of flue gases to be installed in coal fired power stations in some countries. Certainly, many other countries will follow this approach in the future. The installation of the related chemical processes in thermal power stations for this purpose requires additional electric power.

Approximate values for the auxiliary power demand, for different types of power stations, related to the rated power of the unit, are:

- Gas turbine power station 1 %
- Hydro power station 1 %
- Combined cycle power station 2 %
- Thermal power station, gas fired 4 %
- Thermal power station, oil fired 5 %
- Coal fired power station 7 to 10 %
- Desulphurisation and denoxation plant 2 to 3 %

Typically, a 600 MW plant has an increased power demand of between 10 and 20 MW, depending on the type of power station, the quality of the coal used and the process used for desulphurization.

This issue greatly influences the power supplies for auxiliaries and is of particular importance for new power stations, which need to meet regulatory emissions levels and for older stations where retrofiting of the desulphurization and no reduction installations have to be considered.

Another example of a more recent development is the increasing use of large gas turbine power stations in a “combined cycle” process. The flue gas of these turbines still contains a significant energy potential due to its high temperature. By installing a steam generator to one or two or even more gas turbines the otherwise wasted energy can be utilised in a conventional steam turbine. The total efficiency of such a power plant is significantly increased by this installation. Combined cycle power stations are frequently used as base load stations.

Nowadays, thermal efficiencies of combined cycle power stations are levelling off at about 55 %, which means reductions in fuel costs and in emissions, particularly of carbon dioxide. Some very large combined cycle projects have recently been commissioned or are under construction around the world.

3.3. **Aim of the questionnaire**

The questionnaire was sent to all members of Cigré SC 23 for distribution to utilities in their respective countries. Utilities from 18 countries responded.
The questionnaire was intended to provide data on power station electrical distribution schemes by ascertaining for various types of power stations, the configuration of auxiliary electric power systems in use, together with those factors which influenced the design.

The aim of the questionnaire was to collect data on current practice. The utilities were asked to prepare answers for generating units for which construction was approved from 1980 onwards, and only for units with a rated power of 100 MW or above. The reason for this restriction was to exclude installation designed for particular solutions that do not fit into general trends.

The data extracted from the questionnaire is presented in Chapter 6 “Criteria for the choice of equipment”. It was not the intention of the questionnaire to collect data for extensive statistical analysis. Therefore, the utilities were asked to complete the questionnaire for one or two representative examples only. The graphs presented in chapter 6 are, therefore, not an overview of the installed equipment, but they give an indication of the popularity of certain equipment used in representative Power Stations. This information is included to provide the design engineer general design criteria and equipment data for guidance in the selection of equipment.

4. Guide for the selection of schemes

4.1. General

A single line diagram is a graphical representation of an electrical power system. It shows, graphically, the inter-connection of generators, transformers, motors and switching devices which facilitate the distribution of power using conventional symbols for devices and their interconnections.

This paper does not discuss the following issues that need to be made for the system design (refer to documents listed in ref. 1 and 2):

- the use or not of a generator breaker,
- the position of the tapping point for the supply of the unit auxiliary transformer (at the HV or MV side of the generator transformer),
- the number and type (single or three phase) of the generator transformer(s),

Two categories of single line diagrams may be considered depending on the design objectives and the stage of the project:

- Preliminary single line diagrams (one or more alternatives)

  They are established during the feasibility study for the whole power station and are developed up to and including the preliminary design phase.

  These preliminary single line diagrams will be used:
  - by the layout designers to establish the different plot plans;
  - by the project team to give a first estimation of the capital cost.
• Final single line diagram

This is established during the final design stage of the study and is developed up to and including the as built phase of the power station.

This final single line diagram will principally be used:

- by the I & C team to finalise the architecture of the I&C supply system and to complete the specification for I&C equipment;

- by the electrical team to complete the specifications for electrical power equipment and to make the final space reservations for cable trays and equipment;

- by the layout designers to finalise arrangement details.

4.2. Methodology for establishing a single line diagram

4.2.1. Preliminary single line diagrams

4.2.1.1. Feasibility study

At this stage, the following data is required:

• the general design of the process (general description);

• the equipment list based on preliminary process flow diagrams;

• the safety requirements (e.g. definition of the different categories of auxiliaries, redundancy criteria, physical separation of the routing of cables and of the layout of equipment, electrical independence of redundant equipment, ...);

• the knowledge of the different electrical networks available in the neighbourhood of the site of the power station;

• the preliminary calculation notes giving the main characteristics of the power plant distribution networks (e.g. maximum short-circuit power on the switchboards supplying the auxiliaries);

• considerations of availability, safety, maintenance and economic aspects;

• establishing of network types (IT, TN, TT) and kind of networks as normal, stand-by power supply (diesel, uninterruptible power supply)

4.2.1.2. Preliminary design

At this stage, the principle process criteria will have been established and the range of possible solutions for the detailed process requirements is examined. Therefore, a preliminary single line diagram is prepared for each proposed solution or alternative.

More precise data on main fluid systems and equipment are now required, namely:

• the general design basis;
• the flow diagrams of the main systems, or preliminary P&ID’s (Process and Instrumentation Diagrams);
• the functional data of main equipment;
• an equipment list based on the main flow diagrams;
• preliminary consumers list.

In parallel, the following documents are prepared.

• the preliminary descriptive and functional specifications of the electrical systems, based on the preliminary single line diagram and describing the system and its components as well as its operation in the plant.
• the possible alternatives of the single line diagram and their associated preliminary descriptive and functional specifications.

All these documents are then discussed by the project team to select best solutions.

These preliminary single line diagrams (and associated specifications) will be used:

• by the I & C team to design the possible alternatives of the architecture of the I&C (Instrumentation and Control) supply system and to preliminary estimate the number and dimensions of the I&C equipment;
• by the electrical team to make a preliminary estimation of number and dimensions of the power equipment, and to make the necessary space reservations (in the layout) for the cable trays and equipment;
• to make a preliminary estimation of heat losses of the electrical and I&C equipment required for the preliminary design of the Heating Ventilation and Air Conditioning (H.V.A.C.) equipment;
• by the layout designers to perform the preliminary implementation design.

4.2.1.3. Contents of the preliminary single line diagrams

The preliminary single line diagrams represent:

• the grid connections;
• the main generators and their eventually associated generator circuit breakers;
• the generator, unit auxiliary and station transformers;
• the MV switchboards and dependant LV (Low voltage) a.c. switchboards power supplied through the auxiliary MV/LV transformers;
• the MV (Medium Voltage) motors;
• the standby power supply equipment (diesel generators, rectifiers, batteries, inverters, converters and the associated distribution switchboards);
• the main electrical connections between the main electrical equipment.

These preliminary single line diagrams give also:

• the selected voltage levels;
• the estimated rated power of the main electrical components.
4.2.2. Final single line diagram

4.2.2.1. Final design

At this stage of the design, one of the single line diagram proposals will be selected.

To allow the final design or final single line diagram to be established, the following data related to all fluid systems are required:

- the descriptive and functional specifications;
- the flow diagrams (P&I D’s);
- the functional data of the equipment.

The following documents are prepared in parallel with the final single line diagram:

- the electrical consumers list with the assignment to their supplying switchboard;
- the balance sheet of the electrical consumption of the plant auxiliaries;
- the balance sheet of the electrical consumption of the d.c. supply;
- the different calculation notes giving the electrical characteristics of the distribution networks of the plant, namely:
  - the voltage and frequency variations of the external networks feeding the plant auxiliaries;
  - the allowed voltage and frequency variations on the MV and LV motors;
  - the rated voltage levels of the different consumers;
  - the maximum short-circuit power requested for the electrical switchboards at all voltage levels;
  - the corresponding maximum impedance voltage for the MV/LV transformers;
  - the voltage ratio’s and impedance voltages of the generator, unit auxiliary and station transformers;
  - vector groups for all transformers;
  - the volt drop calculations;
  - the cable cross-section calculations;
- the final descriptive and functional specifications for the electrical system. These specifications will include the requirements for normal operation as well as for start-up and shutdown of the plant, taking into account synchronisation, island or house load operation, black-out, black start, … ;
• the design principles of the electrical protections at all voltage levels (from HV to LV) and the associated calculation notes for the settings (selectivity analysis);
• the I&C specifications of the electrical systems;
• the study and calculation of the earthing grid, with associated principle and detail diagrams;
• the study of the lighting (normal, emergency and escape route lighting);
• the typical diagrams of the MV, LV switchboards and MCC’s incoming and outgoing feeders (standard circuit diagrams);
• evaluation of final balance sheet showing the heat losses of the electrical and I&C equipment.

Moreover, for certain projects, the following studies may be included:
• probabilistic studies on electrical power sources availability;
• stability study of auxiliaries supply networks;
• qualification programs on electrical equipment

This final single line diagram will be used:
• by the I & C team to finalise the architecture of the I&C supply system and to determine the final number and dimensions of the I&C equipment;
• by the electrical team to determine the final number and dimensions of electrical power and I&C equipment and to make the final (space) reservation for cable trays and equipment;
• by the layout designers to finalise their implementation design.

4.2.2.2. Contents of the final single line diagram

The contents of the final single line diagram is as followings:
• its framework (structure) is the same that the framework of the preliminary single line diagrams;
• it shows all the generators, transformers, switchboards, MV motors, busbars and secondary connections as well as the associated switching and isolating devices, rectifiers, batteries and inverters;
• it is completed by the indications of the electrical characteristics of the equipment used and the associated functional benchmarks.

4.3. Remarks

a) The methodology described above is an iterative process. All drawings documents and data are interactive pieces of a puzzle that have to be continuously revised throughout the project. As the details relating to one discipline (mechanical, civil, electrical) change they will impact on others, which will need to be updated.
b) The methodology described above is an ideal description of the work. Practically, however, the hazardous and unforeseen events due to the type of the plant as well as to the time schedule constraints, generally require provisional assumptions to be made to mitigate the consequences of the lack of essential information at a particular time. Such practices are treated with particular care and are clearly identified for correction later if needed, when the information becomes available.

c) Modifications introduced during the execution of the project can also be considered as unforeseen events. Such modifications result in revisions of document and studies and must be treated with the same precautions described in §.b) above.

5. General design

5.1. General

In this section, the different steps leading to the achievement of the final single line diagram of a typical power plant will be examined.

To establish the principles, the development of the single line diagram of a power plant is considered, the basic design of which includes only one generator unit.

5.2. Basic data

The following basic information and data is the minimum required for the project:

- general design of the process (e.g. type of plant, drawing or description of main fluid circuits, …);
- equipment list at least for the main fluid circuits;
- existing loads or distribution networks to be supplied by the new power plant electrical system;
- catalogues of electrical equipment manufacturers;
- information about equipment budgetary costs and required minimum performances;
- external networks main characteristics;
- generator and excitation main characteristics;
- redundancy criteria for systems;
- separation criteria for auxiliaries (due to e.g. classification into units, station, common auxiliaries, …)
- auxiliaries classification criteria (categories of auxiliaries by importance or by mode of operation) (e.g. normal, emergency …);
- ambient conditions such as temperature, humidity, ….
• codes and standards (e.g. IEC standards, national codes and standards, …);
• national network requirements (national grid code).

5.3. Definition of the structure of the single line diagram

5.3.1. Concept of the structure
The structure of a single line diagram can be represented as a tri-dimensional (3D) box (see figure 1) containing all the distribution switchgear which forms the basis of the single line diagram. The box is fed from the top face by the main generator, the different external networks and the emergency sources like diesel generators, and feeds in turn all the auxiliaries of the plant through its bottom face.
The various distribution switchboards are arranged inside the box according to the following criteria:

- the vertical axis (Z or height) defines the different levels of voltages. From top to bottom: MV, LV a.c., LV d.c;

- the first horizontal axis (X or width) defines the redundancy and separation criteria of the auxiliaries. From left to right:
  - either system 1, system 2, system 3 ... auxiliaries for the redundancy criteria;
  - or unit, station, common (to several units), ... auxiliaries for the separation criteria;

- the second horizontal axis (Y or depth) defines the auxiliaries classification criteria. From front to rear: normal, emergency 1st level, emergency 2nd level, ... auxiliaries.

The various switchboards may then be connected together, in two different ways:

- either directly if the connections are made in the same horizontal plane (same level of voltage);

- or through transforming equipment (like transformers between MV and LV a.c. or rectifiers between a.c. and d.c.) if the connections are made between different horizontal planes.

5.3.2. Representation of the structure of the paper

Starting from the 3D structure described above, the representation in a two-dimensions (2D) drawing is straight forward.

If we look to the “3D Box” described above from its front face (plane X-Z), we can make a series of slides corresponding to the categories of auxiliaries (axis Y) and represent each plane parallel to the X-Z plane by a separate figure, using arrows and numbers to represent the crossed links between planes (see figure 2).
Figure 2

Y = NORMAL

Y = EMERGENCY 1
5.4. Practical methods of developing a single line diagram

5.4.1. Guide for the choice of voltage levels (Z axis)

The first way to partition the auxiliaries of a power plant is to classify them by their voltage level relating to their rated power.

There are no general rules for determining the voltage levels to be used in a power plant, but the key items of plant need to be examined as a starting point.

The following points may be considered, but it must be borne in the mind that some of these may counteract each other and the designer's ability to make appropriate compromises is critical to reach the best result and the most flexible electrical distribution system.

a) Starting with the general process design and the associated equipment list of main fluid circuits, the rated powers of the largest motors must be considered to determine whether or not MV level is required.

In most of the thermal power plants with a rated power of 100 MW or more, a MV level is necessary, due to the rated power of large motors (Boiler FW pump, FD fan, ...).

The choice of voltage levels depends on the rated power of the individual drives, on the rated power of the different systems and on the total power of the auxiliary supply.

The number of voltage levels should be kept to a minimum. However, IEC Std 38 needs to be taken into account.

b) A detailed examination of the largest loads, will determine if one or several levels of MV are required, taking into account:

- the minimum and maximum powers that are, realistic values for motors (manufacturers catalogues will be helpful);
- the other constraints on the site, such as the need to supply other MV loads, independent of the power plant;
- the possibility of choosing one or several voltage levels for the LV a.c.;
- the catalogues of electrical equipment manufacturers giving, for instance, the range of the possible rated powers of their equipment (motors, transformers, ...) for each level of voltage (MV or LV);
- the client's or national standard voltage levels;
- the possibility of using variable speed drives.

c) Taking all these preceding points into consideration, the next step is to establish the voltage levels values for all MV and LV a.c. systems.

Generally, at this stage the economic criteria for using the optimum number of voltage levels to standardise equipment as far as possible, should also be taken into account. These criteria give the opposite result to the technical considerations, which adapts the voltage to the rated power for each consumer, and result in increasing the number of voltage levels.
d) The same process will then be applied to the d.c. systems to determine the need of one or several d.c. voltage levels, namely:

- for the control of the switchboards;
- for the d.c. emergency motors;
- for the main control system of the plant;
- for the uninterruptible power supplies giving a.c. regulated voltage for I&C purposes.

5.4.2. Application of the redundancy and/or separation criteria (X-axis)

Another way of designing auxiliary systems for a power plant, is to segregate them to one or several independent systems based on redundancy or separation criteria.

a) According to their importance in the process or the power rating of the electrical equipment to be used to achieve a particular function in the process, redundant electrical components (e.g. motors) need to be installed to provide security of operation and/or safety of the system to which they belong.

This may result in systems with certain components repeated 2, 3 or 4 times, e.g.:

- four pumps each rated 33 % of required flow (3 out of the 4 pumps are required to achieve 100 % of the flow);
- three diesel generators each rated 50 % of the required power to be supplied to the auxiliaries (two out of the three diesels are required to achieve 100 % of the supply);
- two pumps, each rated 100 % of the required flow (only 1 pump is sufficient to achieve the flow).

This is the criterion of redundancy that determines the number of components to be supplied independently and separately from their redundant counterpart. This criterion is generally used in nuclear power stations.

b) In non-nuclear power plants, the criterion of separation of the auxiliaries will be applied to create several independent distribution networks based on their particular use on the site e.g. :

- the unit auxiliaries, which are the auxiliaries necessary to run the unit (or process) under any circumstances from start-up to shutdown through full power running (example: feed water pumps);
- the station auxiliaries, which are those not directly tied to the operation of the process, but are required to operate the site (or station) auxiliaries (example: lighting);
- the common auxiliaries, which are those that may be shared between several units and for which a common auxiliary plant may serve several units (example: coal handling, water treatment, ...).

These two main criteria will lead to the development of two or more distribution networks acting in parallel and independently of each other.
The increase in the number of auxiliary systems inevitably results in increased levels of capital costs.

Economic considerations will include the review of costs of different electrical suppliers, standardisation of equipment such as transformers, switchgear, U.P.S. components, motors, and so on.

Basic data to be used for this classification are namely:

- redundancy criteria for systems;
- separation criteria for auxiliaries.

(see Ch. 5.2.)

### 5.4.3. Classification of auxiliaries (Y-axis)

The third way of distinguishing the auxiliaries in a power station is to classify them according to their mode of operation e.g.:

- auxiliaries which are required to operate the unit or the plant under normal conditions: normal start-up, power operation, normal shutdown, cold standby, …);

- emergency auxiliaries which are required to keep the plant in safe conditions in case of an incident such as loss of voltage from the HV grid, the plant being at stand still in hot standby ready to restart at short notice. Emergency may be categorized into a number of levels (e.g. in nuclear power plant, emergency 1st level corresponding to internal cause of accident in the plant, emergency 2nd level corresponding to external cause of accident of the plant).

Basic data to be used for this classification are auxiliaries classification criteria (see ch. 5.2.).

### 5.4.4. Elaboration of the single line diagram

Following the considerations of the three classifications of systems and auxiliaries referred to above, it is possible to develop the single line diagrams corresponding to these classifications showing the reticulation of switchgear.

The next step is to interconnect these switchboards together using:

- direct connections between switchboards of the same level of voltage;

- connections through transformers or semi-conductor devices between respectively a.c. switchboards of unequal voltage levels or a.c. switchboards and d.c. switchboards.

The main consumers (loads), such as MV motors, will then be added to the single line diagram, using the equipment list for main fluid circuits (giving also the main characteristics of the associated loads), and the type of connection to the external grid and to emergency sources (diesels generators and batteries). The following items need to be considered:

- local situation (connection to the HV grid, start-up, shutdown, …);

- type of power station;

- main mode of operation of the power station (base or peak load and relevant availability of the power station);
• economic criteria (power stations capital cost constraints);
• technical issues (e.g. short-circuit levels versus available equipment);
• use of a generator circuit breaker;
• requirement for the connection of the external source to be made in addition to the main generator connection (depending if the considered source is either the production or the back-up or the start-up network);
• use of a full or reduced capability for a back-up power supply from the external grid (starting from the knowledge of the external grids characteristics);
• point of connection of the diesel generators and batteries according to the level of voltage of the auxiliaries to be emergency power supplied.

Other factors will need to be taken into consideration to determine whether additional switchboards are required, taking into account criteria such as:

• decentralised LV auxiliaries to be fed from a MV switchboard through a decentralised (remote) MV/LV transformer (economic reasons, package, distance, maintenance, …);
• switchboards (mainly LV) to be supplied by two different sources coming from separated systems;
• duplicating switchboards due to the excessive power requirements resulting from the addition of connected loads.

**5.4.5. Sizing of the equipment of the single line diagram**

In parallel with the design of the single line diagram, a certain number of calculations must be done to dimension the equipment on this diagram. Transformers, switchboards, generators, ... must be sized, and their main characteristics must be calculated. The results of these calculations may have an effect on the layout of the single line diagram.

**6. Criteria for the choice of equipment**

**6.1. Power transformers**

**6.1.1. Preliminary remark**

Where numerical values are referred to in the following sub-sections, they have been extracted from the questionnaire responses referred to in section 3.3.

**6.1.2. General**

This section mainly relates to the generator transformers (GT) (or step-up or main transformers), unit auxiliary transformers (UAT) and start-up transformers (SUT) (or station transformers), the rating of which is generally directly related to the output of the main generator of the power station or absorbed by the auxiliaries.

This section deals also with the MV/LV auxiliary transformers used to supply power to the LV auxiliaries from the MV distribution system.
GT, UAT, and SUT power transformers will normally be installed outdoors and separated from each other and from buildings or other equipment by fire resistant walls. They will be equipped with automatic fire protection devices.

Note:

GT transformer is different from UAT, start up and station transformer: latter are not directly connected to the generator output.

6.1.3. Generator transformers (GT)

The generator transformers may be either three phase transformers (85 %) or single phase transformers (15 %). Single phase transformers are used where transportation of three phase transformers is a problem. The weight or dimensions of large transformers can be too much important and transportation by road and rail may not be possible.
Generator transformers will always be of the oil cooled type, with the oil being cooled in coolers using another cooling fluid (air, water, oil, ...). For the power stations concerned in this paper (namely from 100 MW and above), the cooling types referred to in the questionnaire responses are:

- OFAF (48 %) and FOA (2 %) from 105 to 1300 MVA;
- OFWF (19 %) from 100 to 1170 MVA;
- ONAF (7 %) MVA and AF (2 %) from (30) 135 to 780 MVA;
- ODWF (5 %) from 135 to 800 MVA;
- ODAF (4 %) from 690 to 1650 MVA;
- OFOF (3 %) 375 MVA;
- Other types (10 %) from 240 to 500 MVA.

[Code : O = oil; A = Air; W = Water; F = Forced; D = Directed; N = Natural.]
Generator transformers will generally be rated in such a way not to limit the transmission of power produced by the generator.

The need for tap changing equipment is determined by the network to which the generator transformer is connected and the responses to the survey indicate the following proportions using the respective applications.
APPLICATION OF GENERATOR TRANSFORMER TAP CHANGERS

(Remark: the use of a tap-changer is dependent on the voltage range of the generator)

- 43.5% of transformers in the survey are equipped with an OLTC (On-Load tap changer). The associated transformer impedance voltages range between 8 and 18%.

- 43.5% of transformers are equipped with a NLTC (No-Load tap changer) operated only when the transformer is de-energized. The associated transformer impedance voltages range between 8 and 15.9%.

- 13% of transformers have no tap changer. The associated impedance voltages in this case range between 7.5 and 15.5%.

GENERATOR TRANSFORMER UPPER VOLTAGE RANGE

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The selection of the transformer voltage ratio must also take into account the VHV network voltage, the range of the generator voltage, the reactive power to be supplied to the grid or absorbed from the grid by the generator, the voltage limits of the VHV network, and the use or otherwise of a tap changer on the generator transformer.

The vector group of the generator transformer is generally (89 %) of the Wye/Delta type (Wye being the higher voltage and Delta at the lower voltage) and in this case the neutral point at the HV side is generally (76 %) available for connection to ground (connection to the ground directly or through a limiting impedance).

### VECTOR GROUPS OF GENERATOR TRANSFORMERS

![Diagram showing vector groups of generator transformers]

#### 6.1.4. Unit auxiliary transformers (UAT) and start-up transformers (SUT)

These transformers will generally be of the oil cooling type for the power stations concerned in this paper (from 100 MW and above), and more precisely the cooling types encountered in the answers to the questionnaire were:

- for the unit auxiliary transformers:
• ONAN (46%) or AN (11%) from 0.4 to 180 MVA;
• ONAF (18%) or FA (3%) from 0.3 to 63 MVA;
• OFAF (7%) or FOA (1%) from 17.5 to 70 MVA;
• other types combined: 14% from 0.5 to 60 MVA.

- for the start-up transformers:

**START UP TRANSFORMER COOLING SYSTEM**

<table>
<thead>
<tr>
<th>COOLING SYSTEM</th>
<th>PREFERENCE IN %</th>
</tr>
</thead>
<tbody>
<tr>
<td>OTHER</td>
<td></td>
</tr>
<tr>
<td>ONAN</td>
<td>46</td>
</tr>
<tr>
<td>ONAF</td>
<td>18</td>
</tr>
<tr>
<td>ON</td>
<td>11</td>
</tr>
<tr>
<td>OFWF</td>
<td>7</td>
</tr>
<tr>
<td>OFW</td>
<td>3</td>
</tr>
<tr>
<td>OFDAF</td>
<td>2</td>
</tr>
<tr>
<td>OFDA</td>
<td>1</td>
</tr>
<tr>
<td>OFAN</td>
<td>1</td>
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<td>OFAF</td>
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<td>AN</td>
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</tbody>
</table>

• ONAN (48%) or AN (4.5%) from 1 to 100 MVA;
• ONAF (17%) or FA (2.5%) from 4 to 100 MVA;
• OFAF (12%) or FOA (2%) from 1 to 70 MVA;
• other types all together: 14% from 1 to 40 MVA.

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Unit auxiliary transformers and start-up transformers will be sized to comply with the needs of the loads to be supplied in the different modes of operation of the plant. However, the maximum rated power that can be supplied by a (secondary) MV winding will be limited by the characteristics of the associated MV switchgear. Transformers with more than one secondary winding can be used to overcome such a switchgear limitation.

Unit auxiliary transformers and start-up transformers may be equipped either with an OLTC (30% for UAT and 70% for SUT) or a NLTC (70% for UAT and 30% for SUT) as determined by the range of voltage to be guaranteed on the MV distribution system and to the possible load variation on the system.

**POPULARITY OF APPLICATION AND DESIGN OF UNIT AUXILIARY TRANSFORMER TAP CHANGERS**

- **ON LOAD TAP CHANGER**: 30%
- **NO LOAD TAP CHANGER**: 70%

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The rated voltage ratio and the impedance voltage of these transformers will generally be determined taking into consideration the drop of voltage due to the start-up of the biggest MV motor or the total load to be transferred from one transformer to another.

The vector group of the unit auxiliary and start-up transformers will be adapted to the distribution system characteristics and to the system grounding philosophy.

6.1.5. MV/LV auxiliary transformers

MV/LV auxiliary transformers are used to supply the LV distribution system from the MV system.

They will generally have one of the following main cooling arrangements:

**LOW VOLTAGE TRANSFORMER COOLING SYSTEMS II**
LOW VOLTAGE TRANSFORMER COOLING SYSTEMS

- mineral oil type:
  - ONAN (70%) or OA (2%) from 200 to 8500 kVA;
  - ONAF (3.5%) from 3500 to 8500 kVA;
- dry type:
  - AN (18%) from 300 to 5000 kVA;
  - AF (3.5%) from 1250 to 2000 kVA
- other types all together: 3% from 250 to 1600 kVA.

Their rated voltage ratio, will generally be adapted to the related (MV) and LV distribution systems, together with their vector group type. Their rated power will be adapted to the power rating of connected LV loads and the associated impedance voltage will have standardised values.

As a general rule they will be equipped with NLTC (NLTC 91% - OLTC 9%).
Mineral oil type transformers must be installed outside buildings, for fire safety reasons. They will then generally be connected by LV busbars or by parallel single core cables to their associated LV switchgear and by cables to their associated MV switchgear.

Dry type transformers may be installed inside buildings. They will then generally be directly connected by LV connections to their associated LV switchgear (the transformer may be directly connected to one end of the LV switchboard) and by cable to their associated MV switchgear.

Dry type transformers require little maintenance. During operation checks must be made for suspect noises. Dust should be removed and electrical connections will be checked when de-energized as for switchgear.

Heat dissipation and heat removal on MV/LV transformers, will generally determine the selection of indoor or outdoor installation, and as a consequence mineral oil or dry type transformers.

6.2. Generator busbars

For the range of power stations considered in this paper (above 100 MW), the generator will usually be connected to the generator transformer and the unit auxiliary transformer through a generator busbars which are generally isolated phase busbars type, where each phase comprises a coaxial system with a central hollow conductor and a concentric surrounding enclosure connected by radial electrical insulators. Aluminium is the principal material used at this duty for both the central conductor and the enclosure.
With this power rating, the generator busbars will usually be of the continuous type, i.e. each phase enclosure will consist of a continuous tube from the generator to the transformer (some expansion joints may, however, be provided, the electrical continuity of the enclosure being achieved by electrical connections under a flexible bellows) the enclosures of the three phases being short-circuited at every end (generator and transformer(s) sides) by a thick short-circuit plate; one short-circuit plate only being connected to the earth in one point. The busbar enclosure is the earthing conductor. This type of busbars is recommended for high power connections because of its ability to greatly reduce the residual electromagnetic field outside the busbars (lower than 10% of the field produced by a bare conductor).

The busbars will be either of the naturally cooled type or of the forced cooled type depending on the rating of the generator. Generally, the cooling medium will be air, but some manufacturers offer water cooling for the hollow central conductor, or for the first section of busbars connected to the generator terminals.

When forced air ventilation between conductor and enclosure is used for high power generator busbars, and if a generator circuit breaker or load-switch is used, the cooling air may also be directed through part of the generator breaker to reduce losses.

The busbar design needs to be carefully considered in relation to the electrodynamic effects of short-circuits. As the forces on the components of the busbars and on the supporting structures will be maximum at the elbows or in tee (connections to the unit auxiliary transformer or to the voltage transformer cubicles, ...) the designer needs to take particular care in avoiding the unnecessary elbows and tees to reduce to a minimum the number of weak points in the structure.

6.3. Generator breakers

Generator breakers are switching devices in the high-current connection between the generator and the generator transformer. Conventional power plants with a high unit output constitute a preferred application for generator breakers, as do smaller-rated facilities with stringent requirements for safety and availability.

6.3.1. Functions

- Isolation of the generator from the power supply to the auxiliaries
- Synchronisation on the secondary side of the generator transformer
- Switching generator faults
- Switching faults in the generator transformer and/or unit auxiliary transformer
- Switching faults in the link between the high-voltage switchgear and the generator transformer

6.3.2. Advantages

The conventional reserve network, with a starting transformer, corresponding switchgear equipment, and the change-over device, can be dispensed with. The system is started up via the generator and unit auxiliary transformers with the generator breaker open.
Enhanced availability because the auxiliaries remain connected to the network without interruption.

Simple generator synchronisation.

The system can be switched off in less than 100 ms, the effects of any malfunction are less than with high-speed de-excitation.

Generator breakers are reliable devices specifically designed for all switching operations relating to generators. This means simpler operator control, due to clear isolation of the power plant itself from the high-voltage switchgear.

Current transformers, voltage transformers, earthing switches on the generator and generator transformer sides, surge arresters and protective capacitors can be installed in more cost effective space-saving configurations for easy accessibility in the generator breakers (though not in air-blast circuit-breakers).

6.3.3. Circuit Breaker Types

a) For ratings of up to 100 MVA

Up to this rating, both Generator circuit breakers with either SF$_6$ gas or vacuum as the arc extinguishing medium can be used with generator rated below 100 MVA. The operating mechanisms featured are stored-energy spring type. The earthing switches can be operated by hand or by an electric motor-operated mechanism.

b) For ratings of 100 MVA to approx. 700 MVA

For generators rated from 100 MVA to approx. 700 MVA, SF6 generator circuit breakers are used. The equipment can either be a three-pole or single-pole enclosures, or are left unenclosed. They can be installed in enclosure arrangement or open generator bus-ducts.

The circuit-breaker is operated by a compressed-air mechanism, with the compressed air being supplied from a compressor mounted in the base frame. The disconnector and earthing switches are controlled by electric motor-operated mechanisms.

c) Ratings from 400 MVA to approx. 2000 MVA

For generator ratings from 400 MVA to approx. 2000 MVA, air-blast circuit-breakers with an integrated separate isolating distance are used. The extinguishing medium is high-quality compressed air, produced in an autonomous system. Compressed air is also used as for the circuit breaker’s operating mechanism. With its single-phase enclosure, the breaker is readily matched to the generator bus-duct.

6.3.4. General remarks

Installation of a generator breaker must be taken into consideration at a very early stage in the planning phase of a power plant facility. It is important to incorporate the following requirements in construction planning:

- The circuit breaker’s space requirements (dimensions, ingress, accessibility, environmental conditions, pressure relief)
- Space requirements for operating equipment (if necessary) (compressed-air generating system, cooler, control cubicle)
• Constructional requirements (stable foundations, inspection option, accessibility for lifting tackle)

6.3.5. Standards

The current ANSI/IEEE C37.013-1993 standards have been specifically drawn up for these breaker applications. IEC 60056 also applies.

6.4. Distribution switchgear

Medium and low-voltage switchgear as used nowadays in power plant facilities, have attained a high level of sophistication in terms of technical design, availability, operator safety and flexibility.

Stringent requirements apply to the technical design of switchgear, due to the high rated and short-circuit currents encountered in power plant applications.

Equipment availability has cost-efficiency benefits, but is also a measure of the dependability of the power plant as a whole.

Flexibility is required for any modifications to the auxiliaries supply and the concomitant alterations to the substations.

Operator safety is of vital importance, because of the high short-circuit currents encountered in the event of a malfunction.

As far as the station design is concerned, single-busbar arrangements are the most commonly used for the power plant auxiliaries. Their advantage over double-busbar types is their electrical and topographical redundancy and a higher degree of flexibility. These requirements are met by dividing up the substations into busbar sections connected by bus-ties, and by using switchgear in withdrawable module design.

6.4.1. Medium-voltage switchgear and interrupting devices

6.4.1.1. Construction and relevant standards

The way medium-voltage switchgear used to be constructed in the older power plant facilities, inside bays made of masonry or divided up by gypsum panels, has been superseded by radically improved alternatives. Present-day switchgear consist of prefabricated type-tested cubicles in extremely compact design, offering high availability and wide flexibility. Their short-circuit withstand capability has been substantially increased and operator safety significantly upgraded.

Medium-voltage switchgear and switchgear-devices are manufactured in conformity with comprehensive national and international standards, which lay down guidelines for design, construction and testing. Since the degree of harmonisation is extremely high, it can be assumed that type-tested switchgear manufactured in conformity with IEC can be used all over the world. Additional national specifications of course have to be complied with.

The most important international specifications are:

• IEC 60298 Metal-enclosed switchgear
• IEC 60517 SF₆-insulated switchgear
• IEC 60694 Common specifications for HV switchgear & controlgear
• IEC 60056  Circuit-breakers  
• IEC 60265  Switch-disconnectors  
• IEC 60129  Disconnectors and earthing switches  

The type and routine tests required are defined in these specifications.  

In the power plant auxiliaries, switchgear with rated breaking currents of between 16 kA and 50 kA are used. The rated peak currents are correspondingly between 40 kA and 125 kA. The switchgear, with integral busbars, transformers and cable terminal designs, must be adequately dimensioned to cope with the high thermodynamic stresses involved.  

The prefabricated, type-tested switchgear used nowadays, with integrated make-proof devices and safety interlocks, offer a high degree of operator safety. These measures are supplemented by the requirements posed in IEC 60298, referred to as the “PEHLA” tests. The specifics of these are agreed between the manufacturer and the client concerned.  

6.4.1.2. Conventional medium-voltage switchgear 

Conventional medium voltage switchgear is constructed in metal-enclosed cubicles, which are divided into 3 main types:  

• metal-clad switchgear, with metal walls separating the individual switchboard compartments (busbar compartment, circuit-breaker compartment, cable terminals compartment, low voltage compartment) and partitioning the cubicle concerned from the adjoining cubicles. These cubicles have proved to be very robust and on the rare occasions when there has been a short-circuit fault in a cubicle it has remained confined to the particular bay concerned.  

• metal-clad substations with non-metallic partition walls  

• partially clad switchgear, with no or very few partition walls and enclosed compartments  

Depending on how the devices are installed in the cubicles concerned, a distinction is made between:  

• switchgear with fixed installed devices  

• switchgear featuring withdrawable or pull-out devices (circuit-breakers and power contactors can be withdrawn or pulled out, and transported on a separate service truck)  

6.4.1.3. Gas-insulated medium-voltage switchgear  

As previously mentioned, continual design enhancement and technical improvements over the years have resulted in a significant reduction in the switchbay volume per feeder. Another step forward has been achieved with the introduction of gas-insulated designs.
SF₆-gas-insulated medium voltage switchgear is built for rated voltages of up to 36 kV. They are particularly well suited for use in areas with tough operating and environmental conditions. Since medium voltage switchgear is used in power plant facilities with rated voltages of 6 kV or 10 kV, and the switchgear is located in enclosed and well-ventilated switchrooms, conventional air-insulated metal-clad switchgear in switchgear truck design continue to be the best solution in terms of engineering and cost-efficiency.

New developments in the field of gas-insulated switchgear, encompassing an innovative concept with all active components grouped together in one gas-insulated enclosure and computer-controlled bay units combining control, protection and interfacing with the control system, together with sensor technology, may encourage the use of this switchgear in power plant applications.

6.4.1.4. **Medium voltage circuit breakers**

**Introduction**

Minimum oil circuit breakers (MOCB) and air magnetic circuit breakers (AMCB) were used for many years for high short circuit breaking on auxiliary power supplies in power stations.

Satisfactory service experience was accumulated, using both switching principles.

Whilst MOCB's have limitations on the number of the switching operations AMCB's could be built for very high number of switching operation requirements.

The advantage of the MOCB's lay to a great extent in the self-extinguishing switching principle whilst for the AMCB's an additional energy source in the form of the special compressed process air had to be provided.
Figure 3. - Percentage share of the world-wide production of the single MV type circuit-breakers

The graph clearly shows the percentage decrease of the MOCB’s and AMCB’s purchased world-wide, in the seventies and eighties.

In the nineties a rapid change in switching principles took place. In the market place of today scarcely any MOCB’s or AMCB’s are available. These were almost completely replaced by vacuum and SF₆ circuit breakers.

This switchgear distinguishes itself through high reliability and low manufacturing costs.

**SF₆ Circuit Breakers**

In this switchgear Sulphur Hexafluoride (SF₆) is used for arc quenching and as an insulating medium.

The arc quenching system is extremely simple and uses a SF₆ blast generated by auto-compression through a system of pistons. During the switch motion the gas is compressed in a cylinder and the arc extinguished in a nozzle.

In a further development a part of the arc energy is used for gas compression so that the actuator power requirements are reduced.

Construction and functional characteristics can thus be summarised as follows:

- insulation and current interruption using SF₆ gas with high dielectric characteristics and an exceptional arc quenching capacity without any overvoltage
- main contacts housed in double-layer insulating cylinders of fibreglass and epoxy resin with internal surfaces protected against the effects of decomposed SF₆
- highly reliable pressure seal system
- leak monitoring by pressure switches and associated breaker lockout facilities

The most significant features of SF₆ circuit breakers are:

- reduced overall dimensions and weight
- long electrical life
- costs comparable to those of vacuum circuit breakers

**Vacuum Circuit Breakers**

The vacuum switching principle demands no external energy source for arc extinguishing. This crucial advantage means additionally that simple actuators with minimum energy requirements can be built. This advantage becomes more evident with increasing short circuit values.

The vacuum level inside the bottle is approximately $10^{-8}$ Torr and the bottle is made from porcelain.
The arc quenching system is also extremely simple. It is located within vacuum interrupters. After separation of the contacts and up to the next current zero the current flows through a plasma formed by the vaporisation of contact material when the contacts separate. The charge carriers in the plasma condense very rapidly on the metal surfaces (condensation screen) of the interrupter chamber.

They are replaced by charge carriers generated by the vacuum arc itself, once again by vaporisation of electrode material at the arc bases. Formation of the charge carriers ceases around the time of the next current zero and the contact gap is very rapidly de-ionised. This completes quenching of the arc.

The number of switching operations that can be achieved with these circuit breakers is in the region of 30,000. Service assessment data indicates that the limitation is because of minor deterioration of mechanical parts.

Also the admissible number of short circuit interruptions lies within 100 operations of that which could be achieved up to the present time using different switching principles.

The most significant features of vacuum circuit breakers are:

- reduction in overall dimensions and weights
- long electrical life
- low energy required for operation (simple and low maintenance magnet drives can be used)
- low production costs

The qualities described give vacuum circuit breakers advantages over their SF₆ counterparts.

The main potential disadvantage of the vacuum circuit breaker is over-voltage (through current chopping), which occurs during the switching of the starting current of small medium voltage motors (starting current <600A), but this can be eliminated through the insertion of modern metal oxide surge arresters.

Vacuum Contactors

The switching principle and arc quenching system are the same as for vacuum circuit breakers.

Contactors differ from vacuum circuit breakers in that they are equipped with spring operating mechanisms for closing and opening, the vacuum contactors are equipped for closing and opening with an electromagnetic drive.

Two arrangements are used:

- electrical latching
- mechanical latching

The number of switching operations under rated operation conditions is in the region of $5 \times 10^6$ for mechanical endurance and $10^5$ for electrical endurance (much higher as for circuit breakers).

The admissible number of short circuit interruptions lies within 25 operations.
Vacuum contactors also differ from circuit breakers in that they provide short circuit protection for motor, transformer or capacitor feeders through the use of current limiting HRC (High Rupting Current) fuses.

The rated breaking and making capacity of the vacuum contactors without HRC fuses is relatively low compared with vacuum circuit breakers (3500A resp. 4500A for contactors and 50 kA resp. 125 kA for circuit breakers).

The maximum rated operating current AC4 according to IEC Std is around 400 A.

The most significant features of the vacuum contactors are:

- reduced overall dimensions and weights
- long electrical and mechanical life
- low energy required for operation
- low production costs (approx. 30% lower than for circuit breakers)
- limiting outgoing fault current by HRC fuses with the result:
  - of reduced outgoing cable size;
  - of limiting the damage of cable box fault;
  - improved operator protection.

These qualities make vacuum contactors, particularly suitable for the following applications:

- motor feeders
- transformer feeders
- reverse starters
- two-speed motor starters
- frequent switched motors

6.4.2. Low Voltage switchgear.

6.4.2.1. Construction and relevant standards

Analogously to its medium voltage counterparts, cubicle construction in the low-voltage range has progressed from individualised erection on site (open construction, baking-tray design) to type-tested, prefabricated switchgear combinations.

Here, too, great importance is attached to enhanced safety for the operating personnel, restricting the effects of malfunctions, fast trouble-shooting, and a high degree of flexibility for maximally unimpeded station modification or expansion.

Nowadays the switchgear-devices are installed on withdrawable modules.
These modules are fitted with isolating contacts for quick, simple installation, thus guaranteeing high flexibility. The space in the cubicle room is more effectively utilized due to the modular construction. The size of the modules will depend on the connected load and the resultant dimensions of the switching devices.

The cubicles are divided up into the following function compartments:

- equipment
- busbar
- cable

It is in the equipment compartment that withdrawable modules are located. The busbar compartment accommodates the busbars and the cubicle distribution busbars. The cable compartment houses the incoming and outgoing power and control cables, plus the module interconnections.

The base frame is constructed of profile sections, which are both encased and subdivided with steel sheeting. The flexibility of construction means that a switchboard can be configured to suit a wide variety of requirements: from stand-alone layouts to multi-bay switchgear with options for single-sided and double-sided (duplex layout) operator control.

As far as basic principles are concerned, the models from almost all the manufacturers are similar. Sheet-sheet cubicles with comparable dimensions are used, to form compartments for related groups or devices. In some cases, the walls separating the functional compartments and the individual modules are constructed as partitions.

In Europe, this type-tested prefabricated switchgear is built in conformity with IEC 60439, and erected/connected in accordance with IEC 60364. Appropriate local national standards must course be complied with.

6.4.2.2. Key electrical data

The rated values given here are attained by the switchgear from almost all prominent manufacturers.

- Rated voltages:
  - Rated insulation voltage: 1000 V 3 AC, 1500 V DC
  - Rated operating voltage: 690 V 3 AC
  - Rated surge withstand capability: 8 kV

- Rated currents:
  - a) busbars:
    - Rated current: up to 5500 A
    - Rated short-circuit withstand capability: up to 100 kA
    - Rated surge withstand strength: up to 250 kA
  - b) cubicle distribution busbars:
    - Rated current: up to 2000 A
    - Rated short-circuit withstand capability: up to 86 kA
    - Rated surge withstand strength: up to 165 kA
6.4.3. Conclusion

In conclusion, it can be stated that a very high degree of operator safety, system availability and design standardisation has been achieved with modern medium and low voltage switchgear used to supply station auxiliaries in power plant.

6.5. Motors and Voltage range

It is recognised that the auxiliary power consumption on a power station is attributable to a few large drives i.e. about 80-90%, of the whole auxiliary power requirements. Therefore, the power consumption of the medium voltage system determines to a great extent the auxiliary power concept.

Figure 4. shows the cost relationship between motor feeders with different motor ratings against voltage levels. The costs are per feeder including switchgear, 200m cable connections with installation and supports together with the motor itself.

![Figure 4. - Cost relationship for motor feeders.](attachment:image.png)

With the higher power range i.e. voltage levels 6 kV - 10 kV, up to approximately 500 kW motor power, only minor cost differences are found. The price advantage results from the somewhat favourable 6 kV motor prices (approx. 20-25%). The switchgear share is about equal. The more favourable cabling costs with 10 kV, from a distance of 200m, compensates for the cost advantage of the 6 kV motor. For greater lengths 10 kV is even more favourable.

Under 500 kW the 10 kV motor becomes disproportionally more expensive. Here the advantages of the 6 kV and 3 kV down to the 690V low voltage levels are evident. The economical power range of the 6 kV and 3 kV levels is valid to approximately 170 kW. From this level the transition to the low voltage should take place.
In the power range for the low voltage levels the clearer advantages in favour of the 690V level are recognised. Here the cabling advantages due to the small cross-section dominate. At less than 10 kW the advantage disappears. Here the 400 V level minimum cable cross-sections range of 2.5 mm-1.5 mm can be provided.

The choice of the voltage range should be determined using the above mentioned economic points, but must also suit the total auxiliary power requirements.

In the medium voltage level the maximum auxiliary power requirement, the maximum short circuit current and the maximum voltage drop are relevant. With the adoption of 6 kV switchgear having a busbar current of 2,5 kA and a short circuit-breaking current of 40 kA, a max. auxiliary power requirement of 26 MVA can be tolerated. With a voltage drop <15% this amounts to a maximum motor switching power of approx. 7 MW. With larger power values it is necessary to adopt the 10 kV level.

In the low voltage range 400/230V is required for the Heating Ventilation and Air Conditioning (HVAC) loads together with lighting, and small power.

If the power demand can be satisfied with the existing 6 kV level the 690V level is not required. The transition from 400V to 6 kV should take place at a motor power of about 200 kW.

With larger auxiliary power requirements the 10 kV level is technically and economically a better solution. In this case the 690V level is available as an additional low voltage level, together with the 400/230V level. The transition from 690V to 10 kV should take place at a motor power of about 400 kW.

6.6. Standby Power Supplies

6.6.1. Battery system design

Once the plant electrical distribution systems have been defined, consideration must be given to the battery system design. It is important to consider total lifetime costs of the system, and not just the initial capital cost of purchase and installation. Capital cost is, however, a significant factor and is dominated by the selection of battery type. Factors affecting lifetime costs are:

- spares
- testing
- maintenance and repair
- system capacity
- process requirements
- seismic requirements
- disposal
- specific maintenance tests (discharge test on resistance).
Defining loads

General Consideration

The battery system capacity is designed to meet the full load over specified time periods and the design process is as follows.

The duty cycle imposed on a battery by any of the conditions described herein, will depend on the D.C. system design and the requirements of the installation. The D.C. power requirements that the battery must supply, occur when:

1) load on the D.C. system exceeds the maximum output of the battery charger;
2) output of the battery charger is interrupted;
3) auxiliary A.C. power is lost (may result in a greater D.C. power demand than (2) above.

The most severe of these conditions should be used to determine the battery size for the installation. The total time span of the duty cycle is determined by the requirements of the installation and need not exceed the time required to reduce the battery load to zero. This may be accomplished by restoration of the A.C. power, restoration of battery charger output, or termination of battery loads.

Load classification

The individual D.C. loads supplied by the battery during the duty cycle may be classified as continuous or non-continuous. Non-continuous loads lasting one minute or less are designated “momentary loads” and should be given special consideration.

Continuous loads are energised throughout the duty cycle. These loads are those normally carried by the battery charger and those initiated at the inception of the duty cycle. Typical continuous loads are:

- emergency lighting
- continuously operating motors
- inverters
- indicating lights
- continuously energised coils
- annunciator loads
- Distributed Control Systems.

Non-continuous loads are energised during only a portion of the duty cycle. These loads may come on at any time within the duty cycle and may be on for a set length of time, be removed automatically or by operator action, or continue to the end of the duty cycle. Typical non-continuous loads are:

- emergency pump motors
- critical ventilation system motors
- communication system (stand alone systems, generally with separate battery)
- fire detection systems (stand alone systems, generally with separate battery).
Momentary loads can occur repeatedly during the duty cycle but are of short duration, not exceeding 1 minute at any occurrence. Although momentary loads may exist for only a fraction of a second, each is considered to last for a full minute, because the instantaneous battery voltage drop for a given momentary load is essentially the same as the voltage drop after 1 minute. When several momentary loads occur within the same 1 minute period and a discrete sequence cannot be established, the load shall be assumed to be the sum of all momentary loads occurring within that minute. If a discrete sequence can be established, the load for the 1 minute period shall be assumed to be the maximum current at any instant. Typical momentary loads are:

- switchgear operations
- motor-driven valve operations
- isolating switch operations
- field flashing of generators
- motor starting currents
- inrush currents.

The above lists of typical loads are not a full catalogue of the D.C. loads at any one installation. The designer should review each system carefully to be sure he has included all possible loads and their variations. For example, it may be possible to consider the increase in inverter input current with declining input voltage.

**Duty cycle diagram**

A duty cycle diagram showing total current at any time during the cycle is an aid in the analysis of the duty cycle. To prepare such a diagram, all loads expected during the cycle are tabulated along with their anticipated inception and shutdown times.

Loads whose inception and shutdown times are known, are plotted on the diagram as they would occur. If the inception time is known, but the time is indefinite, it shall be assumed that the load will continue through the remainder of the duty cycle.

Loads which occur at random shall be shown at the most critical time of the duty cycle in order to simulate the worst case load on the battery. These may be non-continuous or momentary loads. To determine the most critical time, it is necessary to size the battery without the random load(s) and to identify the portion of the duty cycle that controls battery size. Then the random load(s) shall be superimposed on the end of that controlling section.
A standard procedure for calculating this capability is provided in IEEE Std 485-1983 [B5]. Using this procedure, the required D.C. loads are tabulated with respect to magnitude and duration. This tabulation establishes a load versus time profile that is called a “duty cycle”. Using this duty cycle and using manufacturer's curves that show the Ah capacity at a specified discharge rate, the required battery capacity may be calculated. The capacity requirements may be reduced if loads are connected to the battery in a certain sequence, for example, if controls are provided to assure that large motors are not started simultaneously. Typical station batteries range from 200 to 4000 Ah with typical discharge rates of either 2, 3 or 8 hours. The storage capacity of the battery is dependent on the type, construction, operating temperature, rate of discharge, and age of the battery. Although most batteries will show increased capacity for a short time after initial use, all batteries will have decreased capacity with increasing age.

The charger is operated usually in parallel with the battery. During normal operation, the charger will supply the D.C. loads and maintain the battery in a properly charged condition. During abnormal or emergency conditions in which the D.C. loads is high, the battery will assist in powering loads that are beyond the capability of the charger.

To ensure that power for D.C. loads will be adequate, the charger is sized to supply the normal D.C. load while simultaneously recharging the discharged battery in a specified time period. In addition to powering normal D.C. load, the charger must “charge” or furnish charging current to the battery to ensure the battery is maintained at full charge or capacity.

**Battery selection**

By far the most common type of battery cell used in power station standby applications, is the lead acid Planté cell and only small number of power plants install nickel-cadmium cells. Ten percent of stations surveyed confirmed that they used vented lead acid cells, however.

The following design lifetimes should be taken into consideration when selecting the type of battery cell:

- valve regulated (sealed) re-combination lead acid
  - 3 to 5 years life
  - 5 to 8 years life
  - 8 to 10 years life
  - more than 10 years life

- vented lead acid
  - 7 to 25 (or more) years life

- vented nickel-cadmium
  - 15 to 25 (or more) years life

**Full discharge test to check capacity**

This test should be prolonged after the time limit has been reached, in order to give an idea of existing margin and to know the shape of the end of the voltage curve which gives useful indications about the ageing process. If retained, this option can influence the design.
6.6.2. **Uninterruptible power supplies**

An uninterruptible power supply (UPS) provides a highly reliable, uninterruptible source of voltage and frequency-regulated A.C. power. Typical power station loads supplied from UPS equipment are instrumentation, controls, computers, and electronic circuits, which require a continuous source of supply and be available to affect the safe shutdown of the plant.

Uninterruptible power supplies are used where loss of power supply can cause one or a combination of the following:

- loss of essential information, for example real-time or interactive computer systems or hard-to-repeat batch process;
- loss of control of a production process, such as boiler controls, flow, level and temperature controllers;
- shutdown of a plant which has fail-safe shutdown systems in hydrocarbon production processes;
- loss of essential information to process operators, for example, central control of a distributed control system;
- loss of light for emergency escape in office blocks, on offshore platforms and other buildings.

In designing the UPS equipment, the following criteria must first of all be established:

- voltage level
- current rating
- emergency time period.

The number of equipment must be determined to meet the needs of the plant to be supplied and whether this is best served from central or individual units.

The topology of the UPS units is determined to establish the level of redundancy required and what facilities are required to meet the normal operation, mains fail, inverter fail and maintenance operations.

6.6.3. **Standby Diesel generators**

Diesel generators are utilised almost universally on power station plants as a source of standby power to facilitate safe run down of the plant when the primary power source has been lost and the grid infeed is no longer available.

It is a standard practice to connect the diesel generator onto an essential service switchboard from which battery chargers, inverters and any essential actuators and motor drives can be supplied.

Flexibility of operation is provided through the installation of duplicate diesel generators, which is beneficial during times of maintenance or failure of one machine. It is also preferable to equip the plant with automatic start up facilities to minimise the starting time.
Periodic testing of the diesel generator is necessary to ensure that the engine will start when required and that it will be able to provide the specified power. For this power test, the generator should be synchronised to the grid and full operation should be possible.

In some cases diesel generators are installed to provide black start power supplies. These machines are, by their nature, much larger in size and rating since they are required to provide the energy to start the drives needed to start one steam or gas turbine generator. In a deregulated market, the Generating Company will provide such equipment under an Ancillary Service Agreement with the System Operator, who needs the service to re-establish the grid system after a failure.

Diesel fuel storage capacities vary depending on the requirements of the power plant; nuclear power stations, for example, have capacities to last for up to one week, but 100 hours is a more usual figure for conventional plants. Outage times are very much dependant upon the sophistication of the grid system and its black start capacity.

In some cases small gas turbine generators are used for black start purposes as they have the added benefit of providing peak lopping facilities more efficiently than Diesels.

The following criteria must be taken into consideration when determining the rating of a standby Diesel generator:

- engine capability - the capacity to pick-up load can vary with machines of different manufacturers;

- station sequence / load - the sequence of applying loads to the Diesel generator can have an effect; it's rating as can the size of the largest load. In addition it should be noted that the engine rating is the governing factor in relation to the applied load;

- duty - the requirement for continuous or standby duty affects the machine rating;

- terminal voltage - the voltage at the generator terminals is a key factor in calculating its rating;

- motor starting - the type of motor starting equipment, i.e. direct on line (DOL) / soft starters can have an effect on the machine rating.

7. **Maintenance aspects which affect design**

7.1. **Maintenance philosophy (preventive, corrective, condition based)**

Maintenance definition: all activities performed on equipment in order to maintain or restore its operational capabilities.

Maintenance has two major sub-classifications: corrective maintenance, which is performed after a failure and preventive maintenance, which is performed according to a predetermined criteria, to reduce the probability of failure.

Preventive maintenance can also be separated between periodic and conditional preventive maintenance.
Periodic preventive maintenance is performed after a defined amount of time, number of operations (opening, closure, starting, ...) ; some parts are systematically replaced without assessing their real condition.

Conditional preventive maintenance is initiated as a result of condition assessment and comparison with defined acceptance criteria. This type of preventive maintenance requires additional tasks to measure the degradation level. Although they are usually planned at regular intervals of time, these tasks are part of conditional maintenance.

7.2. **Spare parts philosophy**

A choice has to be made between repairing equipment and exchanging it.

Exchange has advantages : short unavailability, "as good as new" equipment, and not just repaired. But it requires higher levels of investment and should not be used in case of minor failures.

Exchange is also beneficial for major failures on equipment such as switchgear and electronic boards.

Spare parts require additional investment and the following issues must be considered :

- assessment of the parts and numbers to be kept in stock. The financial loss due to breakdown with no spare parts, the probability of such an event, its duration and the cost of spare parts have to be taken into account ;
- stock control, timely replenishment and identification of items which have not been used for a long time and which increase the total cost ;
- quality inspection to ensure that the spare parts are of consistent quality;
- Suitable storage conditions ensuring suitable preservation, sometimes for years. Special care must be taken for materials likely to deteriorate with age such as grease or polymers.

7.3. **Development of a document structure**

Judicious design of the auxiliary power system will result in a high availability of the Power Station and a low down time. But even good designs will not prevent failure of components which can result in down time of the auxiliary power system and Power Station. Quick access to the documentation to find information on the failed components type and supplier is essential to keep down times to a minimum.

Auxiliary power systems are complex. For a typical Power Station the documentation belonging to the auxiliary power system consists of a huge amount (several thousands) of drawings, datasheets, component information (type, supplier etc.) and other documents.

There are two aspects that need attention :

1. each document needs a unique code by which it can be identified and
2. each document needs a uniquely defined physical position in the archive.
During the design phase of the auxiliary power system the design of the document coding system needs special attention. The link between the physical equipment and the associated drawings, datasheets, type and supplier information can be made via the document code. A possible solution is to make the tag name of the physical equipment part of the document code. An example is the KKS coding system (In German: Kraftwerk Kenzeichnungs System. In English: Power Station Tagname System).

Such a coding system enables ready determination of which documentation to access, but not where it is physically located in the archive. Therefore, an archiving system must be designed that makes easy retrieval possible.

With the introduction of the computer and document management software and the increasing availability of documents in digital form the search for particular documents is simplified. Several software packages are currently available and a lot of effort is put in standardisation of product data. An example is STEP (Standard for the Exchange of Product model data).

7.4. Redundancies

Principle design criteria for plant redundancies are reliability and availability. However, an indirect benefit of such design may be improved maintenance access.

While maintenance is largely the responsibility of plant personnel, the auxiliaries systems designer can take certain steps to improve system reliability. For example, the scheme might permit some of the maintenance to be performed with the unit carrying load. This could be accomplished by providing spare capacity for certain loads or alternate feeds to the loads.

As an example, let us consider the two following schemes a) and b) (see Figure 5.):

In scheme a) we find:

- on one side a charger, the battery and the discharge bank;
- on the other side, a second charger and the circuit breakers to the different loads.

Theoretically, this scheme allows the maintenance of the battery, with the loads being supplied by the second charger. Practically there is a risk of disturbance on the DC bus as a result of a disturbance on the AC side (switch from one transformer to another for example). If this is unacceptable, scheme b) can be used.
In this scheme b), another battery and additional circuit breakers have been added. In this case, maintenance of one battery after the other is possible without any effect on the supplied loads.

The need for maintenance and the effect on the availability of the unit must be taken into account at the design stage.
7.5. Electrical safety considerations

a) Earthing and Isolation.
Means shall be provided to facilitate safe maintenance.
Examples shall be:

• removable links in the busbar to the auxiliary transformer
• fixed earthing switches on generator busbars
• isolating switch in series with the generator breaker for visible isolation.
• use of fixed equipment for earthing rather than flexible means like “wires”.
  Earthing switches generally exist on medium voltage switchboards but safety rules often require a specific earthing equipment close to the working area. In addition, there is no guarantee that flexible earthing equipment shall withstand the very high short-circuit current in case of accidental supply, ...

b) Sufficient room and space to access the equipment and to place tools and parts of the equipment when dismantled
The equipment should be located so that it is accessible for inspection, removal, dismantling, and repair. The work space should be well lighted, adequately ventilated, and safe for personnel.

c) Accessibility of maintenance areas and equipment
Examples are:

• accessibility of measuring points on generator busbars
• good accessibility to generator circuit breaker parts, ...

d) “Entrance to electrical rooms” philosophy
The electrical rooms are very important for unit operation and personnel security. Their access should be limited to qualified people, in the frame of their activity.

7.6. Optimisation of maintenance
It is preferable to base maintenance on supplier’s manuals for tasks and frequency. In addition, a complete inspection after one year of operation is generally recommended. Then, with the experience gained, tasks and frequency periodicity can be adapted according to the recorded failures or degradations to achieve optimum reliability.

Special systems like watch dogs or other special permanent monitoring systems can be used to allow the spacing in time of the maintenance periods.

As stated in 5.4.2, it can be economically beneficial to choose standardised products: the purchase price will decrease of course, but in addition, the number of spare parts, the number of procedures required for maintenance will be reduced. There will also be benefits for personnel training.
7.7. **Bibliography**

See References 3. and 4.
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