3. ELECTRICAL ENGINEERING DESIGN

3.1 GENERAL

The mechanical input and the electrical output data of the energy conversion and transformation system vary from one project to another. Low head projects lately were built more and more as bulb sets where the turbine and generator might be pled directly or through a speed increaser. Normally the hydromechanical conditions determine speed and capacity of the turbine and the designer of the electrical equipment takes this data to select the generator characteristics. The most favourable conditions for connecting the plant to the national grid are given by nearby existing lines or grid stations.

On the following pages are given indications for selecting characteristics of hydropower project components, specially used in low head installations. For electrical engineering design the following data is required as first input.

Turbine:	**Grid:**
- Speed	- Voltage (+ fluctuations)
- Inertial constant	
- Capacity (max.)	- Frequency
- Capacity (min.)	- Load, demand, load flow
- Energy (over time)	- Short circuit capacity
- Auxiliary requirement	- Protection
- Space	- Over Voltages
- Shaft height	- Special requirements (operational)
- Bearings	- Line configurations
- Axial forces	- Existing grid stations
- Radial forces	- Connection availability
- Centrelines	- Stability criteria
- Number of units	- Auxiliary power
- Prime energy	- Line requirements
	- Losses

3.2 GENERATOR

3.2.1 TYPES OF GENERATOR

There are two main types such as:

- Synchronous
- Asynchronous

3.2.1.1 SYNCHRONOUS GENERATOR

Any generator that can rotate only with the speed (rpm) defined by the network frequency and by the numbers of poles of the generator is called synchronous generator. They are:

- Need for reactive current generation
- Large size of generator
- Isolated operation

Synchronous generators need certain inertia for synchronising and stabilised operation. The inertia also determines the speed increase in case of a sudden load rejection.

The permissible speed increase that is expected nowadays is about 50% to 60%. For the electrical side this speed increase is acceptable as it is possible to maintain the voltage increase in permissible limits. It is very important to define if the generator shall be suitable to work for an isolated network or if it will be synchronised to a strong system.

To maintain the unit stable under no load conditions, a minimum inertia is required that can be calculated with a standing time constant of 2 to 30 sec. For isolated operation the calculation of the inertia should be based on a starting time constant 6 to 8 seconds.

3.2.1.2 ASYNCHRONOUS GENERATOR

The asynchronous generator receives its magnetising current from the connected network. Therefore it is not really capable to operate in an isolated system. The requirements exist for the regulation of speed. The advantages are simplicity and low price. A special synchronising is not required so the generator is suitable to be installed in remote controlled hydro power plants. The disadvantages of the asynchronous generator are the fact that it lowers the power factor of the whole system. This is not very significant in case of small capacities. Capacitor banks can compensate this. The generator is attractive to be used together with capacitors in full automatic hydro power plants without operation personnel. The generator got more and more importance in bulb turbine installation as its diameter can be kept smaller because a high inertia is not required.

The use of this type of generator may be permitted only in the case of extremely low powered stations. They are

- Small size of generators
- Automatic operation (without personnel)
- Need of inductive current
- No flywheel needed

3.2.2 NUMBER OF GENERATORS

The number of generators totally depends upon number of turbine units. If not determined, optimisation may be executed. With available prime energy and turbine size calculate yearly energy as function of number of units. Increase in investment (yearly) costs equal to decrease of production (yearly) for optimum installed capacity (number).

3.2.3 SIZE OF UNITS

Normally corresponds to the maximum plant output divided by number of units. For optimising determine energy not generated when reducing capacity of generator. Decrease of (yearly) installation cost equal to increase of (yearly) lost energy, when most favourable size is found.

3.2.4 VOLTAGE OF UNITS

Economic values are given in Figure: 3.1 to 3.3. For standardisation purposes a higher nominal voltage might be chosen.

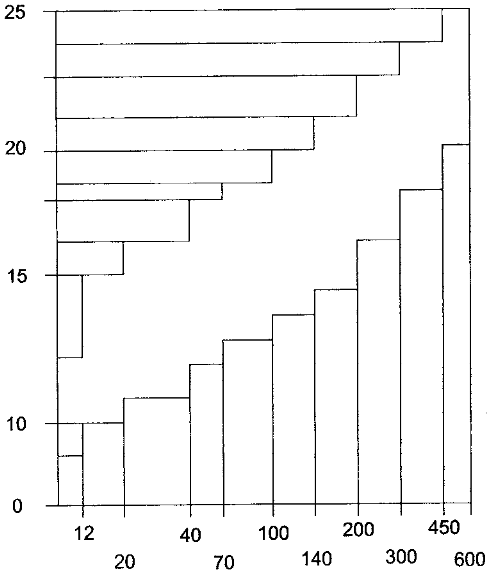


Figure 3-1 Voltage of Units

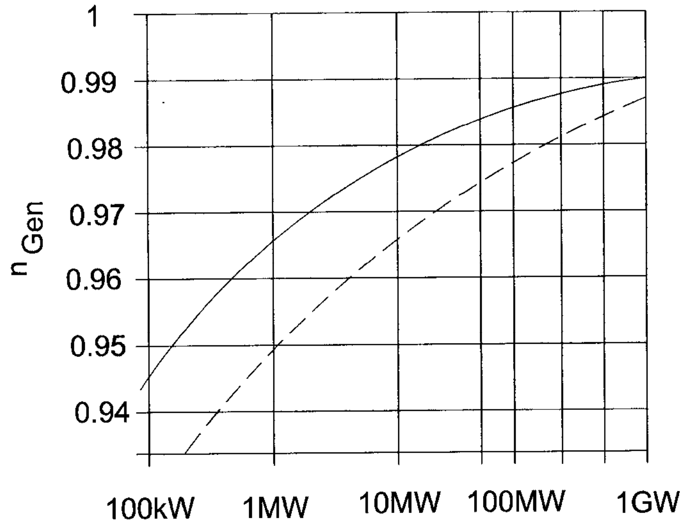


Figure 3-2 Voltage of Units

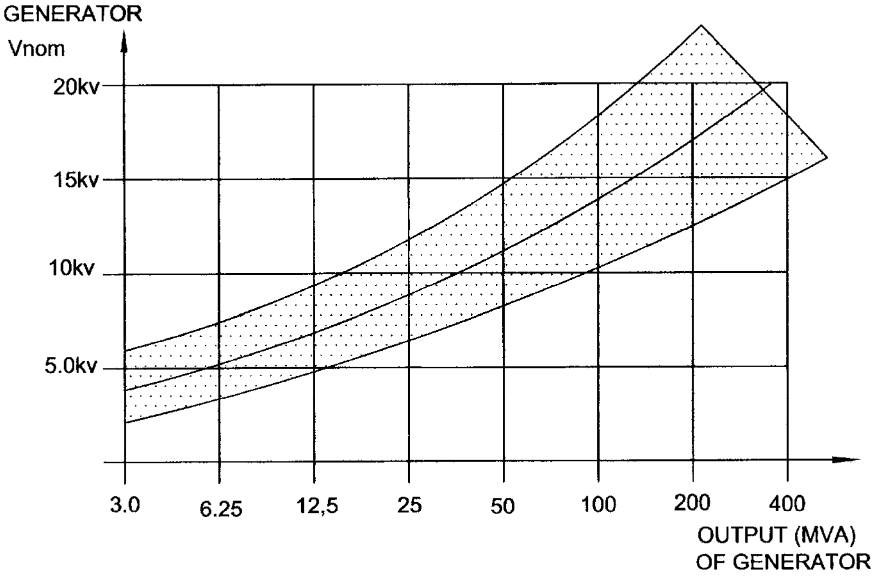


Figure 3-3 Voltage of Units

3.2.5 COUPLING OF TURBINE AND GENERATOR

There are two basic solutions generally available for load and torque transmission between turbine and generator such as:

- Direct coupling, which implies the use of a common shaft or coaxial shafts for both turbine and generator.
- Gear drive, which may be perpendicular drive (Bevel gear) or parallel drive (Spur or Pinion gear)

Bulb and vertical Kaplan type directly coupled, Pit and S-type with speed increaser, selection depends basically on turbine speed and size.

The requirement of speed increaser is felt especially in case of very low head and high power because it implies very low speed. Too low speeds (very low head) require too many poles, if coupled directly as can be seen from this table.

Because of production difficulties due to special gear-cutting technology, gear transmission is limited to 1:12 in one single stage. A disadvantage of gear is that efficiency goes down with increased ratio limits of transmission and hence loss of output. The efficiency of well built gear will reach 97-99%. If the ratio of gear transmission is higher than the limit value the gear ratio can be reduced such as:

- By increasing the number of poles of the generator
- By increasing the turbine speed either increasing number of turbine unit or turbine with higher specific speed.

The direct driven solution is always preferred, but only disadvantage relating to it is that high capacity unit must be supplied with generator having a large number of poles which are naturally more expansive.
Diameter would be too big compared with turbine runner diameter in bulb type turbine.

$$D_{\text{generator}} < 1.2\ D_{\text{turbine runner}}$$

3.2.6 SPEED OF GENERATOR

For reasons of cost, the generator speed shall be as high as possible. Pole section cannot be too small, so higher speed is required

Table 3-1: Possibilities of winding of generators in relation to nominal speeds.

N.Poles	Speed	Cote	N.Poles	Speed	Cote	N.Poles	Speed	Cote
6	1000	***	38	158	**	70	85.6	**
8	750	**	40	150	***	72	83.3	*
10	600	**	42	143	**	74	81	*
12	500	**	44	136	***	76	79	***
14	428	**	46	130	*	78	77	*
16	375	***	48	125	***	80	75	***
18	333	*	50	120	**	82	73.2	*
20	300	**	52	115	***	84	74.5	**
22	273	**	54	111	***	86	69.8	*
24	250	**	56	107	***	88	68.2	***
26	231	**	58	103	*	90	66.7	*
28	214	**	60	100	**	92	65.2	**
30	206	**	62	97	*	94	64	*
32	187	***	64	93.3	***	96	62.5	***
34	177	**	66	91	**	98	61.2	*
36	167	*	68	88.3	**	100	60	***

***	Good possibilities
**	Sufficient
*	Possibilities

3.2.7 INSULATION AND TEMPERATURE

With higher possible temperature costs for insulation (generator) will rise, losses in this case are relatively high. Recommended operation with one temperature class below.

Example:

Class F	155 C (built)
Operation with class B	130 C

Fibreglass, epoxy impregnated insulation for the stator winding shall be used.

3.2.8 COOLING

Possibilities: air or in special cases water: Recooling of air by:

a). Air to water heat exchangers
b). Using turbine-generator bulb housing for direct recooling.

$$\mathrm{Pv} = \frac{\mathrm{P}\,(1-\mathrm{n})}{n}$$

Pv = losses [kW]
P = nominal capacity of generator [kW]
n = efficiency [%]

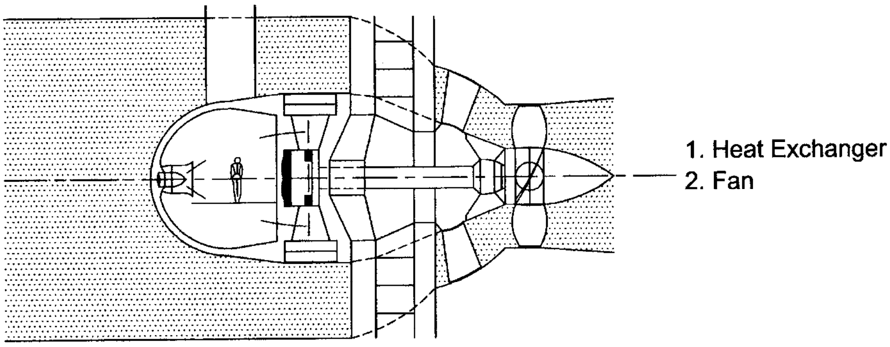


Figure 3-4 Cooling Possibility.

$Q = \sigma * \theta * A$
Q = heat flow [kW]
A = convection area
θ = temperature difference
σ = constant for heat conduction

With A = [/2] * D^2 the maximum installed capacity in a bulb housing and bulb surface cooling shall be

$$\mathrm{P} = \frac{\pi}{2}\ x\ \sigma\ x\ V\ x\ \theta\ x\ D^2\ x\ \frac{\mathrm{n}}{1-n}$$

P = generator capacity [kW]
D = bulb diameter [kW]

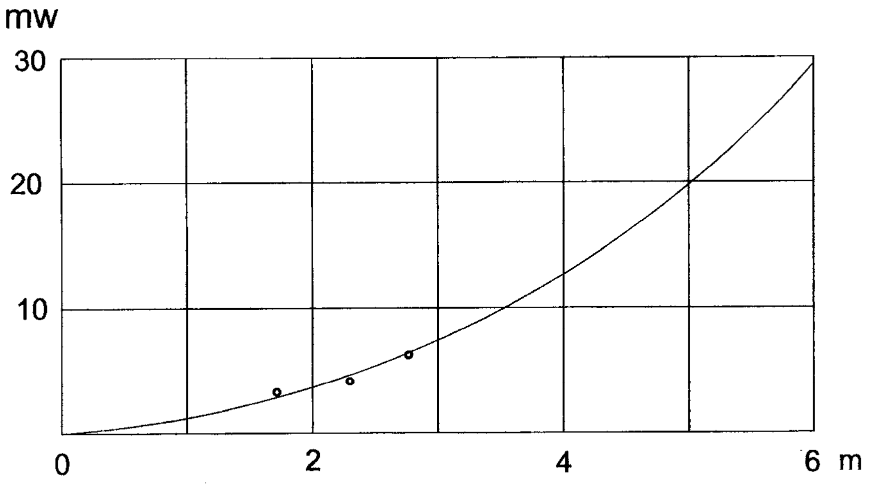


Figure 3-5 Experienced relation in installed units.

To guide the air to be recooled, one additional fan is needed to compensate pressure drops of airflow.

3.2.9 EFFICIENCY

Optimum efficiency of generators depends on sizes. Standard values shall be taken (see corresponding curve), as they are optimised for the generator layout.

3.2.10 DIMENSIONS

Diameter and length of the boring of the generator are given by:

$$P = C\ x\ D^2\ x\ L\ x\ N$$

[E. Mosonyi, Low Head Power Plants]

where:

P = apparent capacity of generator [kW]
C = constant of utilisation [between 4 to 5.5 kVA. min/m^3]
L = length [m]
D = diameter of rotor (boring) [m]
N = speed [rpm]

Relation between diameters and length as construction requirements and speed available.

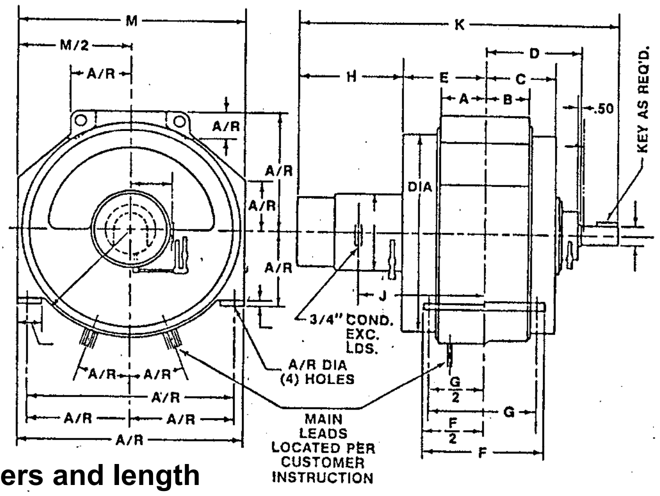


Figure 3-6 Relation between diameters and length

3.2.11 CONNECTIONS AND NEUTRAL

Normally in why (star), neutral floating for easy insulation failure detection. When local load with generator voltage distribution exceptional neutral grounding possible (use limiting device). Preferable insulation transformer between generator-bus and distribution system. Size as load requires, the neutral voltage transformer preferably shall be installed in the bulb itself.

3.2.12 BEARING REQUIREMENTS

If needed axial and radial forces shall be specified. Normally the turbine or the speed increaser takes these loads with their bearings. Selection of construction type and support of bearing as required by layout. Normally open construction to prevent external airflow.

3.2.13 OVERLOAD REQUIREMENTS

It is expected that each generator is capable of an overload of 5% without exceeding the maximum allowed temperature under specified operating conditions. This overload shall be continuous and might reduce lifetime of the insulation when applied during more than 10% of operating duration.

3.2.14 GENERATOR CONNECTIONS

Basically there are two different ways of connections between generators and step-up transformer (or common generator bus).

- Bus duct for high capacities
- Cables (middle voltage) for smaller currents

Additional advantages of the bus duct are

- Reliability
- Higher capacity
- Better protection
- Easier repair

Advantages of cable connections

- Less space needed
- Lower costs
- More flexible

In many occasions bulb constructions for turbine-generator units have not much space available for bus ducts, so many installations of low head plants show cable connections. Investment costs are significantly lower than in case of bus ducts. An adequate mechanical protection of the cable runs is essential.

3.2.15 EXCITATION

Systems frequently used are

3.2.15.1 EXCITER

- Transformer-rectifier-collector-field
- Auxiliary generator-commutator-collector-field
- Auxiliary generator-rotating diodes-field

3.2.15.2 TYPES OF VOLTAGE REGULATOR (CONTROLLER)

- Mechanical variation of resistance (Tinill)

- Magnetic amplifier
- Electric amplifier

The most used combinations now-a-days are brushless (rotating diodes) system or excitation transformer-controlled rectifier bridge arrangements, normally combined with an electronic voltage controller. Characteristic items:

3.2.15.3 BRUSHLESS

Reduced maintenance, relatively slow response, low stability

3.2.15.4 TRANSFORMER

Disadvantage of brushless and carbon dust, fast response, better stability for low head hydro generators.

3.2.15.5 DC-VOLTAGE

This is a flexible parameter, which can be adjusted to generators. For de-excitation reverse polarity possible.

3.2.15.6 TRANSFORMERS

Shall be specified by supplier of excitation system, preferred dry type, connected directly to the generator lead.

3.2.15.7 TIME CONSTANT

The no load time constant decides about the dynamic behaviour of the generator. It depends on the number of poles and the size of the generator.

The time constant for the field winding can be kept low, but requirements for exciter energy will be higher.

T field = 0.02 / 0.6 sec

Time constant for loading

$$\mathrm{Ti} = T'_{do}\ x\ \frac{(\mathrm{Xe} + \mathrm{Xd}')}{(Xe + Xd)}$$

where

Xe = reactance of load
Xd' = transient reactance of generator
Xd = synchron reactance of generator
T'do: = No load time constant of synchrogenerators, in relation of generator capacity Pg for different nominal speeds "N".

CURVE	1	2	3	4	5	6
N [RPM]	3000	1000	750	600	500	375
CURVE		7	8	9	10	11
N [RPM]		300	200	150	100	62.5

.

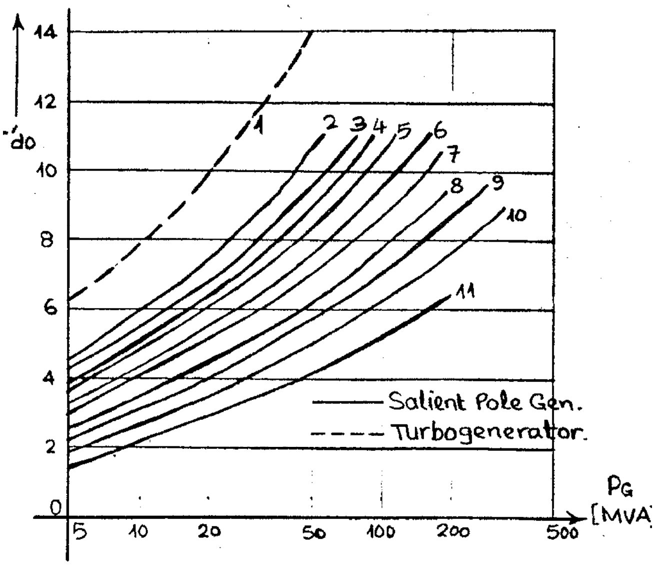


Figure 3-7 Load Time constant in relation with Generator Capacity.

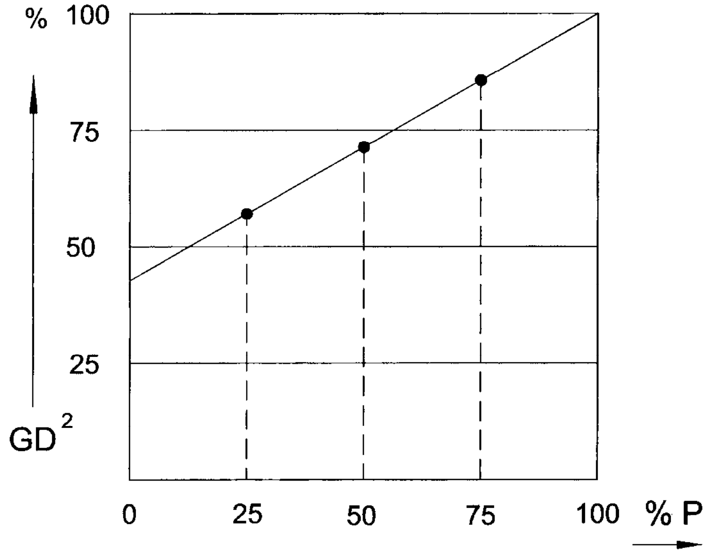
3.2.16 FLYWHEEL REQUIREMENTS

For stable operation a minimum flywheel effect is necessary for bulb type units.

$$GD^2 = \frac{P}{N^2}\left[\frac{253 \text{ x Q}}{(D x H + 404}\right] \qquad [tm^2]$$

Where

P = turbine capacity full load [Hp]
N = turbine speed [rpm]
Q = water flow through turbine with full load $[m^3/s]$
H = head [m]
D = diameter of turbine runner [m]



GD^2 can be reduced as indicated with reduced load to be expected on the generating unit

Figure 3-8 Flywheel requirements

Turbine and speed increaser normally do not contribute significantly to raise GD^2 of whole arrangement.

Generator GD^2 has to be taken from information of manufacturer.

3.2.17 COST

For different sizes, but constant speeds and efficiencies, normal GD^2, 200% runaway speed and same nominal voltage and power factor the relation is given by the following equation:

$$\frac{K_1}{K_2}=\left[\frac{P_1}{P}\right]^{07}$$

Reference point for P	= 10 MVA, 750 RPM
Cost (10 MVA)	= 680,000 - US$ (1.1989)

Without:

- Excitation
- Installation
- Transport
- Taxes

3.2.18 EFFICIENCY

Average efficiencies for synchronous generators are expected to be as follows:

1.0	MW	94.4%
2.0	MW	95.0%
5.0	MW	95.8%
10.0	MW	96.4%
15.0	MW	96.7%
20.0	MW	96.9%

$$M = 94.42\ P^{0.008}$$

The efficiency of energy conversion in a synchronous generator depends on the volume of material involved in the construction of the unit. High weights of steel and copper result in a high efficiency. The limits for investment costs determine the economical optimum efficiency. The average values of such and efficiency are shown below for different sizes of built generators.

3.2.19 GENERATOR-TRANSFORMER PROTECTION (SEE ALSO FIG 2.1.18, SEE PAGE 32)

The indicated protection and instrumentation is normally considered as sufficient. In small units the differential protection is not very frequent, because of the relatively high costs. (Limits about 8 to 10 MVA).

The excitation system lately is preferred to be static and the voltage controller electronic type. This system includes all possibilities of protection, that is not necessary to be installed additionally. An out of step protection device is recommended, because of possible stability problems of low head power plants. Protection scheme is shown in the attached figure.

3.2.20 GENERATOR FIRE PROTECTION

Besides the electrical protection of the generators a device for extinguishing fire shall be required. The most frequent reasons for fire in generators are

- winding short circuit
- bearing problems
- heater problems

Normally several unfavourable events get together. The development of fire is favoured by the circulating cooling ATR.

Fire protection of the generator is an essential feature of generator design. Dust, soot, moisture and mortar particles falling from the machine room ceiling will, as already mentioned, attack the stator insulation of the generator and may cause short circuits. The latter may result in an insulation being fully burnt out, because the strong cooling-air draft will readily extend the fire from the burning spot and feed it with fresh air. Various methods are used for generator fire protection. The use of carbon dioxide is generally accepted. By the installation of remote-controlled electric thermometers and contractors the carbon dioxide cylinders may be opened automatically in the case of fire danger. Since a saturation of machine room and its surrounding atmosphere by carbon dioxide may be harmful for the personnel, carbon dioxide extinguishing equipment should be used in closed-circulation air-cooling systems only.

A necessary condition for efficient fire protection is a quick shutoff of the cooling-air flow. The control of automatic extinguishing equipment must, therefore, simultaneously operate the shutoff control of throttles or other equipment in the air ducts. Air duct shutoff devices must have efficient sealing. It is self evident that in case of fire the generator must be automatically switched off by the bus bars and at the same time de-excited simultaneously with the operation of fire-extinguishing equipment.

In case of minor generator units built without circulation type air-cooling system, powder type fire extinguishers are generally used. Higher-powered generators of recent design are, as a rule, cooled by closed air circulation systems; in this case -- according to the specifications of the Hungarian Electrical Research Commission -- with generators of 10 MVA power and more it is advisable, and above 25 MVA power it is absolutely indispensable, to equip them with carbon dioxide fire-extinguishing devices.

Experiments carried out in the Soviet Union are aimed at using pulverised water as well as water jets for extinguishing purposes. In Germany a special gas named "Ceagol" has been developed.
The most frequently used and easy to handle system is based on carbon dioxide, one or more batteries of carbon dioxides.

3.2.21 BULB GENERATOR DESIGN

3.2.21.1 CONSTRUCTION

The bulb diameter must not be more than 20% larger than the runner diameter, on the other hand the minimum bulb diameter seems to be limited to 20% less than runner diameter for reasons of electrical design.

Thus, the inside stator-diameter may only range between 50 percent and 75 percent of the diameter of the corresponding conventional set, for a head in the region of 6-10 m. The generator output, in terms of construction, can be given by the formula:

$$P = C_{oyn} \cdot n \cdot l_i \cdot D_i^2$$

$$C_{oyn} = \left(\frac{\pi^2}{\sqrt{2}} \right) * \zeta_n * A * B_{1\max}$$

Where:

C_{oyn} = Electric compactness factor [kVA/m^3 REV/MIN]
n = Rotating speed [rpm]
l_i = Stator length [m]
D_i = Inside stator diameter [m]
ξ_n = Winding factor
A = Current of periphery [A/Cm]
B_{1max} = No load induction in air gap [Tesla]

To determine the value for C_{oyn} some typical data are mentioned in Table: 3-2

Table 3-2 Comparison of flux and current densities

	Conventional Generator	Bulb Generator
A	0.7 T	0.9 T
B	500 A/cm	650-700 A/cm

with these densities some examples of built units exist in France. It should be taken into consideration, that special cooling of the generator has to be applied.

Many studies and model tests were carried out and several experimental sets were installed by EDF in the centre of France and ultimately at St-Malo. Within eight years this resulted in a 10 MW bulb unit for the Rance tidal power project, with the generator operating under absolute air pressure equal to 2 x 10^5 N/m^2. Progress from the St-Malo experimental set to the Rance machine, and later to the Beaucaire unit, can be seen from Table II. At this point, all the engineering problems had been identified and solved, and there were no further obstacles to impede development of the runner size and design capacity.

The values shown in Table 3-3 should be considered as extremely high for conventional generators to be used in Pakistani projects.

Table 3-3 Progress in bulb unit development

	C_{syn}
Conventional Kaplan	5.20
Bulb-St-Malo	5.36
Bulb-La Rancw	7.65
Bulb-Beaucaire	9

For conservative designs a value for C_{syn} = 4

$C_{syn} < 4.0$ kVA/m^3 REV/min

should not be exceeded. Other statistical information is given below:

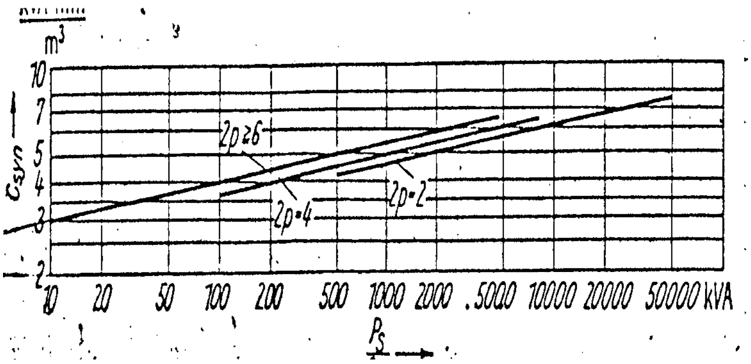


Figure 3-9 Statistical Information on generator construction

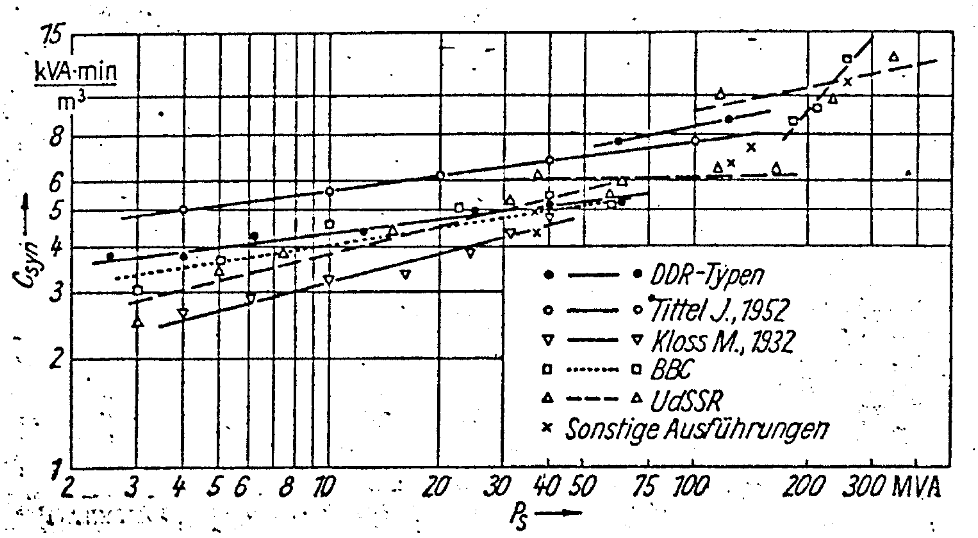


Figure 3-10 Pole Synchron Generator, C_{syn}

For the construction the following arrangement will be taken into consideration:

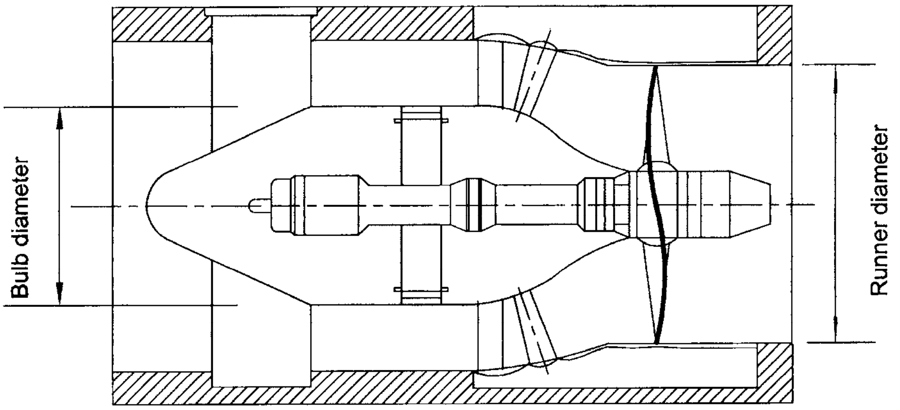


Figure 3-11 Bulb/Runner Diameters

3.2.21.2 DIMENSIONS

The periphery of the boring of the generator is divided by the number of poles p

$$\mathrm{Tp} = \frac{\mathrm{D_i} \ \mathrm{x} \ \pi}{P}$$

The relation between li and tp can be optimised (postnikon, J. M. Selection of optimal dimensions of electrical machines). The used value varies between 0.8 and 4.5. Frequently used constant shall be 3.0.

From the equations

$$\mathrm{P} = C_{syn} . n . l_i . D_i^2$$

and

$li = 3 * tp$
$= 3 * Di \ / p$

The inner diameter Di shall be

$$\mathrm{D_i} = 3 \sqrt{P \frac{P}{C_{syn} * n * \pi * 3}}$$

and the stator length

$li = (3\pi / p) * Di$

The air gap between rotor and stator shall be approximately (in the middle of the pose)

$S_O = \ . tp . A / B_{i \ max}$

where ✟ = 0.45 for salient poles machine

✟ = 0.25 for synchron 2 poles machine
$[10^{-4} . Vs . cm / (m^2 . \_)$

For the dimensions of the outer generator diameter is considered a relation of

{dour} / Di = 1.2 / 1.4

Depending on the structure of the stator housing.

3.2.21.3 GENERATOR WEIGHT

The generator weight is basically composed by:

- Stator
- Poses of excitation
- Mass for inertia
- Shaft
- Other

The corresponding data's shall be used for the layout of the generator turbine bearings, flywheel effect and cost figures. For lifting purposes the powerhouse crane specification shall take into consideration the weight of the rotor, with poles or without poles.

An approximate formula allows an estimate as follows:

$$W = \left(\frac{n}{400}\right)^{-.04} x \left(\frac{\mathrm{P_{mva}}}{27.5}\right)^{0.8} x\,K$$

Where

K = 80 for Rotor
K = 45 for Stator
K = 146 for total

These are statistical values and useful for rough estimates. For detailed calculation the following considerations.

3.2.21.3.1 STATOR:

The basic dimensions are given with

Li = length of stator [m]
Di = inside diameter [m]

The volume can be determined:

$$V = (Di + Hs) \,.\, \pi \,.\, Hs \,.\, li$$

Where

Hs = height of the stator yoke.

This is approximately close to half pole width plus - the depth of the slots for the stator coils.

H . Width = π . Di / 4.P

The slot depth depends on the electrical characteristics of the generator.

It can be assumed with almost the same length as the half pole width (for estimate only). So the volume of the stator shall be

$$V = \mathrm{l_i}\left(\mathrm{D_i} + 2\pi\pi\frac{\mathrm{D_i}}{4\mathrm{P}}\right)\pi.2\pi.\frac{\mathrm{D}}{4\mathrm{P}}$$

$$= \mathrm{l_i}\,.D^2\left(4 + \frac{2\pi}{4\mathrm{P}}\right)\pi^2\,\frac{2}{4\mathrm{P}}$$

$$V_{St} = \mathrm{l_i}\,(\pi\ D_i)^2\left(1 + \frac{\pi}{2\mathrm{P}}\right).\ \frac{1}{2\mathrm{P}} \qquad (Appr.\ 1)$$

This volume shall be filled with steel and copper. To get the weight it shall be multiplied by the specific weight.

= 7.88 (for copper 8.92)

Including the insulation portion, an average over all the material can be used with 7.88. For the head connections of the coils an additional portion must be added to this weight. For short stators this influence is very significant, for long stators less important.

An estimate allows the following numbers:

The length of each connection is Appr.3

$$Lh \approx \sqrt{2} \cdot \frac{\pi \mathrm{D_i}}{2\mathrm{P}}$$

The number W and size of connections are depending on the number of slots. It is assumed that two layers are normally used. The size of each of the two layers is

$$A_{cn} \approx \frac{\mathrm{D_i}\, \pi}{2\mathrm{W}} \cdot \frac{\pi D_i}{4P}$$

The total copper volume in head connection shall be Appr.

$$\begin{aligned} V_{cn} &= 2 \cdot A_{cn} \cdot Lh \cdot W \\ &= 2 \cdot \frac{\mathrm{D_i}\, \pi}{2\mathrm{W}} \cdot \frac{\pi D_i}{4P} \cdot \frac{\sqrt{2} \cdot \pi \cdot D_i}{2P} \cdot W \\ V_{cn} &= \frac{\mathrm{D_i^3}\, \pi^3 \sqrt{2}}{8\mathrm{P}^2} \end{aligned}$$

And the weight shall be V_{cn} . Pac . A reduction of 10% for insulation shall be introduced. The total weight of the stator results in

Wst = Vst . 7.88 + Vcn . 8.92 . 0.9

3.2.21.3.2 POLES OF EXCITATION

The weight of each pole depends on its dimensions, of the steel and the copper portion.

Vp (Steel) = li . Ap

The area of the pole depends on the size and was partially mentioned under point 1. The other dimensions can be taken from figure: 3-12 mentioned below.

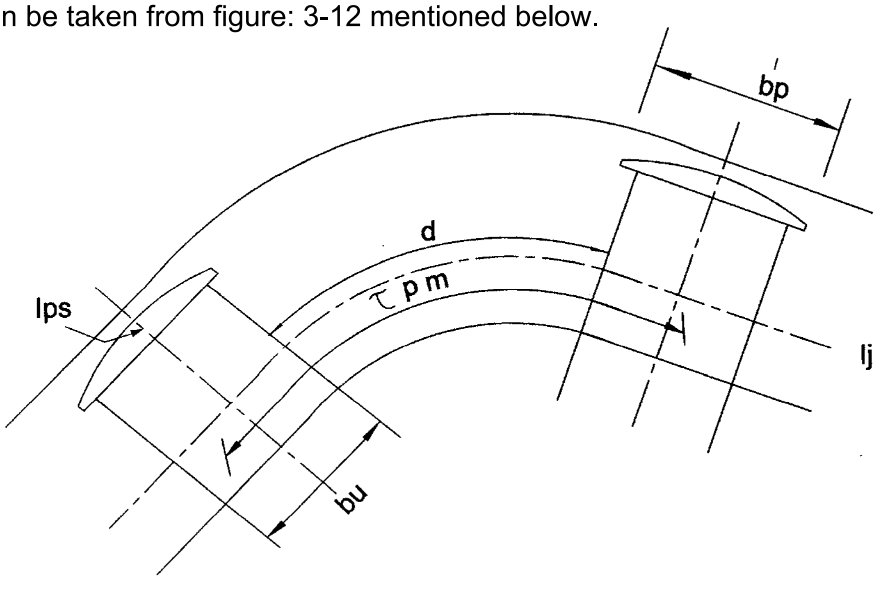


Figure 3-12

$$T_{Pm} = \frac{\mathrm{D_i}\ \pi}{\mathrm{P}}$$

$$bk \approx \frac{\pi\ D_i}{2\mathrm{P}}\ .\ 0.95$$

$$lj \approx 2\ .\ \frac{bk}{2}$$

$$bp \approx 2\ .\ bk$$

$$lps \approx \frac{1}{4}\ .\ bp$$

The area Ap is

$$Ap = lj\ .\ bk + \frac{lps}{3}$$

$$Ap = \left[\frac{0.95.\pi\ .D_i}{2P}\right]^3 + \frac{1}{3}\left[\frac{0.95.\pi\ .D_i}{2P}\right]^2$$

$$= \left[\frac{0.95.\pi\ .D_i}{2P}\right]^2\ .\ 1.35$$

The steel volume of each pole is then

$$Vp = (steel) = l_i\left[\frac{0.95.\pi\ .D_i}{2P}\right]^2\ .\ 1.35$$

The volume of copper is given approximately by the length, width and height of each pole.

V_{cn} ly . bk . o.h . lw

Where the length lw of An average winding is Appr.

$$l_W = 2.\ l_i + 2.bk + \pi\ .\frac{bk}{4}.2$$

$$= 2.\ l_i + 2x\frac{0.95\ .\ \pi\ .\ D_i}{2P} + \frac{\pi}{4}x\frac{\pi\ .\ D_i}{2P}\ x\ 0.95\ x\ 2$$

And

$$C_{cn} = \left[\frac{0.95\ .\ \pi\ .\ D_i}{2P}\right]^2 x\ 0.4\left[l_i + \frac{\pi\ D_i}{2P} + \frac{\pi^2}{2}\ .\ \frac{D_i}{2P}\right] x\ 2$$

$$= \left[\frac{0.95\ .\ \pi\ .\ D_i}{2P}\right]^2 x\left[l_i + \frac{\pi\ D_i\ 0.95}{2P} + \frac{\pi}{2}\ .\ \frac{\pi\ D_i\ \ 0.95}{2P}\right] x\ 0.8$$

The approximate weight of one pole shall be:

$$W_{pole} = V_p\ (steel)\ x\ 7.88 + V_{cn}\ x\ 8.92$$

3.2.21.3.3 MASS FOR INERTIA

The approximate diameter for the pole supporting ring shall be:

$$D_S = Di - 2\,(lj + lps + 8\delta\ )$$
$$= Di - (bk + \tfrac{1}{2}\,bk + \delta)$$

Where: δ is the

$\delta = 45\ .\ t_{pm}\ .\ A/B_{5\ max}$
A 300 ÷ 650 Amp/cm
$B_{5\ max}$ 1.0 ÷ 1.3 Tes/a

Other Dia:

$$D_s\ = D_i - 3\ .\ \frac{\pi\ D_i}{2P}\ x\ 0.95 - 0.9\ \frac{D_i\,\pi}{P}\ x\ \frac{A}{b_{5\ \max}}$$

$$D_s\ \approx D_i - 3\ .\ \frac{\pi\ D_i}{2P}\left(2.85 + 1.8\ x\ \frac{A}{b_{5\ \max}}\right)$$

The inertia constant for the pole mass shall be:

$$GD^2_{(poles)}\ = (D_i\ x\ 0.95)^2\ .\ W_{poles}\ .\ P\ .\ \frac{1}{981}$$

To reach higher values required by the control system. The pole supporting ring shall contribute with:

GD^2 (Ring) = Dm^2 . Wr / 9.81

Where the weight of the ring shall be

$W_r = D_m\ .\ A_r\ .\ 7.88$ A_r = Area of ring cut

GD^2 (Ring) = Dm^3 . A_r . 7.88 / 9.81

3.2.21.3.4 SHAFT

With the shaft diameter D_{sh}. The contribution for the total inertia constant shall be small and can be given by:

$$GD^2_{(shaft)}\ = \frac{\pi}{8}\ .\ D^4{}_{sh}\ .\ l\ .\ \frac{7.88}{9.81}$$

E. Mosonyi is giving a formula as given below from the soviet electrosila works, which makes it possible to get the weight of a vertical shaft hydrogenerator:

DIMENSIONS AND WEIGHTS

Table 3-4 contains several characteristic data of hydroelectric power stations already in operation, such as the main dimensions and other parameters of vertical-shaft hydrogenerators, etc.

The weight of a high-powered vertical-shaft hydrogenerator may be calculated by the following empirical approximate formula of the Soviet Elektrosila works (Leningrad):

$$G = k \sqrt{\frac{N_N}{n}} - 85 \qquad [tons]$$

Where n denotes speed in rpm and N_N gives the apparent generator power in (KVA) kilovolt-amperes, the coefficient k having a value between 25 and 32 according to the design and construction of the generator. According to E. Mosonyi's opinion, for high-capacity low-speed machines the coefficient k may be smaller, with up-to-date generators not more than about 20. The weights of extremely low-speed machines, however, by higher values are covered.

P.C. Nag and K. Madhavan developed a graphic relation for the diameter and weight of the generator as a function of its apparent power and speed, which applies to vertical-shaft hydrogenerators using three guide bearings. This relation has been obtained by the analysis of detailed data on hydroelectric power stations already in operation.

Table 3-4: Particulars of some low-speed vertical-shaft hydro generators

Power station, river, country	Power [kVA]	Voltage [V]	Speed [rpm]	Frequency [cps]	Number of pole pairs	Runner diameter [m]	Diameter of generator [m]	Flywheel effect [tm^2]	Weight		Peripheral velocity [m/sec]	Load on thrust bear
									of the runner [t]	Total [t]		
Wynau II, Aare, Switzerland	2,200	9,500	107.1	50	28	--	--	300	--	66	--	--
Tiszalok, Tisza, Hungary	4,800	5,250	75	50	40	6.0	7.5	1,500	70	110	23.5	
Eglisau, Rhine, Switzerland	5,150	8,500	83.3	50	36	6.5	8.0	1,400	--	123	28.5	
Olten-Gosgen, Aare, Switzerland	7,000	8,000	83.3	50	36	--	--	1,150	--	150	--	
Chancy-Pougny, Rhone, Switzerland/France	7,000	11,000	83.3	50	36	6.9	9.0	2,700	--	--	30.0	
Kachlet, Danube, Germany	8,500	6,300	75	50	40	7.6	9.2	2,800	110	237	29.8	
Vargon, Gota-Alv, Sweden	12,000	11,000	46.9	50	64	--	--	--	--	--	--	
Owen Falls, Victoria Nile, Uganda	16,700	11,000	150	50	20	5.9	7.8	585	130	--	46.4	
Rupperswil-Auenstein, Aare, Switzerland	22,000	5,700	100	50	30	7.7	9.0	6,200	183	243	40.4	
Oerlikon Engineering Company Brown, Boveri and Co. Ltd.	25,000	11,000	100	16	10	7.0	9.0	6,670	225	377	36.7	
Birsfelden, Rhine, Switzerland	26,000	6,600	68.2	50	44	11.25	14.0	20,000	250	395	40.0	
Kama, Kamam USSR	26,300	10,500	125	50	22	6.5	--	3,700	--	265	42.6	
Verbois, Rhone, Switzerland	27,500	18,000	136.4	50	22	6.0	7.6	3,100	145	300	42.8	
Simbach-Braunau, Inn, Germany/Austria	32,000	10,500	83.3	50	36	8.3	--	8,000	160	270	36.2	
Ryburg-Schworstadt, Rhine, Switzerland	32,500	10,500	75	50	40	9.4	11.0	12,500	260	--	36.9	
Ybbs-Persenbeug, Danube, Austria	45,000	10,300	68.2	50	44	10.0	--	16,800	265	405	35.7	
Andre Blondel, Rhone, France	50,000	10,500	107	50	28	8.4	10.3	15,000	--	--	47.0	
Kuibyshev, Volga, USSR	123,500	13,800	68.2	50	44	14.3	17.4	121,000	874	1650	51.0	

For vertical shaft generators are given some statistical data about weight and diameter. It is understood that these are identical with the inner diameter Di and the Total weight of the unit.

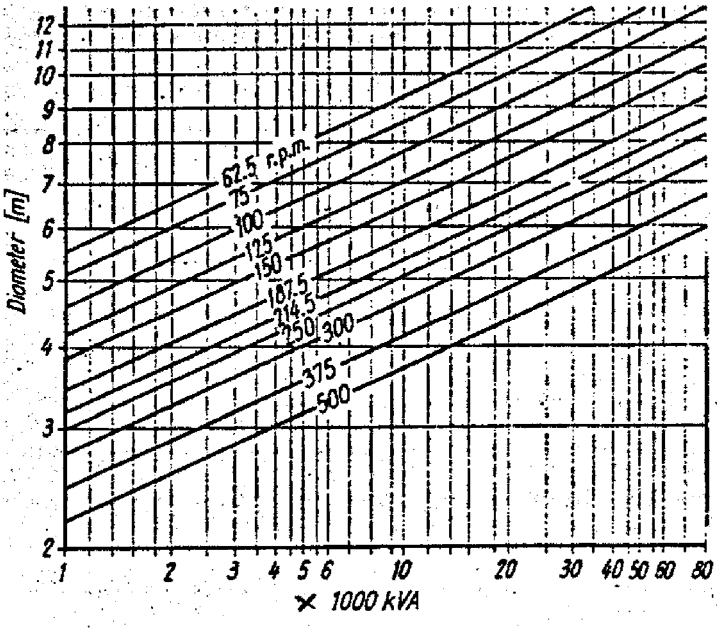


Figure 3-13 Generator Diameter and Output Relationship.

$$D = 37.3 \; x \; \frac{P^{0.234}}{n^{0.457}}$$

Where

P = Power [MVA]
n = Rotating span [rpm]
Di = D/1.3

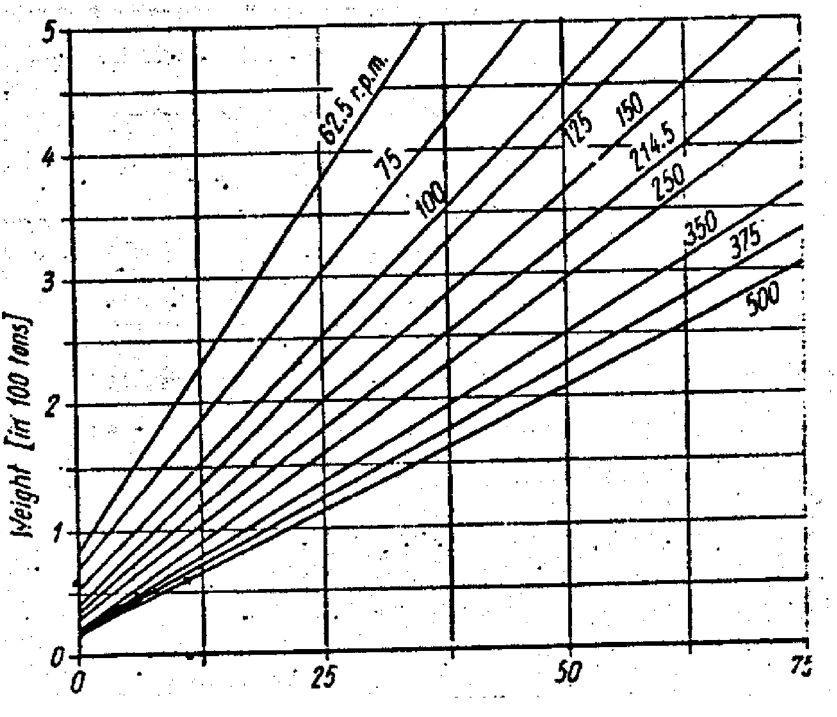


Figure 3-14 Generator Weight and Output Relationship.

Table 3-5: Weight and GD^2 and data of generators after H. Forster

Arrangement	Speed rpm	1,000 kVA 6,000V		3,200 kVA 6,000V		6,400 kVA 6,000V		12,500 kVA 10,000V		25,000 kVA 10,000V	
		GD^2 Tm^2	Weight t	GD^2 Tm^2	Weight t	GD^2 Tm^2	Weight t	GD^2 Tm^2	Weight t	GD^2 Tm^2	Weight t
Horizontal Shaft Type	1000	1	10	3	21	--	--	--	--	--	--
	500	3	14	12	30	35	50	100	80	200	40
	250	13	20	50	45	150	75	250	120	700	200
	125	65	32	220	70	600	110	1000	180	2500	290
	94	130	47	450	95	850	155	2500	250	6000	400
Vertical Shaft Type	1000	1	9	3	19	--	--	--	--	--	--
	500	3	12	12	27	33	45	100	75	200	130
	250	13	17	50	40	150	65	250	110	700	180
	125	65	27	220	60	600	100	1000	160	2500	260
	94	130	35	450	75	850	130	2500	210	6000	350

Some information may be drawn from the particulars given by H. Forster and published in Table II/64. The weight of the revolving part in a vertical-shaft generator (including appropriate section of main shaft) will amount to 50-55 percent of total generator weight.

3.2.21.3.5 INERTIA CONSTANT CALCULATIONS

For calculating inertia constant following procedure may be adopted.

The formula for inertia is

$$J = \frac{G.D^2}{4}$$

Where

J = Moment of Inertia (kg. m^2)
G = Total mass (kg)
D = Diameter of rotor (m)

The other formulae used are

$$D_i = \left(P . \frac{P}{C_{syn} \ x \ n \ x \ 3 \ x \ \pi} \right)^{1/3}$$

$$L_i = \frac{3 \text{ x } D_i \text{ x } \pi}{P}$$

Where

Di = Inside stator diameter (m)
Li = Stator length (m)
P = Power (kVA)
p = Number of poles
n = Rotating speed (rpm)
Csym = Electric compactness factor (kVa/m^3 - rpm)
= (Normally taken as 4)

In the formula

$$J = \frac{G.D^2}{4}$$

D-has been taken as the outside diameter of rotor, which is approximately equal to the inside diameter of stator. Because there are only few centimetres between these two, so we use this value

Where

$$D \cong D_i$$

The formula for calculating weight of generator is

$$G = 146.4 \; x \left(\frac{n}{400}\right)^{-0.4} x \left(\frac{P}{37.5}\right)^{0.8}$$

(Based on statistical data)

Where

P = Power (MVA)
n = Rotating speed (rpm)

Some other useful formulae are

Formula No.1

$$M = \frac{P}{w} \, x \; Nm$$

Where

$$w = \frac{2.\pi .n}{60}$$

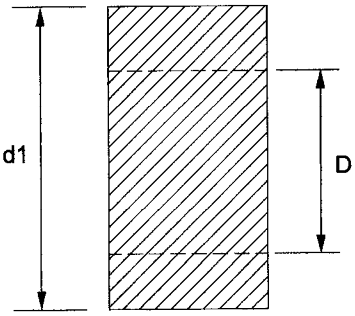
$$n = \frac{120 \text{ f}}{P} \qquad [rpm]$$

Formula No.2

$$J = \frac{1}{8} m d_1^2 = \frac{G.D^2}{4}$$

Where

$$D = 0.707 \; x \; d_1$$



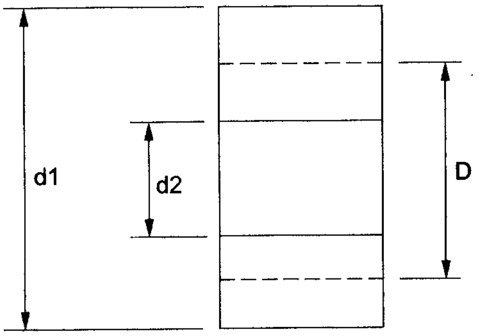


Figure 3-15

$$D = \frac{\sqrt{d_1^2 + d_2^2}}{2}$$

Formula No.3 (In case the speed increaser is used)

$$J_2^2 = J_1^{\,2} \left(\frac{W_1}{W_2} \right)^2$$

$$GD_2^{\,2} = GD_1^{\,2} \left(\frac{n_1}{n_2} \right)^2$$

EXAMPLE

For calculating the weight of the generator to be used at C-J link, following is the data & calculations

STATOR

H = 0.5 m
W = 1.2 m
P = 12.2 Mw
N = 150 RPM
p = 40
p.f = 0.8

ROTOR

H = 0.2 m
W = 0.5 m

Specific weight of Fe = 7.8 Ton/m^3

$$D_i = \left(P . \frac{p}{C_{syn} \ x \ n \ x \ 3 \ x \ \pi} \right)^{1/3}$$

$$= \left(12.2 \ x \ \frac{40 \ x \ 100}{4 \ x \ 150 \ x \ 3 \ x \ 0.8 \ x \ \pi} \right)^{1/3}$$

= 4.76 m

$$L_i = \frac{3 \text{ x } D_i \text{ x } \pi}{p}$$

$$= \frac{3 \text{ x } 4.76 \text{ x } \pi}{40}$$

= 1.12 m

Now

Volume of stator = 2 * π * r * W * H
= 2 * π * 2.38 * 0.5 * 1.2
= 8.97 m^3

Weight of stator = 8.97 * 7.8
= 69.98 Ton
Weight of rotor = 27.99 Ton (40 % of stator's weight)
Weight of Poles = (0.2 * 0.5 * 1.12) * 7.8 * 40
= 34.98 Ton
Total Weight = Weight of stator + rotor + poles
= 69.98 + 27.99 + 34.98
= 132.95 Ton

$$J = \frac{G.D^2}{4}$$

= (132.95 * 4.76 * 4.76) / 4
= 753 Ton – m^2

STATOR

L = 1.12

ROTOR

L = 1.12

$H = 0.375$ $H = 0.3$
$w = 0.35$

$Di = 4.76$ m
$Li = 1.12$ m

Volume of stator = $2\pi r * H * L$
= $2\pi * 4.76/2 * 1.12 * 0.375$
= 6.28 m^3
Weight of stator = $6.28 \text{ m}^3 * 7.8 \text{ Ton/m}^3$
= 48.98 Ton
Weight of poles = $(0.3 * 0.35 * 1.12) * 7.8 * 40$
= 36.69
20 % less = 7.34
Weight of poles = 29.35
Weight of rotor = 44.12 (73.47 - 29.35)
Total weight (1 + 2 + 3) = 48.98 + 29.35 + 44.12
= 122.45 Ton

$$J = \frac{G.D^2}{4}$$

$$= \frac{122.45 * (4.76)^2}{4}$$

$$= 694 \text{ Ton} - \text{m}^2$$

3.2.21.3.6 CALCULATIONS FOR GENERATOR COST:

For the calculation of generator's cost the graph shown in Figure: 3-16 and Figure 3-18 is used. Various curves are plotted in this graph for different speeds having various capacities.

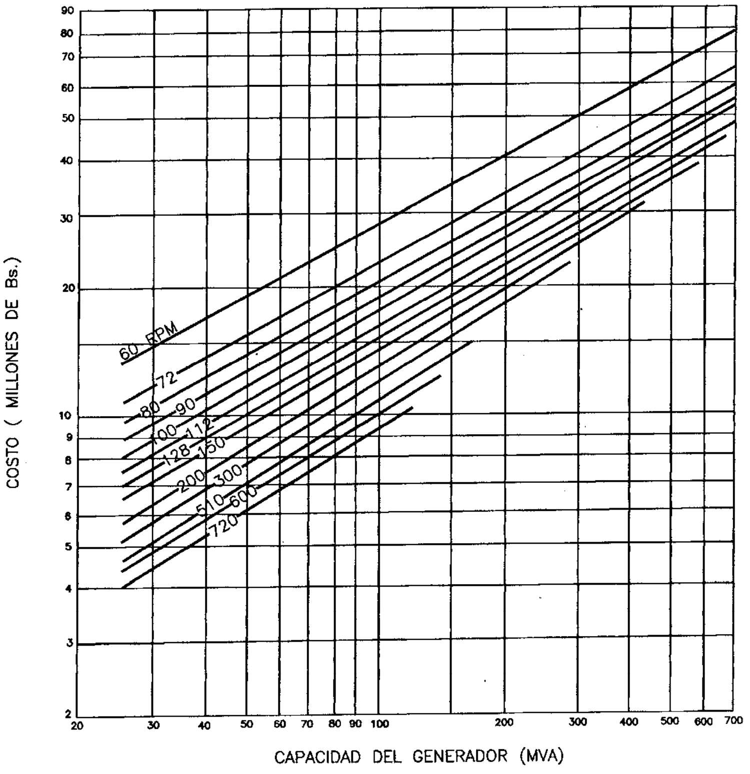


Figure 3-16 Generator Cost

Using the equation:

$Y = ax^b$ .... (1)

Where

b is the slope
a is the intercept
(x and y) are the co-ordinates of the line.

for speeds of 60,100,150,200,300,600 rpm the values of b and a can be calculated. Then for the desired capacity the corresponding cost would be calculated.

The conversion factor is

1 US$ = 4.28 Bs [for year 1980]

An escalation rate of 4% year will be used.

As the graphs are in log the Equation (1) can be written in Log form i.e.

$Y = ax^b$
$\log Y = \text{Log } a + b \log x$

the variables a and b in Equation (1) can be calculated as follows:

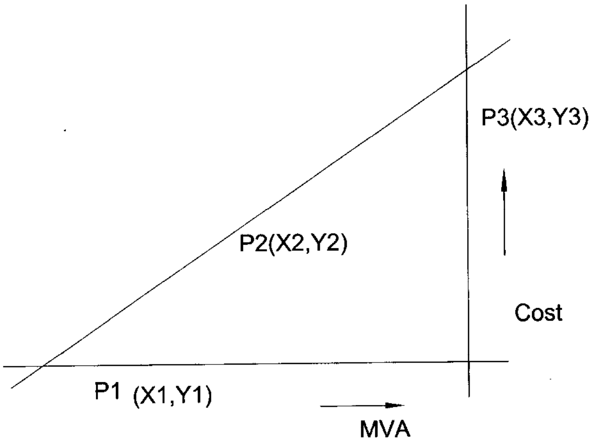


Figure 3-17 Generator Cost Parameters

- the slope with point P_1 & P_2 i.e.

$$b = \frac{\log Y_2 - \log Y_1}{\log X_2 - \log X_1}$$

- ‘a’ will be obtained by putting the value of P_3 (x_3, y_3) in the Equation (1) i.e.

$Y = ax^b$

Replacing the co-ordinates of point P_3 in it

$Y^3 = a \; x_3^b$

Hence obtaining a & b the cost of the generator for any desired capacity can be obtained from the graph.

To make a general relation for the calculation of generator's cost for any required speed, the following procedure may be adopted.

The relation between 'a' and speed (rpm) is developed by using Equation (1) & Figure 2-16

$Y = ax^b$

$\log Y = \log a + b \log x$

$Y' = a' + b x'$

putting $x' = 0$

$Y' = a'$

$a' - f \; (rpm)$

$Y' = f \; (rpm) + b \; x'$

$f \; (rpm) = a = k1 + k2 \; \log \; (rpm)$

the final equation would be

$1n\log \; (a - a_0) = K1 + K2 \; \log \; (rpm - r_0)$.............................(2)

the values of different constants in Equation (2) are

$a_0 = 0.525$ $K1 = 2.262$

$r_0 = 20.000$ $K2 = -1.2294$

rpm = variable

'a' would be calculated and putting it in Equation (1) i.e.

$Y = ax^b$

Where
Y is cost of generator Mill Bs. 1 US$ = 4.28 Bs.
X is power in MVA

with values of 'b' for different speeds, the cost of generator will be obtained.

Example 1:

speed 60 rpm

$P_1\,(30, 14.7),\;\; P_2\,(700, 78),\;\; P_3\,(60, 21.8)$

$$b \;=\; \frac{\log 78 \;-\; \log 14.7}{\log 700 - \log 30} \;=\; \frac{0.7248}{1.3680} \;=\; 0.529$$

$$Y \;=\; a\,X^{b}$$

$$21.8 \;=\; a\,(60)^{0.529}$$

$$a \;=\; 2.50$$

$(b \;=\; 0.529;\; a \;=\; 2.50)$

Example 2:

speed 100 rpm

$P_1\,(30, 9),\;\; P_2\,(700, 53),\;\; P_3\,(100, 18.3)$

$$b \;=\; \frac{\log 53 \;-\; \log 9}{\log 700 - \log 30} \;=\; \frac{0.7700}{1.3680} \;=\; 0.563$$

$$Y \;=\; a\,X^{b}$$

$$18.3 \;=\; a\,(100)^{0.563}$$

$$a \;=\; 1.269$$

$(b \;=\; 0.563;\; a \;=\; 1.269)$

Example 3:

speed 150 rpm

$P_1\ (30, 7.2),\ \ P_2\ (500, 37),\ \ P_3\ (50, 9.6)$

$$b = \frac{\log 37 - \log 7.2}{\log 500 - \log 30} = \frac{0.7109}{1.2218} = 0.582$$

$$Y = a X^b$$

$$9.6 = a(50)^{0.582}$$

$$a = 0.985$$

$(b = 0.582;\ a = 0.985)$

Example 4:

speed 200 rpm

$P_1\ (30, 6.4),\ \ P_2\ (400, 30.8),\ \ P_3\ (60, 9.8)$

$$b = \frac{\log 30.8 - \log 6.4}{\log 400 - \log 30} = \frac{0.6824}{1.1249} = 0.607$$

$$Y = a X^b$$

$$9.8 = a(60)^{0.607}$$

$$a = 0.816$$

$(b = 0.607;\ a = 0.816)$

Example 5:

speed 300 rpm

$P_1\,(30, 5.8),\ \ P_2\,(200, 18.75),\ \ P_3\,(60, 8.9)$

$$b = \frac{\log 18.75 - \log 5.8}{\log 200 - \log 30} = \frac{0.5096}{0.8239} = 0.618$$

$$Y = a\,X^b$$

$$8.9 = a\,(60)^{0.618}$$

$$a = 0.709$$

$(b = 0.618;\ a = 0.709)$

Example 6:

Speed 600 rpm

$P_1\,(30, 9),\ \ P_2\,(100, 10.3),\ \ P_3\,(60, 7.5)$

$$b = \frac{\log 10.3 - \log 4.9}{\log 100 - \log 30} = \frac{0.3226}{0.5229} = 0.617$$

$$Y = a\,X^b$$

$$7.5 = a\,(60)^{0.617}$$

$$a = 0.599$$

$(b = 0.617;\ a = 0.599)$

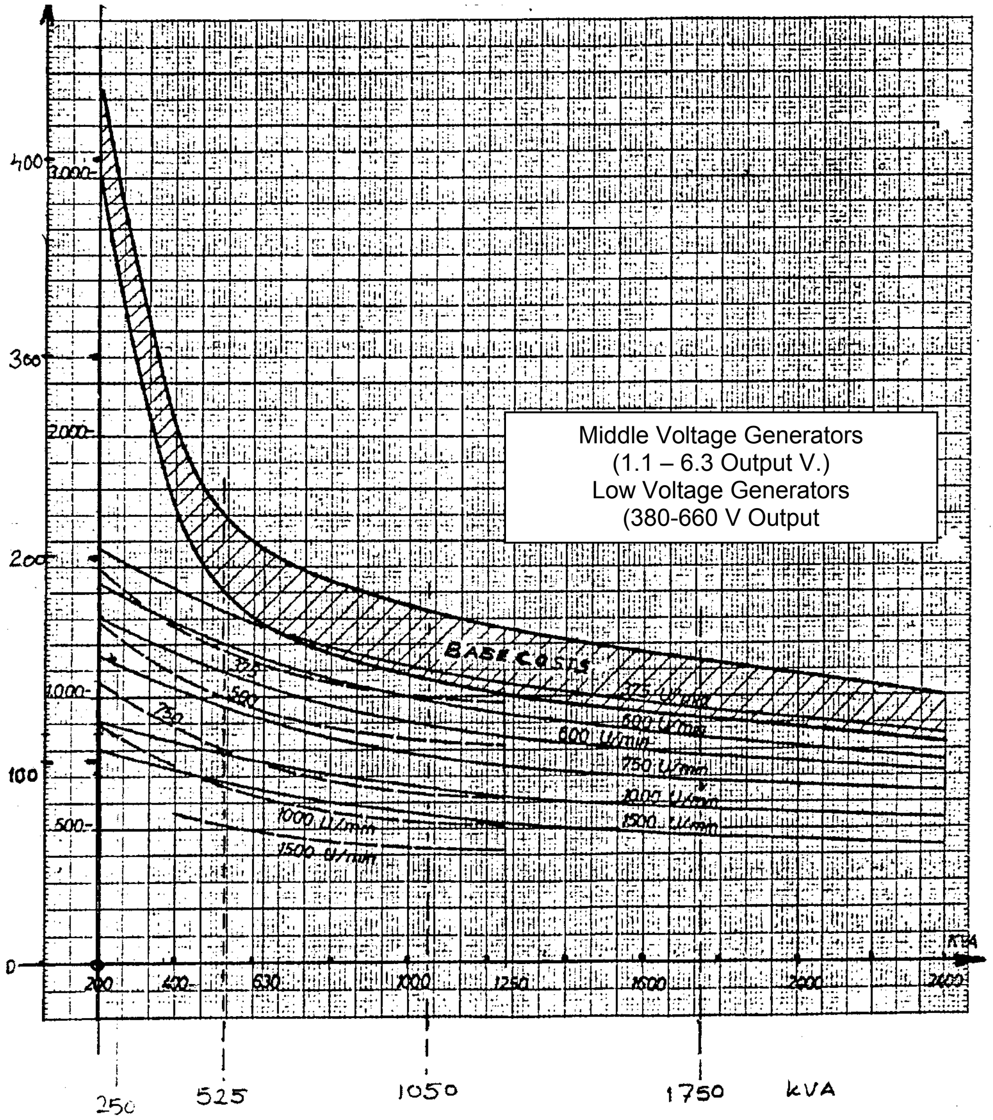


Figure 3-18 Generator Cost Graph

Table 3-6: Standard Sizes Motors - Generators – Transformers

R5	R10	R20	R40
1.00	1.00	1.00	1.00
			1.06
		1.12	1.12
			1.18
	1.25	1.25	1.25
		1.40	1.40
1.60	1.60	1.60	1.60
			1.70
		1.80	1.80
			1.90
	2.00	2.00	2.00
			2.12
		2.24	2.24
2.50	2.50	2.50	2.50
			2.65
		2.80	2.80
	3.15	3.15	3.15
			3.35

R5	R10	R20	R40
		3.59	3.55
			3.75
4.00	4.00	4.00	4.00
			4.25
		4.50	4.50
	5.00	5.00	5.00
			5.30
		5.60	5.60
			6.00
6.30	6.30	6.30	6.30
			6.70
		7.10	7.10
			7.50
	8.00	8.00	8.00
			8.50
		9.00	9.00
	10.00	10.00	10.00

3.2.22 GENERATOR DESIGN FOR SMALL HYDEL APPLICATIONS

Generators for small hydro schemes in the range of 500 kW to 5 MW must satisfy a number of criteria which range from the ability to withstand high overspeeds to ease of maintenance.

The design of generators for hydroelectric applications hinges on two main parameters that is, the overspeed reached under fault conditions and the inertia required to prevent damage. Nevertheless, for reasons of reliability and economics, many aspects of the design and construction are based on substantial experience of generators for standard applications.

To ensure that the generator is able to remain undamaged at the runaway speed of the turbine means that substantial changes to a conventional diesel- or gas turbine-driven generator must be made. The main problem is the high stresses imposed on the rotating components. The rotor construction of a typical multi-pole salient pole generator consists of a laminated or drum spider to which is attached the requisite number of pole pieces, each of which carries a field coil (Figure.3-19). Drum-type spiders have bolted-on pole pieces which are made up of laminations clamped between pole end plates. This method of attachment is rarely acceptable for hydro generators, because limiting the stress in each of the bolts to a safe level would mean that so many bolts are necessary that it becomes physically impossible to fit the required number into the area available. Consequently, most hydro generators have a laminated spider which is cut or punched from a high quality, high tensile strength material. The poles are again laminated and are also made of a high tensile strength steel. Each lamination and the two endplates are secured to the rim by a dovetail or tee-head arrangement as shown.

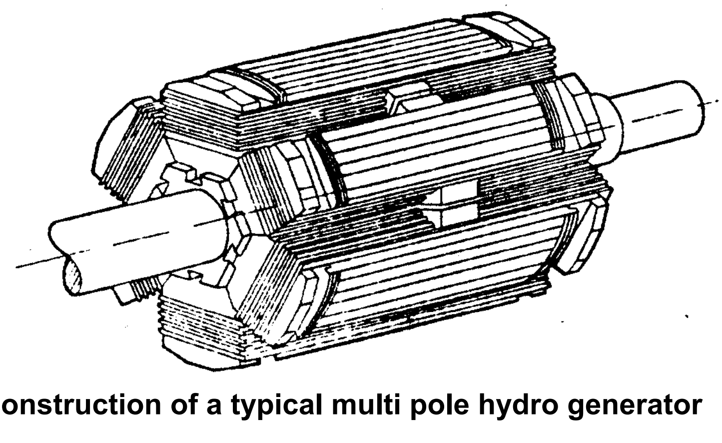


Figure 3-19 Rotor construction of a typical multi pole hydro generator

The centrifugal force exerted on the field coils has radial and circumferential components, the latter necessitating the provision of one or more V-blocks to restrain any movement of the field winding at overspeed. These V-blocks may restrict the ventilation compared with that of a standard generator, requiring thermal network design investigations, to avoid excessive temperatures.

The damper windings on the poles, which may or may not be interconnected depending upon the customer's specification, must also be made mechanically secure. This is achieved by making them an integral part of the pole assembly, thereby preventing any excessive movement under the action of centrifugal forces.

3.2.22.1 EXCITERS AND PERMANENT MAGNET GENERATORS

These ancillary machines are an inherent part of the generator and consequently are subjected to the same high overspeeds. The rotating components of the exciter, which in modern brushless machines is a small inverted a.c. generator, comprise an armature winding and a series of rotating rectifiers. Adequate bracing for the winding is usually ensured by an encapsulation process, while the diodes and their leads must also be firmly braced. Special diodes may well be required for operating under the rotational forces and accelerations.

The rotating assembly of a permanent magnet generator comprises a set of pole bodies made of permanent magnet material, which are held down by steel pole shoes through which are passed non-magnetic screws. The drum and screws will, of course, have to be designed to withstand the stresses imposed on them at overspeed.

3.2.22.2 PROVISION OF INERTIA

The inertial requirements for the generator (see also box below), can be accommodated in two ways.

INERTIA

When the electrical load is suddenly removed from a hydro generator, the speed of the rotating machinery will rise. This sudden removal of electrical load may be because of a load rejection or an electrical tripping of the generator, initiated, for example, by one of the protection devices fitted to the set. To limit the rate of rise of speed and hence the overspeed attained before the turbine governor regains control, a large amount of inertia has to be built into the generator. The inertia may be provided in the form of a separate large rotating mass or alternatively incorporated in the rotor of the generator. The actual value of the inertia required is calculated by the turbine manufacturer for each application, and this is one of the essential pieces of information needed to match a generator to the turbine.

OVERSPEED

A characteristic of all water turbines is the fact that in the event of a governor failure they will run up to a maximum speed known as the runaway speed.

Synchronous generators are restrained from running synchronously when connected to a grid system. However, once tripped from the grid, the speed will continue to increase to the maximum overspeed value unless the turbine governor acts to prevent this. Thus, generators intended for small hydro applications must be capable of operating at this overspeed. It is calculated by the turbine manufacturer and this is another piece of essential information needed by the generator designer.

In the form of a ring, of an appropriate mass and diameter, to which are attached the poles. This method of construction is only practicable if the machine can be made with a large diameter, which is uneconomic for small hydro-generators.

Consequently, the extra inertia in a small machine is usually provided in the form of a flywheel. This flywheel can be positioned in a variety of locations depending upon the machine construction. Thus a machine with endshield-mounted bearings will mostly readily accommodate a flywheel overhung at the drive end (Figure 3-20). The most convenient position for the flywheel when the generator has pedestal bearings is not so clear.

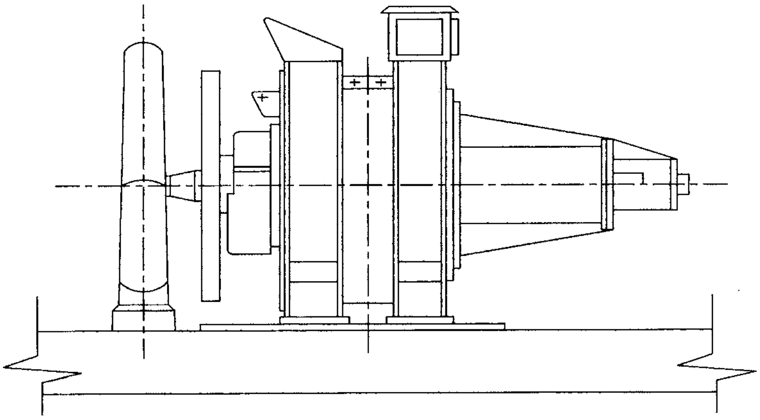


Figure 3-20 Generator with endshield bearings showing overhung flywheel and turbine runner

Normally, the flywheel would be of the largest possible diameter to achieve the maximum inertia while using the minimum mass of material. Thus the outside diameter of the flywheel might well exceed the overall dimensions of the generator. If the generator is mounted on a baseplate, then the position of the flywheel is somewhat limited. The baseplate would restrict the outside diameter of the flywheel if it were to be accommodated inboard of either of the generator bearings. Thus the flywheel is usually positioned outboard of one or other end of the baseplate.

Brushless generators of the type used for mini hydro stations usually have the exciter mounted at the non-drive end of the generator. This allows easy access to the rotating diodes while assisting with their cooling. The stationary part of the exciter can be located either on the baseplate or on a separate concrete plinth. If the latter arrangement is adopted, then the flywheel can be situated between the exciter and the non-drive end bearing. If the former arrangement is used then the flywheel can only be accommodated outboard of the drive-end bearing (Figure 3-21). In this location, it would usually be mounted between the generator and turbine couplings. In this case a third bearing may be provided.

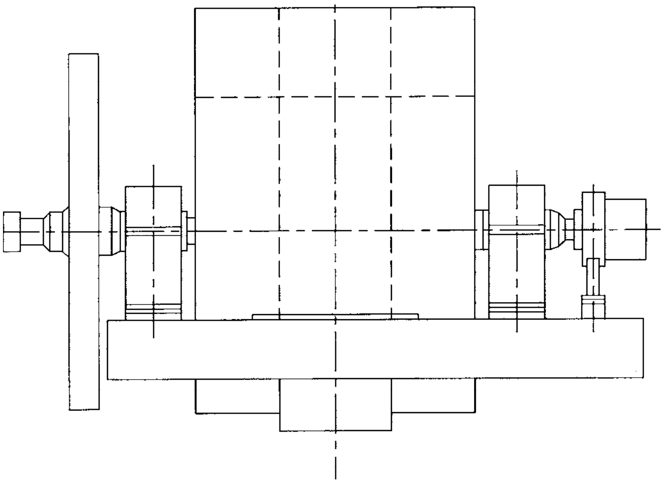


Figure 3-21 Generator with pedestal bearings, baseplate and overhung flywheel.

The flywheel, in common with the other components of the rotor, is subjected to the same high overspeeds, which means that a good quality high tensile steel is required. An adequate margin of safety is used to limit the maximum stresses to ensure the integrity of the flywheel. The properties of the material, and the overspeed it will be subjected to, determine the maximum diameter that can be used. Stringent quality control is necessary including ultrasonic crack detection and dye penetrate tests.

3.2.22.3 MECHANICAL DESIGN

The presence of the flywheel dictates certain changes to the mechanical construction of the generator. The need to avoid critical speed problems or to control torsional or pending stresses of the shaft system usually means that diameters than would normally be required in a conventional generator. Additionally, the shaft must be capable of withstanding the torsional stresses resulting from interaction of the generator short circuit torques and the flywheel stored energy (in the event of an electrical fault on the generator).

These requirements result in a heavier rotor and the problem is further compounded by the loads which are imposed on the generator bearings by the water turbines. Axial loads are an inherent feature of Francis and Kaplan machines. These must be countered by the provision of a thrust face and tilting pads in one of the bearings, assuming that plain bearings are employed. Additional radial load, generated particularly by Pelton turbines, together with the turbine and flywheel weight, means that a larger bearing and shaft section are needed to accommodate this additional loading.

These additional radial and axial loads result in extra losses in the bearings, with the consequent problem of removing the heat generated. This is usually accomplished by water coolers in the oil sump or an oil circulation system, although occasionally the cooling surface of the bearing is adequate to keep the temperature to a suitable level.

The use of an external oil system is best avoided, if possible, for reasons of simplicity. If this is not feasible because of the high loadings or customer's requirement for reduced oil temperatures, several choices are available. An air-blast oil cooler can be used, blowing air at ambient temperature over an oil-filled heat exchanger. The oil can be circulated by a pump driven by the same motor as that driving the fan. A second choice is for the oil to be circulated by a small pump through a heat exchanger located in the tailrace of the turbine. Each of these methods, although requiring additional equipment, has the advantage of avoiding any scouring of an internal water cooler in the bearing by waterborne particles or blocking by sedimentation.

3.2.22.4 SIMPLICITY AND RELIABILITY

The two overriding factors which permeate the whole design process of generators for hydropower applications are the need for simplicity on the one hand and reliability on the other. To a certain extent these two factors are incompatible. The need for reliability will dictate the provision of duplicate items such as pumps and of a good deal of instrumentation to monitor temperatures, pressures and electrical parameters of all parts of the equipment. These requirements are clearly at odds with the concept of simplicity.

The compromise adopted is generally the provision of a substantial amount of instrumentation while simplicity is observed in the machine design and the methods used in the erection, maintenance and dismantling procedures.

Instrumentation would normally include the monitoring of the temperature of the stator winding by embedded temperature detectors, the temperature of the oil and/or the white metal pads in each of the bearings, the flow of oil and cooling water (if appropriate) to each bearing, and the failure of any one of the rotating diodes.

It must be assumed that erection, maintenance and dismantling will all be carried out by local personnel who may be attempting the job with inadequate tools and little knowledge or experience. Thus, it is essential that a comprehensive tool kit be provided including all special tools. Detailed instructions must be provided to enable the users to undertake any tasks necessary to keep the equipment running.

The provision of spare falls into the same category. The assumption that any normal replacement parts needed are readily available is unrealistic if the hydro station is situated in some remote and inaccessible part of a development country. Thus it is necessary to ensure that all potential requirements are provided with the machine.

3.2.22.5 CONCLUSIONS

The various considerations required to render a generator suitable for use in small hydro application which have been highlighted in this article are summarised as follows.

The inertia requirements are met by the provision of a flywheel which may be located in a variety of positions. The optimum position will simplify the foundation arrangements and at the same time allow a good mechanical design to be achieved.

To withstand the overspeeds, the laminated components of the rotor must be of a high tensile strength material. The field coils will need supporting with V blocks while the damper winding must be an integral part of the pole assembly. Similarly, the rotating exciters and permanent magnet generators must be protected by using high tensile materials and firm bracing of the windings and diodes. The flywheel, too, must be of high tensile material, ultrasonically tested.

Bearings must be able to absorb axial and radial thrusts generated by the turbine without overheating. Sometimes, this will dictate the use of water cooling, an oil circulation system and heat exchangers. Harsh water conditions may mean that an air blast oil cooler or radiator in the tailrace will be needed.

To increase reliability, comprehensive instrumentation is supplied. Spares and standby auxiliary equipment must be provided together with the requisite tools and instructions needed to undertake maintenance. Simplicity of erection, operation and maintenance is essential necessitating careful design and clear, detailed instructions.

3.3 STEP-UP TRANSFORMER

3.3.1 SELECTION OF NUMBER

The most used configuration for the three phased transformation is:

- Unit block transformer, each generator is connected to its own step-up transformer.
- Group transformer, where two, three or more generators are connected to the same step-up transformer with two or three low voltage winding and one common high voltage winding.
- Common generator bus and one, two or more step-up transformers connected in parallel.

The number of transformers is given by the number of generators and the selected configuration.

Single phase transformers should be used only for high capacities and high voltages.

3.3.2 SELECTION OF NOMINAL VOLTAGES

Nominal voltages are given by the generator output and the grid requirements. In view of the voltage drop related to inductive current going through the transformers, the ratio normally shall be changed by 5% (the high side above or the low side 5% below rated value).

3.3.3 OPTIMUM SIZE OF TRANSFORMER

Optimum size of transformer depends on the power to be transformed but even more on the efficiency.

Two different types of losses are observed in transformers:

- No load losses (magnetising)
- Winding losses (short circuit)

Optimising of the size depends on investment cost and efficiency. It is understood that the transformers shall be energised during the whole operation time of turbine generator units. Winding losses are proportional to square of transformed generation. For that purpose the sum of P^2 (P^2) shall be calculated from available production during one year.

Losses are

$$P_1 = \frac{R}{365}\ x\ v^2\ x\ \Sigma p^2\ x\ \Delta t\ x\ P_m$$

where

P_m = magnetising losses
= 1 day
R = transformer resistance
V = rated voltage of transformer

Each transformer will take its portion of load given by the configuration.

The calculation of yearly costs for losses and for capital and the total value (adding both) permit to determine the minimum cost over different transformer sizes. Power factor of 0.8 should be taken into consideration. Approximate calculation is:

Losses per year:

$$v = V_o + W = \left[6.8 + P_N\ x\ 0.7182\right] + \left[30 + P_N\ x\, 4.33\right] \Sigma P^2\ x \frac{t}{P_N^{\ 2}}$$

where

V_o = 6.8 + P_N * 0.7182
W = 30 + P_N * 4.333
P_N = nominal capacity in [MVA]
V_o = no load losses in [KW]
W = winding losses in [KW]

Capital Costs:

Transformer price approximately

CTR = 5.05 * 10^4 * $(P_N)^{0.61}$ [US $]

with standard auxiliary equipment.

Vc = CTR * P/100 per year shall be the capital costs, assuming that it includes the interests and the pay back.

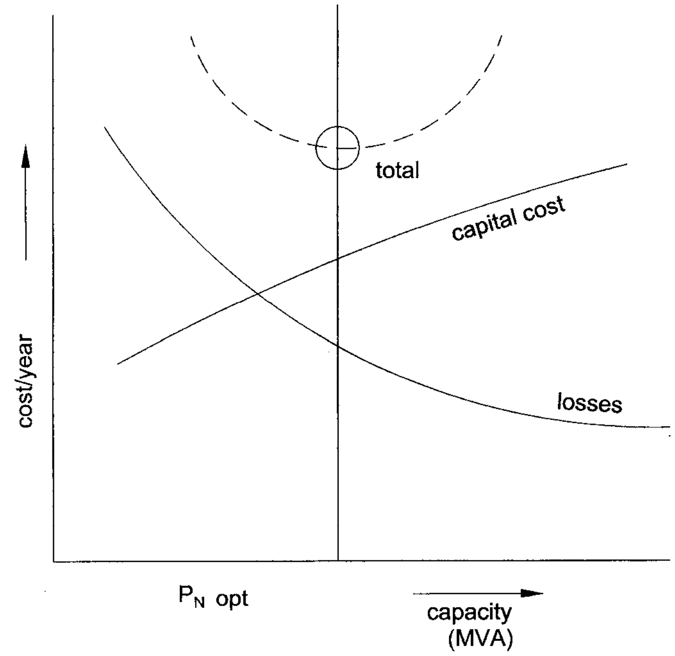


Figure 3-22 Transformer Capacity and Cost Relationship

3.3.4 CONNECTION

To step-up, the following connections of the windings are possible:

- Delta-Why, which is the most used configuration. Suppression of 3rd, 9th etc. harmonic of generator grounding of neutral on high side and floating neutral on low side. Non-symmetric load from grid not affect the generator. Load supply of MV-Energy only through additional transformer or third winding.
- Delta-Delta, only used when special requirements exist.
- Why-Why with third winding when local supply on MV-level is required.

3.3.5 TAPS

For step-up transformers the normally used taps on the high side with a range of ± 2 * 2.5% have proved to be sufficient, (see also nominal voltage). The more flexible regulation of the voltage can be done by the generator voltage control system. Taps shall be used for base settings.

3.3.6 COOLING AND TEMPERATURE RISES

- Natural cooling (radiators)
- Fan cooling (radiators and fans)
- Pumped oil cooling (in case of oil immersed transformers, through radiators)

Abbreviation: (ONAN, ONAF, OFAF)

In special cases water cooling, when

- Indoor installation
- Outdoor installation (lack of space etc.)

- Adequate cooling water conditions

oil-water heat exchangers required.
Temperature conditions, frequently used:

- Ambient 40 ^{O}C
- Temperature rise 55 ^{O}K in hot spot for lowest cooling procedure
- Temperature rise 65 ^{O}K for highest cooling procedure.

3.3.7 CABLE CONNECTIONS

3.3.7.1 TRANSFORMERS WITH TERMINAL BOX FOR CABLE CONNECTION

Cable terminal box affording degree of protection IP 44 (or IP 54 if fitted with venting nozzle or IP F5 if fitted with dehydrating breather.)

The cable terminal box is of horizontally split construction and has its lower part permanently welded to the transformer tank cover. The top of the cable terminal box is removable (8 fixing screws). An air gap permitting circulation of the air (IP 44) can be provided by the insertion of spacer washers between the top and base of the box on assembly if degrees of protection IP 54 or IP 65 are required. The HV and LV cables can be swung in and out easily.

Cables of diameters up to 85 mm can be connected. This cable connection system can be sued in normal and in hazardous industrial areas. Both indoors and outdoors.

3.3.7.2 TRANSFORMERS WITH PLUG TYPE CONNECTIONS FOR THE HV CABLE

LV side : DIN bushings that can be rendered safe to touch by means of a terminal box or by individually covering them with tabular plastic guards.

HV side : Plastic insulated bushings designed as sockets for BIL 125 kV. The plug connectors on the associated cables also serve as sealing ends (and necessitate the use of plastic insulated cables).

The clear height requirement of this transformer design is relatively low. This advantage is also offered by transformers having a conservator, because the absence of liquid insolent in the HV bushings enables the conservator to be fitted at a very low level.

This cable connection system therefore lends itself for use in load-centre substations and under-floor stations where space is at a premium.

3.3.7.3 TRANSFORMERS WITH TERMINAL BOX FOR FLANGE CONNECTION

Switchgear and/or distribution cubicles can be flanged direct to both sides (HV and LV sides). The terminal box is of un-split construction. The terminals are accessible through a handhold with detachable cover (700 x 700 mm).

The flange dimensions are standardised for BIL 20 kV. 75 kV and 95 kV. If a conservator is provided, it is mounted on the left end of the tank when looking from the HV side.

This connection system is preferably used in factory assembled packaged load centre substations requiring a minimum of floor space.

3.3.7.4 HOOD TRANSFORMERS WITH NEW SAFE-TO-TOUCH CABLE CONNECTION SYSTEM

Hood transformers are liquid insulated units with a built-on grounding switch. These transformers use the standard tanks and core-and coil assemblies of Transform Union's various type series of distribution transformers up to 1600 kVA. The tank cover assembly with the bushings and the aluminium hood fits the corresponding tanks from the standard type series.

Table 3-7 Transformer Growing Relations

ITEMS	Growing Dimension by Factor n	Growing Capacity by Factor p
Average Length of Winding	n	p¼
Length of Magnetic Path		
Surfaces	n^2	p½
Masses and volumes	n^2	p¾
Approx. Prices and costs		
Inner Apparent Power (~ .)	n^4	p
Losses	n^3	p¾
Relation Mass/Power	n^{-1}	p-¼
Relation Losses/Power	n^{-1}	p-¼
Heat Dissipation Losses/Surface	n	p¼
Voltage Between Windings	n^2	p½
Relation Magnetising/Mom C.	n^{-1}	p¼
Relation Ohmic volt. Drop/Nom. Volt.	n^{-1}	p-¼
Relation Ind. Volt. Drop/Nom. Volt.	n	p-¼
Current Forces / F ~.	n^4	p

3.3.8 ALTITUDE OF INSTALLATION

The transformers are suitable for operation at altitudes up to 1000 m a.s.l. Site altitudes in excess of 1000 m necessitate the use of special design (at a surcharge of 2% for every 500 m or part thereof in excess of 1000 m) or reduction of the transformer rating (by 2% for every 500 m or part thereof in excess of 1000 m).

3.3.9 TYPE OF TRANSFORMERS

- Liquid filled distribution transformers of 50 kVA to 1600 kVA and system transformers of 2 MVA to 10 MVA.
- Sheet-steel encased packaged substations up to 630 kVA at 12 kV and up to 1000 kVA at 24 kV
- GEAFOL cast-resin dry-type transformers of 50 kVA to 8000 kVA
- HV starting transformers and starting reactors.
- Transformers for electro-chemical industries furnaces and drives.
- Oil-immersed three-phase transformers of 12.5 MVA to 80 MVA.
- Explosion-proof (flameproof) dry-type transformers for high-voltage up to 6 kV for coal mines.

The details about other types of transformer can be taken in (1), however all details about first type of transformer is described below.

3.3.9.1 LIQUID-FILLED DISTRIBUTION TRANSFORMERS OF 50 KVA TO 1600 KVA AND SYSTEM TRANSFORMERS OF 2 MVA TO 10 MVA.

3.3.9.1.1 STANDARDS AND REGULATIONS

The transformers are manufactured in conformity with VDE 0532 and thus comply with the recommendations laid down in IEC Publication 76. The regular product line also includes transformers built to foreign standards and regulations such as BS or ANSI. The technical data and prices stated herein apply to transformers designed to the IEC Recommendations; an inquiry should be made where other standards have to be complied with.

3.3.9.1.2 DESCRIPTION

Distribution transformers with ratings up to 1600 kVA are available with conservators or as hermetically sealed (Tumetic) units. The windings are either of copper or aluminium.
The following types of transformers are customary corrugated tanks for ratings up to 3.15 MVA. plain tanks with welded in pressed cooling sections or plain tanks with flagged on radiators for rating from 2 MVA to 10 MVA. Where particularly heavy stressing is to be expected during sea or land transportation the reinforced type of corrugated tank should be ordered.

Transformers use either transformer oil or Askarel as cooling and insulating liquid.
All transformers are finished with several coats of paint.
Conversion to 60 Hz Operation

The technical data and prices apply to transformers for 50 Hz rated frequency. The data and prices of transformers designed for 60 Hz rated frequency can be derived from the 50 Hz data as described below:

- Same rated power, same technical data: 5% price reduction.
- Same rated power, but temperature rises reduced by 10% so that max. permissible ambient temperature is 50 C price unchanged.
- 10% increase sin rated power, 10% increase in impedance voltage. price unchanged.
- 20% increase in rated power 30% increase in no-load loss. price unchanged.

3.3.9.1.3 TEMPERATURE CONDITIONS

The following standard temperature conditions are laid down in the IEC Recommendations.
Winding temperature rise 65° K; oil temperature rise 60° k: maximum ambient temperature 40° C.

Deviating temperature conditions affect the prices or power ratings as follows:

1.5% surcharge for each 1° K above maximum ambient temperature, or

1% reduction of rated power for each 1° K above maximum ambient temperature.

(These adjustments apply up to 10° K above maximum ambient temperature).

Table 3-8: Standard scope of supply for three-phase system transformers with rating from 2000 to 10000 kVA.

Quantity		Accessories, Fittings and monitoring Services
2	2	Grounding Terminals
4		Fist or flagged wheels, relocatable by 90
4		4Lifting lugs for the core-and-coil assembly and tank cover (with units up to 5 MVA also for fitting the complete transformer).
	4	Lifting lugs on transformer tank
	4	Jack pads
4	4	Hauling lugs for longitudinal and transformers travel
1	1	Gate valve, DN 40, with extension standpipe as upper oil treatment connection
	1	Oil sampling valve
2	2	Alternative connections for oil conservator
	1	Clean-out fitting

Quantity		Accessories, Fittings and monitoring Services
1	1	Vent
		(or screw plug if dehydrating breather is fitted)[1/]
	1	Dehydrating breather nozzle[1/]
	1	Filter nozzle with blank flange[1/]
	1	Drain nozzle with flanged valve[1/]
1	1	Inter branch[1/]
1		Intermediate section in pipe to oil conservator, permitting subsequent fitting of a Buchnolz relay
	1	Stop valve in pipe to oil conservator
1	1	Stop valve in pipe from tap-changer to oil conservator
		(in on-load tap-changing transformers only)
1	1	Oil level sight glass
3	4	Thermometer wells
(1)	1	Temperature monitor
(1)	1	Contact making thermometer
(1)	1	Buchholz relay
1	1	Diverter switch protection
		(in on-load tap-changing transformers only)
(1)	1	Dehydrating breather with silica per cartridge
1	1	Terminal box
(where more than 2 monitoring devices have to be connected in the case of on-load tap-changing transformers, where the terminals cannot be accommodated in the tap-changer drive compartment		

1/ On the conservator, items shown in (1) are optional extras.

Table 3-9: Technical data, selection tables and reference prices (Deutsche for liquid filled three-phase distribution transformers of standard design with conservator

Rated power: 50 - 1600 kVA
Rated frequency: 50 Hz
HV rating: up to 36 kV
Tapping on HV side: ± 5% or ± 2 x 2.5%
LV rating: 400 - 720 V (Special designs for up to 10 kV can be built for power ratings 630 kVA)
Connection: HV winding : delta or star
LV winding : star
(up to 200 kVA : zigzag)

Impedance voltage at rated current: 4% (only up to HV rating 24 kV and 630 kVA) or

6% (up to HV rating 36 kV and 400 kVA)

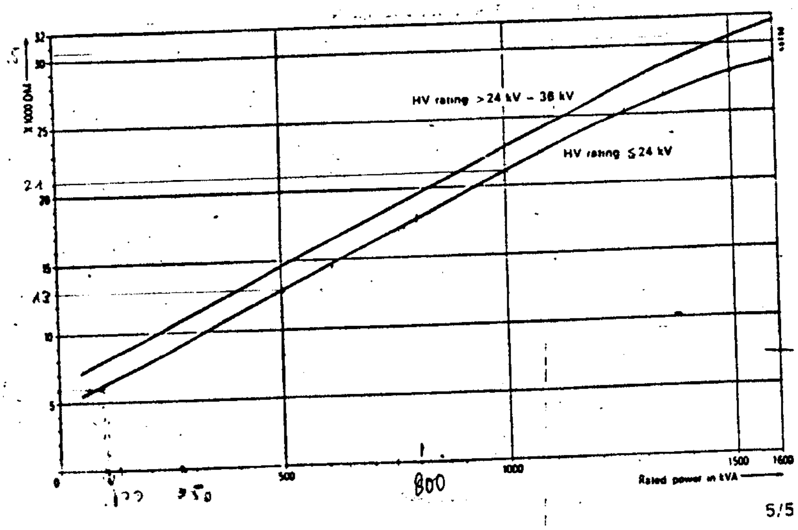
BIL (basic impulse insulation level): 75 kV with HV ratings 3-12 kV

125 kV with HV ratings > 12-24 kV
170 kV with HV ratings > 24-36 kV

Note: Corrugated tank shown in illustration is the preferred design. With HV ratings up to 24 kV and rated power up to 250 kVA (and with HV ratings > 24-36 kV and rated power up to 800 kVA) the conservator is fitted on the longer side just above the LV bushings.

Rated Power kVA	HV rating 24 kV											
	Dimensions L/W/H mm			@ mm	Total weight kg	Oil weight kg	Dimensions L/W/H mm			@ mm	Total weight kg	Oil weight kg
50	900	690	1490	520	590	160	-	-	-	-	-	-
100	970	720	1640	520	770	200	1160	760	1550	670	680	220
160	1030	720	1680	520	930	220	1170	740	1650	670	910	300
250	1160	730	1740	520	1120	280	1300	740	1670	670	1110	340
400	1540	870	1850	670	1700	400	1540	1020	1850	670	1520	420
630	1630	1000	1950	670	2350	490	1730	1150	2000	670	2060	530
800	1800	1100	2100	670	2750	630	1830	1280	2120	670	2580	700
1000	1860	1070	2290	820	3450	760	2130	1250	2400	820	3300	850
1250	2050	1200	2400	820	4000	900	2170	1270	2500	820	3800	990
1600	2100	1270	2500	820	4750	1050	2210	1300	2600	820	4450	1160

Reference prices (Deutsche Mark) for oil-immersed three-phase distribution transformers. A surcharge of approx. 25% applies for Askarel filled transformers.



(35)

Figure 3-23 Price for Liquid fill Transformer.

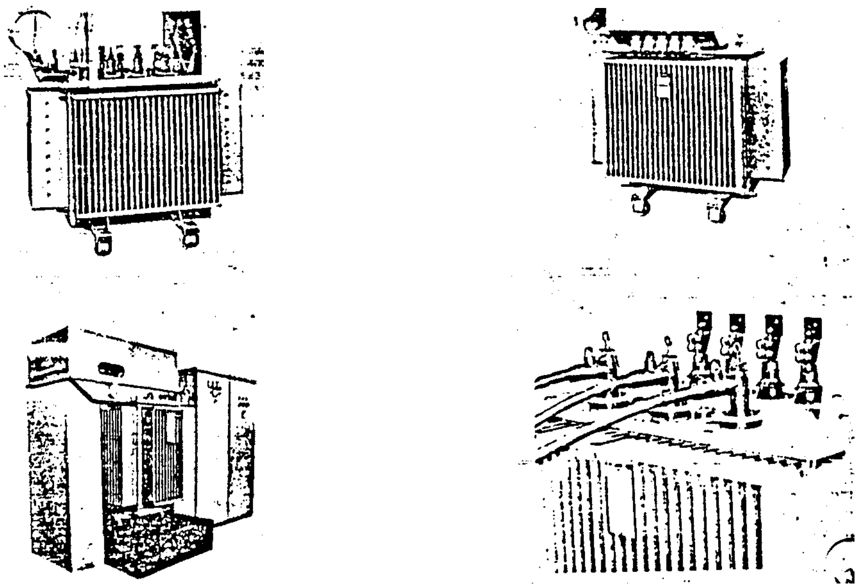


Figure 3-24 Liquid fill Transformer.

Table 3-10 Technical data, selection tables and reference prices for liquid filled three-phase distribution transformers , TUMETIC models (Hermetically sealed , no gas cushion).

Rated power:	250 - 1600 kVA
Rated frequency:	50 Hz
HV rating:	up to 24 kV
Tapings on HV side:	± 5% or ± 2 x 2.5%
LV rating:	400 (units with other LV rating up to 720 V available as special designs)
Connection:	HV winding : delta LV winding : star

Impedance voltage at rated current: 6% only 400 kVA

4% only 630 kVA

BIL (basic impulse insulation level): 75 kV with HV ratings 3-12 kV

125 kV with HV ratings > 12-24 kV

Notes: Corrugated tank shown in illustration is the preferred design.

Rated Power kVA	HV rating 24 kV					
	Dimension L/W/H mm			@ mm	Total weight kg	Oil weight kg
250	1370	800	1430	520	1330	350
400	1490	820	1500	670	1610	380
630	1640	860	1680	670	2210	510
1000	1780	1020	1860	820	2960	710
1100	1850	1150	2220	820	4050	970

Reference prices (Deutsche Mark) for oil-immersed three-phase distribution transformers. A surcharge of approx. 25% applies for Askarel filled transformers.

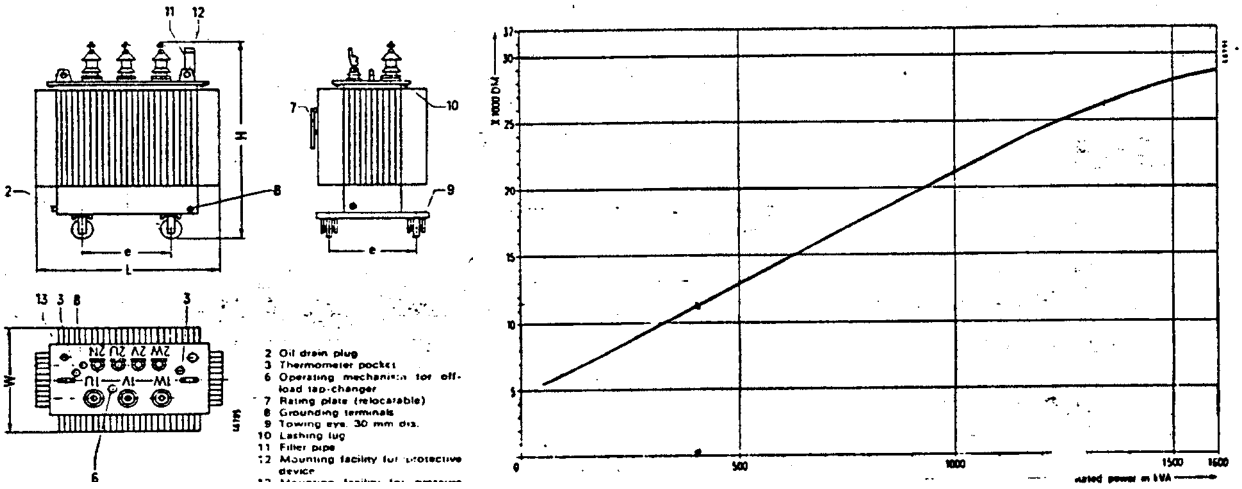


Figure 3-25 TUMETIC Model.

Table 3-11Technical data, selection tables and reference prices (Deutsche Mark) for liquid-filled three phase system transformers with off-load tap-changer.

Rated power: 2000 - 1600 kVA
Rated frequency: 50 Hz
HV rating: 10 to 125 kV
Tapping on HV side: ± 5% up to 125 kV or
± 2 x 2.5% up to 36 kV
LV rating: 6-24 kV with HV rating 10-72.5 kV
400 V possible with rated power up to 4000 kVA
Connection: HV winding : star
delta connection alternatively available up to 24 kV
LV winding : star or delta

BIL (basic impulse insulation level): 75 kV with HV ratings 3-12 kV

125 kV with HV ratings > 12-24 kV
170 kV with HV ratings > 24-36 kV
325 kV with HV ratings > 36-72.5 kV
550 kV with HV ratings > 72.5-125 kV

Notes: Tank with pressed cooling sections shown in illustration is the preferred design. With HV ratings up to 36 kV and rated power up to 250 kVA (and with HV ratings > 24-36 kV and rated power up to 800 kVA) the conservator is fitted on the longer side just above the LV bushings.

Table 3-12

	HV rating 10 kV to 36 kV: LV rating 6 kV to 24 kV						HV rating 50 kV to 72.5 kV LV rating 6 kV to 24 kV											
Rated Power kVA	Dimensions L/W/H mm			@ mm	Total weight kg	Oil weight kg	Dimensions L/W/H mm			@ mm	Total weight kg	Oil weight kg	Dimension L/W/H mm			@ mm	Total Weight kg	Oil weight kg
2000	2400	1450	2700	1070	5000	1200	-	-	-	-	-	-	-	-	-	-	-	-
2500	2450	1500	2800	1070	5600	1350	-	-	-	-	-	-	-	-	-	-	-	-
3150	2600	1600	2900	1070	6500	1500	-	-	-	-	-	-	-	-	-	-	-	-
4000	2800	1700	3000	1070	7600	1700	3100	2300	3630	1070	10800	3100	-	-	-	-	-	-
5000	2900	1750	3100	1070	8900	2100	3150	2490	3730	1070	12200	3300	-	-	-	-	-	-
6300	3000	1800	3350	1505	10700	2550	3200	2690	3880	1505	13600	3700	4780	2600	4540	1505	18900	6600
8000	3100	1850	3700	1505	12900	3100	3250	2850	4000	1505	15900	4200	4880	2630	4690	1505	21500	7300
10000	3250	1900	3800	1505	14900	3350	4000	2750	4170	1505	18200	4700	4970	2900	4810	1505	25000	8600

Reference prices (Deutsche Mark) for oil-immersed three-phase system transformers with off load tape-changer. A surcharge of approx. 20% applies for Askarel filled transformers.

3.4 HIGH VOLTAGE SWITCHYARD

3.4.1 GENERAL

The connection of a low head hydropower project to the grid is given by existing line and substation facilities. As the capacity of these projects normally do not justify long live constructions, the selection of the normal voltage of the switchgear depends basically in near-by existing installations. The economically most favourable solution can be determined by a rough estimate based on line costs and substation costs (use assumed approximate values). The line losses shall be included in the optimisation scheme.

The most attractive configurations should be analysed by a load flow study and the short circuit calculation. In many occasions a stability analysis is required. The standard distances for a switchyard are given in Table 3-14.

3.4.2 RATED VOLTAGES

- 11 kV for direct local distribution
- 66 kV for sub-transmission and distribution level
- 132 kV for transmission through short distances
- 220 kV for high voltage transmission line
- 500 kV for South-North inter-connections

For low head projects normally 66 kV or 132 kV will be chosen, depending on availability and line construction costs.

3.4.3 TYPES OF HV SWITCHGEAR

Different arrangements of HV switchgears are used, bay means (complete set of equipment to connect transformer or line to main bus).

- One step-up transformer together with one line bay, without HV bus. One spare transformer, standby, not connected.
- Two step-up transformer bays together with one or two line bays. A third transformer might be kept in standby without the need of another transformer bay.
- One transformer bay for each turbine-generator block connection. One and more line bays as required by generation.

3.4.4 COST OF TRANSMISSION LINE

Transmission line costs and substation costs determine the optimum voltage level, when several alternatives are possible. Refer Figure:3-26 and Table 3-13

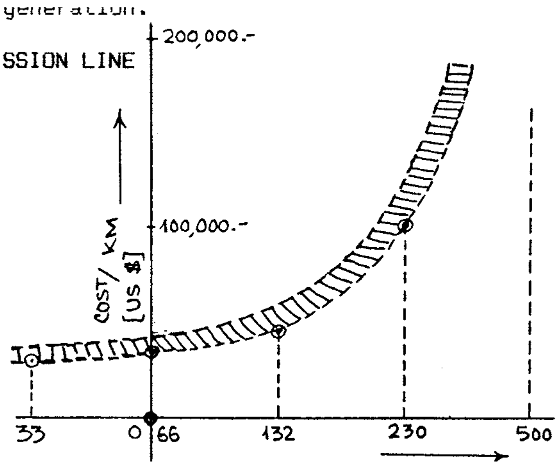


Figure 3-26 Cost of Transmission Line

Table 3-13 Cost of Transmission Line

V	Cr	Tower/Pole	Conductor	Cost/Km (Million Rs)
66	S/C	T	Dog	1.2
66	D/C	T	Dog	1.6
132	S/C	T	Lynx	1.5
132	D/C	T	Lynx	2.7
132	D/C	P	Lynx	5.8
132	SDT	T	Lynx	2.1
132	SDT	P	Lynx	5.0
132	D/C	T	Rail	4.4
132	D/C	P	Rail	8.5
132	SDT	T	Rail	3.0
132	SDT	P	Rail	7.0
132	D/C	T	Greely	4.7
132	D/C	P	Greely	8.9
132	SDT	T	Greely	3.2
132	SDT	P	Greely	7.2
220	D/C	T	Rail	3.5 5.0
220	D/B	T	Tail	5.0 8.0

3.4.5 COSTS OF SUBSTATIONS

(As "Hydroelectric Power Evaluation" by US Department of Energy). The cost equation is given by:

$C_{susst} = 15.8 * 10^{3} * p^{1.2}$ US$ (1988)
P = Capacity handled [MVA]

These costs include costs for circuit breaker manually operated disconnected switches, instrument transformer, power line carrier coupling equipment and all other auxiliary equipment. Site preparation, cleaning, drawing, the foundation, supporting and auxiliary structures. Estimated investment costs for typical substations can be found in Tables 3-15, 3-16, 3-17.

Another formula can also be used such as:

FORMULA OF CALCULATION OF COST OF COMPLETE SWITCHYARD

COST = ${}_{n}B$ (132) * 151000 + ${}_{n}B$ (66) * 105000 + ${}_{n}B$ (33) * 675000 + ${}_{n}1$ (33) * 38000 + ${}_{n}1$ (11) * 25000 +${}_{nT}r$ (132) * (3.6 * ${}_{PkV}A$ * 50000) + ${}_{nT}r$ (66) * (3.6 * ${}_{PkV}A$ * 35000) + ${}_{nT}R$ (33) * (3.6 * ${}_{PkV}A$ * 25000) + ${}_{nB,P}T$ (132) * 63000 + ${}_{n}B$, PT (66) * 43000 + ${}_{nB,P}T$ (33) * 23000 + nAUX * 1 * 67000 + 67000

Where:

${}_{n}B$ (132) = Number of 132 kV bays
${}_{n}B$ (66) = Number of 66 kV bays
${}_{n}B$ (33) = Number of 33 kV bays
${}_{n}I$ (33) = Number of 33 kV indoor cells
${}_{n}I$ (11) = Number of 11 kV indoor cells
${}_{nT}r$ (132) = Number of 132 Kv transformers
${}_{nT}r$ (66) = Number of 66 Kv transformers

nT^{r} (33) = Number of 33 Kv transformers
nB,P^{T} (132) = Number of 132 Kv bus bar & P.T bays
nB,P^{T} (66) = Number of 66 kV bus bar & P.T bays
nB,P^{T} (33) = Number of 33 kV bus bar & P.T bays
nAUX = Auxiliary equipment

3.4.6 CONFIGURATION OF SWITCHYARD

Different types of switchyard arrangements are used in hydro power projects:

- Indoor
- Outdoor
- On top of building
- Separated from powerhouse

The selection depends on the requirements of the project.

Indoor installations for high voltage normally can not be included in the building because of lack of space. Preference is given to outdoor location. Small generator capacity preferably keeps the switchyard area apart from the powerhouse. High generator currents justify the installation of the high voltage equipment closer to the powerhouse and even on top of it. In any case some rough economical estimates should be made to justify one or the other solution.

3.4.7 EXTINGUISHING MEDIUM OF BREAKERS

The main component of the switchyard arrangement is the power circuit breakers. Selection can be made between different types:

a) Oil breaker
b) Small amount of oil breaker
c) Air blast breaker
d) Magneblast breaker
e) Vacuum breaker
f) SF6 breaker
f) SF6 encapsulated breaker/substation

Breakers under (a) and (d) are not use for the high voltage switchgear.

The most economical equipment for connection is the type (b). Air blast breakers are used less and it is recommended not to include these components in future projects. The vacuum breaker has its advantage in case if frequent operations. SF6 filled breakers are used more frequently, so that cost reductions in the future can be expected.

The SF6 encapsulated breaker/substation arrangement is more favourable for lack of space and high contamination. Investment costs are still relatively high and maintenance requires qualified technicians.

3.4.8 EQUIPMENT

3.4.8.1 POWER CIRCUIT BREAKERS

Rated voltage equal or higher than nominal bus voltage (including voltage fluctuations).
Interrupting capacity shall be selected considering future system expansions.

Rated current at least 200% of maximum expected load current (see standards of WAPDA).
BIL, depends on ambient conditions. Dust and poor rainfalls shall require one level higher insulation voltage.

CONDITIONS OF INSULATION

Examples : 1 kV < Vm < 52 kV

Nominal Voltage Vm	Basic Impulse Level (VBIL)		Nominal maximum (Vax) 50 Hz Phase to Ground 2N, 3N
kV	List 1^{3N} kV	List 2^{2N} kV	kV
3.6	20	40	10
7.2	40	60	20
12	60	75	28
17.5	75	95	38
24	95	125	50
36	145	170	70

N = floating neutral (not effectively grounded)

Insulation Group

1. Insulators, fuse supports
2. Insulators transformers, cable, metering
3. Prefabricated switchgears
4. Insulation of neutral
5. Insulation of rotation machines

Insulation levels for 52 kV < Vm < 300 kV

NE : System with neutral effectively grounded
SE : System specially protected against over voltage.

Nominal Voltage Vm kV	Reference Voltage 2/ 3 Vm kV	Basic V_{BIL} kV	Impulse Level BIL	Nominal V_{max} kV	Maximum voltage 5z Phase to ground
52	42.5	250		95	
72.5	59	325		140	
123	100	450	3N) 4N) 2NE)	185	4N) 2NE) 3NE)
145	118	550	2N) 1NE)	230	2N) 3N)
170	139	650	4N)	275	4N)
245	200	750	3NE) 25E) 3SE)	325	2SE) 3SE)
		850	2NE)	360	2NE) 3NE)
		950	3N) 1SE)	395	
		1050	2N) 1NE)	460	2NE) 3N)

3.4.8.2 DISCONNECTING SWITCHES

Different types are available, horizontal and vertical break.

Specifications depend on:

- Nominal circuit capacity
- Unsymmetrical fault condition

Insulation under power circuit breaker.

3.4.8.3 INSTRUMENTATION TRANSFORMERS

Ratio as expected voltage and current level

Current (CT), nominal secondary rating 1.0 A

Precision/Current	0.2% for metering up to 120% of nominal rating
	3.0% for relaying up to 10 times nominal rating

Overload as calculated in short circuit case.

120% shall be possible continuously.

3.4.8.3.1 BUSHING CURRENT TRANSFORMERS (BCT)

This type of transformer is preferable to reduce space in switchyard and costs of equipment. Taps on transformers permit flexibility in case of later changes. Capacity given by connected burdens.

3.4.8.3.2 POTENTIAL TRANSFORMERS

Nominal secondary rating 110/ 3 V

Up to 132 kV, inductive coupling

150 kV and higher capacitive potential divider.

For power line carrier capacitive coupling in any case.

Capacities and precision shall be determined as required in different applications.

Table 3-14 STANDARD DISTANCES SWITCHYARD

(All dimensions in mm)

132 kV		
Switchyard Area	63000 x 57000	
Gantry Column to Gantry Column	=	12000
Gantry to Switchyard Fence (Line Bay)	=	18000
Gantry to Switchyard Fence (P.T. Bay)	=	10000
Gantry to Switchyard Fence (Opp. P.T. Bay)	=	5000
Switchyard Fence to Earth Mast	=	2400
Earth Mast to Centre of Transformer Way	=	4600
Width of Transformer Way	=	4500
Bus Insulator Position	=	Exactly Below
	=	Gantry Beam
Bus Isolator to Current transformer	=	3500
Current Transformer to Circuit Breaker	=	3000
Circuit Breaker to Line Isolator	=	3500
Circuit Breaker to Lightning Arrester	=	3000
Lightning Arrester to Power Transformer	=	4000
Power Transformer to 11 kV Structure	=	3800
11 kV Structure to Centre of Transformer Way	=	3500
66 kV		
Switchyard Area	43000 x 48000	
Gantry Column to Gantry Column	=	7500
Gantry to Switchyard Fence (Line Bay)	=	14500
Gantry to Switchyard Fence (P.T. Bay)	=	8000
Gantry to Switchyard Fence (Opp. P.T. Bay)	=	5000
Switchyard Fence to Earth Mast	=	2400
Earth Mast to Centre of Transformer Way	=	4600
Width of Transformer Way	=	4500
Bus Insulator Position	=	Exactly Below
	=	Gantry Beam
Bus Isolator to Current transformer	=	3000
Current Transformer to Circuit Breaker	=	2500
Circuit Breaker to Line Isolator	=	3000
Bus Isolator to Lightning Arrester	=	3000
Circuit Breaker to Lightning Arrester	=	2500
Lightning Arrester to Power Transformer	=	4000
Power Transformer to 11 kV Structure	=	3800
11 kV Structure to Centre of Transformer Way	=	3200
Bus Isolator to Potential Transformer	=	3000

Table 3-15 Estimated investment costs of typical substations, excludes, excluding land (included 15% general overheads).

Nominal kV & Capacity KVA	Items	Transformer 1 Position	Circuit Breakers 4 Positions	Air-break Switches 3 Positions	Total Substation	Dollars per kilovolt ampere capacity
34.5 (5,000)	Equipment	$ 45.205	$ 134.240	$ 20.445	$ 199.890	------
	Structures and accessories	30,730	104,710	42,115	177,555	------
	Total	75,935	218,950	62,560	377,445	75.49
46.0 (10,000)	Equipment	79.380	142.640	21.885	243,905	------
	Structures and accessories	92,875	141,215	55,370	289,460	--------
	Total	172,255	283,855	77,225	533,365	53.34
69.0 (20,000)	Equipment	103.680	150.800	24.945	279.425	------
	Structures and accessories	139,970	176,435	84,565	400,970	------
	Total	243,650	327,235	109,510	680,395	34.02
115.0 (50,000)	Equipment	227.880	299.580	30.270	557.730	------
	Structures and accessories	221,045	377,470	98,890	698,406	------
	Total	448,925	677,050	130,160	1,296,135	25.12
230.0 (200,000)	Equipment	636.650	589.720	45.630	1,272.000	------
	Structures and accessories	496,585	713,560	153,315	1,363,407	------
	Total	1,133,235	1,303,280	198,945	2,625,460	13.18
345.0 (600,000)	Equipment	1,672,410	1,138.120	59.235	2,869.765	------
	Structures and accessories	719,135	591,820	172,965	1,483,920	------
	Total	2,391,545	1,729,940	232,200	4,353,685	7.26
500.0 (1,200,000)	Equipment	1,858.905	2,246.620	96.915	4,202.440	------
	Structures and accessories	699,205	988,515	258,765	1,946,485	------
	Total	2,558,110	3,235,135	355,680	6,148,925	5.12
765.0 (2,500,000)	Equipment	8,357.310	2,872.480	143.505	11,373.295	------
	Structures and accessories	2,214,330	1,120,265	383,160	3,717,755	------
	Total	10,571,640	3,992,745	526,665	15,091,050	6.04
1,100.0 (5,000,000)	Equipment	18,259.020	5,355,500	199.980	23,814.500	------
	Structures and accessories	4,837,870	2,088,645	533,945	7,460,450	------
	Total	23,096,880	7,444,145	733,925	31,274,950	6.25

Note: For 765 kV and 1,100 kV substations, three single-phase transformers were used which are not shown in the exhibits which follow. Separate estimates were developed in co-operation with Industry for 2 winding units at 833-MVA and 1.66 MVA for the appropriate voltage. While equipment of these sizes and descriptions have not been built, it was estimated that list prices in current dollars would approach $ 2,831,000 and $ 5,202,000 respectively.

Table 3-16 Marginal Energy and Capacity Costs at Various Voltage Levels

Cost at	Cumulative Capacity Cost Rs/kW/a	Components								
		Gene-ration	500 kV	220 kV	132 kV	66 kV	33 kV	11 kV	400 volts	Total
Generation	1108	1108								1108
500 kV	1340	1120	222							1342
220 kV	1436	1138	224	72						1434
132 kV	1654	1174	232	74	174					1654
66 kV	1738	1212	240	78	180	30				1740
33 kV	1738	1212	240	78	180	30	-			1740
11 kV	2002	1254	248	80	186	30	-	204		2002
0.4 kV	2572	1422	280	90	212	34	-	232	302	2572

Table 3-17 Marginal Energy Costs at Various Voltage Levels

Voltage Level	Peak		Off-peak		Average	
	Loss % 1/	Cost Rs/kWh	Loss % 1/	Cost Rs/kWh	Loss % 1/	Cost Rs/kWh
Generation		0.76		0.65		0.69
500 kV	1.1	0.77	0.9	0.66	1.0	0.70
220 kV	1.7	0.78	1.5	0.67	1.5	0.71
132 kV	2.9	0.80	2.5	0.69	2.6	0.73
66 kV	3.1	0.83	2.6	0.71	2.8	0.75
11 kV	6.9	0.89	5.9	0.75	6.2	0.80
0.4 kV	15.9	1.06	13.6	0.87	14.3	0.93

1/ Losses as % of units sent out at each level.

3.5 LOW VOLTAGE SWITCHYARD

3.5.1 GENERAL

The arrangement of outdoor switchgear installations is influenced by economic consideration, in particular adoption to the space available and the operational requirements of reliability and ease of supervision. A span length of 50m is economical for suyed wire, busbars. The number and design of portal structure is governed by the overall length of the installation. The wider spacing T1 and T2 of the busbar bays must be taken into account when planning the station layout.

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

The overhead lines leading from the transformer stations are generally also used for power line carrier. The necessary equipment i.e. line trap, capacitor is incorporated in the outgoing of head lines.

Each bay consists of the circuit breaker with its disconnecting switches and control cubicles, current transformer, voltage transformer & surge arrestor.

The height to the top edge of the earthen insulator base must be at least 2300 mm. The H.V apparatus are generally mounted direct on equipment support structure.

The 1½ breaker configuration is employed for all voltages above 110 kV, but predominantly in the very high voltage range the more economical solution of stranded conductors is often used for the links to the apparatus, because with the relatively short distances between supports even the highest s.c. currents can exert only limited stresses on the equipment terminals.

The branches are always arranged in two rows. The disconnectors used are of the pantograph and two column vertical break types. Vertical break disconnectors are employed in the outgoing line.

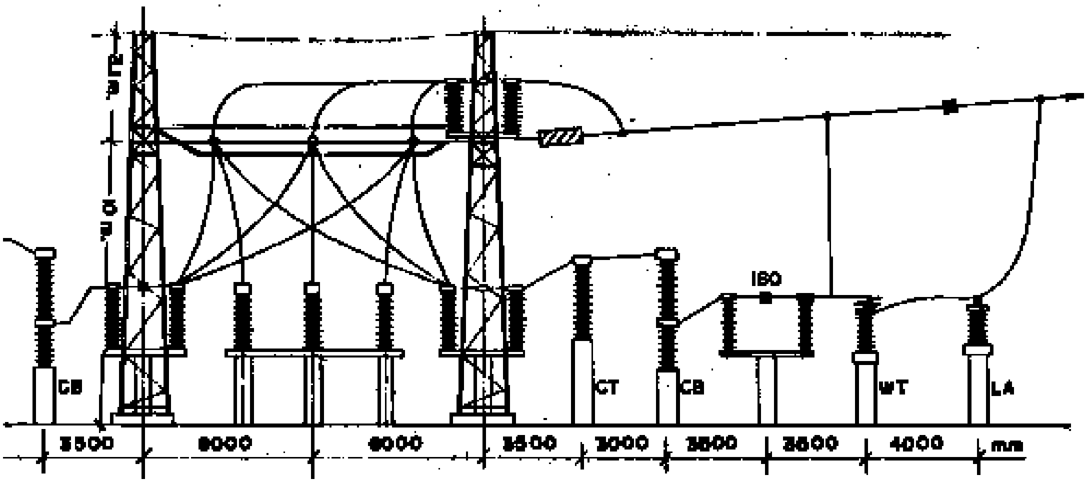


Figure 3-27 TRANSFORMER AND LINE BAY

3.5.2 LOW VOLTAGE (L.V) SWITCHGEARS AND SWITCHBOARD

1: L.V Switchgear is used for switching and protecting electrical equipment. The various devices are selected according to their required functions, e.g. isolating disconnecting loads, short circuit breaking, switching motors, protecting against overloads and danger to human life. The device can perform one or more switching functions according to design. The switching functions can also be performed by a combination of several devices.

A selection used for L.V switchgear

1. Circuit breaker general
2. Fuse
3. Disconnector
4. Load break switch
5. Fused switch disconnector
6. Motor starter
7. Contactor
8. Overload relay
9. Switch disconnector with fused
10. Residual current circuit breaker
11. Miniature circuit breaker
12. Residual current circuit breaker with over current trip
13. R.C.D. operated miniature circuit breaker

3.5.3 CIRCUIT BREAKERS

Circuit breakers must under normal operating conditions be able to make, carry and break current and under specified abnormal conditions up to a short circuit be able to make the current, carry it for a defined length of time and interrupt it. Circuit breakers with instantaneous overload and short circuit trips are used for routine switching and for overload protection of apparatus and parts of system having a low operating frequency. Circuit breakers without over current release, but with a special open circuit shunt release (0.1 to 1.1 x UN) are employed as network protectors to prevent reverse voltages.

Circuit breakers are available for dependent or independent manual actuation and also for actuation by dependent power or energy storage devices. The breakers can be opened manually, electrically by a motor or electromagnetic or by releases of the following kinds, open circuit, over current, under voltage, reverse power or reverse current.

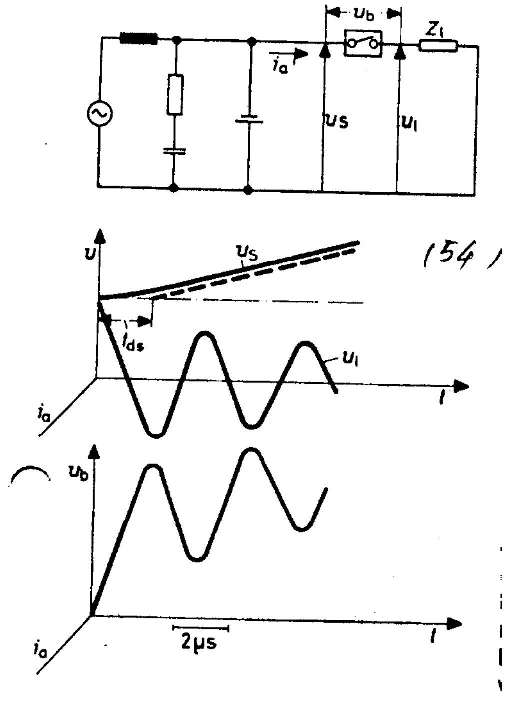
Circuit breakers are classified according to their design principle into current Zero breakers and current limiters.

3.6 DEVELOPMENT IN HIGH VOLTAGE CIRCUIT BREAKERS

For many years the development of high-voltage circuit-breakers was promoted primarily by the increase of the breaking capacity this being the most important factor determining the design. In recent times other parameters have been emphasised namely the reliability and the economy. For circuit-breakers above 100 kV this fact caused a trend towards SF6 single-pressure breakers. The AUTO-PNEUMATIC breaker, a special type of this kind, equipped with an insulating nozzle, is characterised by particular simplicity.

3.6.1 DYNAMIC DEVELOPMENT

In past decades the most powerful impetus for the development of high-voltage circuit-breakers came for the increase of the short-circuit currents, since it is the breaking capacity that



Where

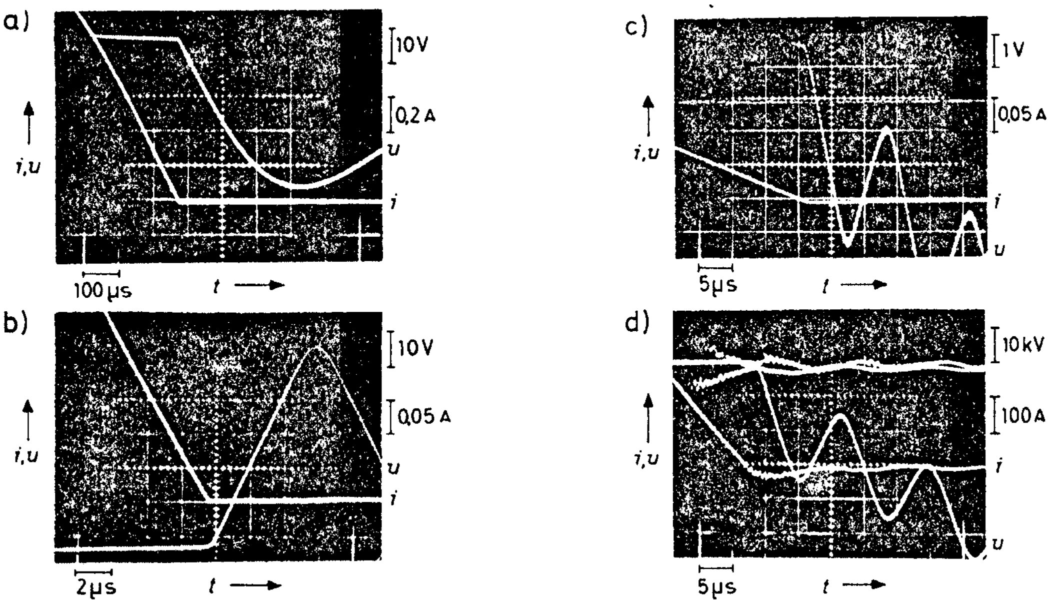
ia	breaking current
us	transient recovery voltage of the source side
u1	transient recovery voltage of the line side
ub	voltage at the breaker terminals
z1	rated surge impedance of the line
tds	time delay of the source side TRV

Figure 3-28 Breaking current and prospective transient recovery voltage (TRV) under the terminal fault conditions (1980 status)

affects the design of a circuit-breaker most of all. A great influence was also the aggravation of the test requirements (1), particularly the increasingly exact definitions for the transient recovery voltage. For example, now-a-days eleven parameters have to be taken into consideration when testing a circuit-breaker under short-line-fault conditions (Figure 3-28)

1a	f (Ur; ks; tds; u; t; u1; t1; Uc; t2; Z1; K1)
1a	breaking current;
Ur	rated voltage;
ks	amplitude-factor on the source side;
tds	time-delay of the delay-line
u & t	final points of the delay-line
u1, t1, uc and t2	co-ordinates of the four-parameter transient recovery voltage;
Z1	rated surge impedance of the line;
k1	rated peak factor of the line.

The improvement of the test requirements also extended the range of duties of the high-power testing stations. Thus, for testing a circuit-breaker under short-line-fault conditions, for example, the current injection method is available. Furthermore there must be available the short circuit power needed in synthetic test circuits for testing the breaking performance of the circuit-breakers. A duty of almost equal importance is the measuring technique. The measurement of current declines and voltage rises during interruption of large currents under the direct influence of powerful magnetic fields is a difficult task that can be solved only by intensive development work (Fig.3-29).



a. current and prospective transient recovery voltage of the source side
b. current and prospective transient recovery voltage of the line side
c. current and resultant transient recovery voltage of the test circuit
d. current and transient recovery voltage at test.

(the prospective transient recovery voltage was measured using the current injection method [2,3])

Figure 3-29 Breaking current and transient recovery voltage when testing an AUTO-PNEUMATIC circuit-breaker 420 kV (54 kA) with two breaks per pole under 90% short-line-fault condition

Extensive investigations in the field of arc research have led to better understanding of the process in the breaker and enables large development steps to be dared successfully. Decisive for the dynamic development was also the extension of the duties for circuit-breakers, such as the interruption of small inductive currents with small over voltages, the switching of capacitive currents without restrikes, the energising of long lines during auto-reclosing with a small over-voltage factor, switching under out-of-phase conditions, and the reduction of the total break time. The aggravation of the requirements concerning environmental protection have also caused a noticeable contribution to further development work.

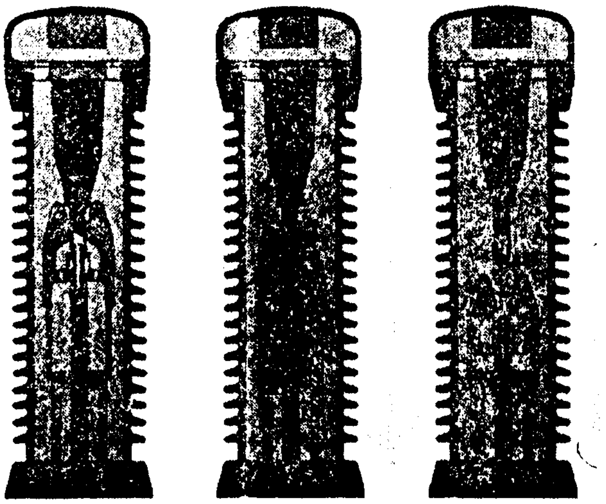


Figure 3-30 Section through the breaker chamber of a SF_6 circuit-breaker with insulating nozzles.

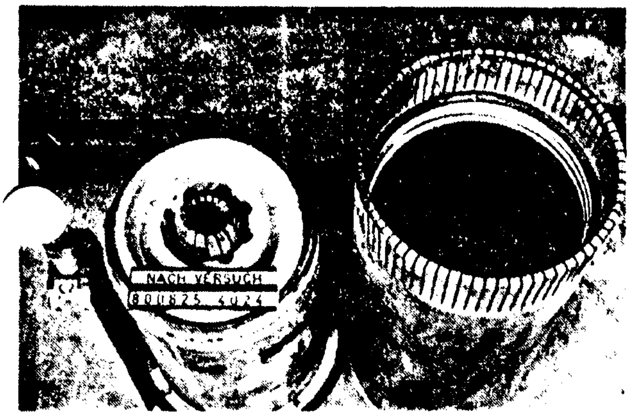


Figure 3-31Contacts of an AUTO-PNEUMATIC breaker 245 kV (63 kA) with a rated current of 4,000 A after six interruption under short line fault conditions (95% and 85%, each three times).

3.6.1.1 TREND TO SF_6 SINGLE-PRESSURE BREAKER

However, all these development impulses cannot explain the change in breaker engineering leading to the fact that all over the world for rated voltages above 100 kV only one breaker principle dominates, namely the SF_6 single-pressure breaker. They produce the pressure required to extinguish the arc by compression during opening operation.

Two parameters above all have caused this change, the safety and reliability on one hand and the economy on the other, feasible to a high extent with breakers of this type.

The safety and reliability of a circuit-breaker are determined chiefly by its principle and design. Different principles were realised also with single-pressure breakers. Breakers of particular simplicity are AUTO-PNEUMATIC breakers equipped with insulating nozzles, whose features relevant to safety are illustrated below.

3.6.1.2 AUTO-PNEUMATIC CIRCUIT BREAKERS

The interruption-chamber (Fig.3-30) of this breaker [4] has only a few moving parts, no valves and, as dynamic sealing elements, simple piston rings without particular sealing requests. High rated currents can be realised easily by tubular parallel current paths (Fig.3-31). The construction of the breaker is also simple. Support insulator and breaker chamber together form an SF_6-filled compartment (Fig.3-32) each pole column has only one sealing at earth potential, through which the operating rod is being passed from outside into the SF_6 compartment. This sealing flange is equipped with several guide rings and ring seals.

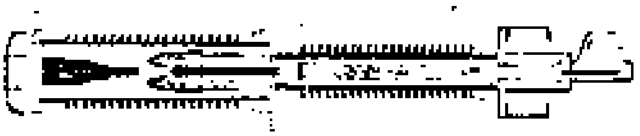


Figure 3-32 Section through a pole of an AUTO-PNEUMATIC breaker with one break

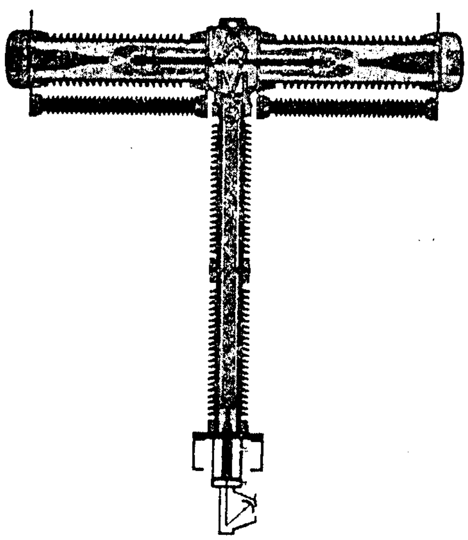


Figure 3-33 Breaker pole with two breaks.

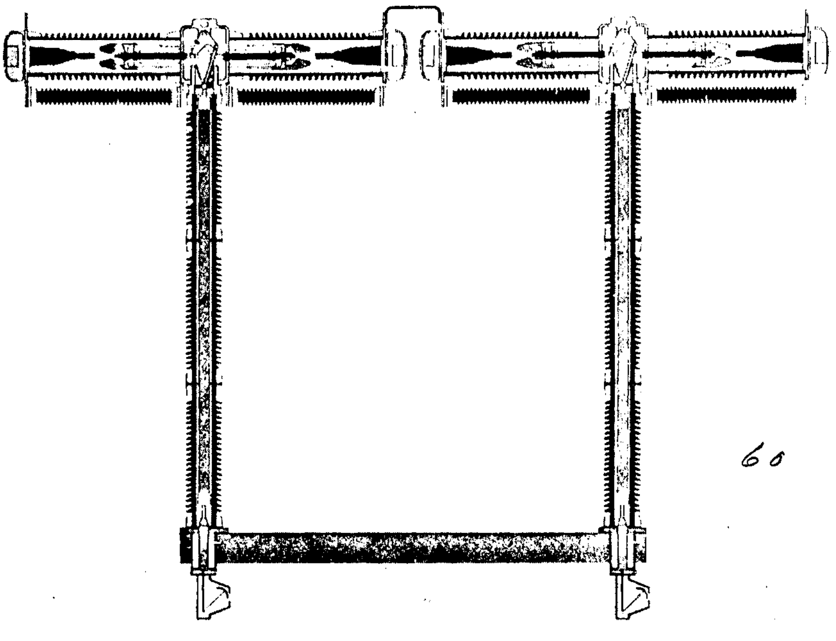
Series connection of several breaks is possible (Figure 3-33, 3-34 & 3-35). Circuit-breaker with a high breaking capacity have more breaks per pole than would be required to withstand the test voltage alone. SF_6 gas, which combines a high electrical withstand strength with large arc extinguishing performance, permits a comparatively small number of breaks per pole particularly in the case of breakers with insulating nozzle; that means a considerable contribution to safety and reliability. For by reducing the number of similar elements in a technical system, its reliability will be increased in the same way. High specific ratings cause low weight per power ratios (Fig.3-36).

3.6.1.3 DRIVES OF SINGLE-PRESSURE BREAKERS

With SF_6 single-pressure breakers the drives demand special attention since these drives have to generate the SF_6 pressure required to extinguish the arc, during the opening operation. The driving forces therefore largely exceed those of breakers with other quenching principles. With a comparatively small input power of 100 to 200 W, a drive power in the range of several hundred kilowatts has to be set free within a few milliseconds. For the reliability of a single-pressure breaker it is decisive how these conditions are realised.

At the beginnings of the SF_6 single-pressure breakers hydraulic drives were widespread. However, such drives have basic disadvantages which come into effect, especially when units are manufactured under license in foreign countries: At the high operating pressure of 325 bar and above high demands must be made on the material of components and sealing subject to pressure. The elements of the hydraulic system, such as valves and receivers. demand very high precision, only attainable using special machines. Long time tightness of the high-pressure tubing is achievable only with the greatest care in manufacture and erection. For the assessment of hydraulic drives it is a significant fact that a circuit-breaker forcibly has to be taken out of service in case of a leakage on the nitrogen side of the high-pressure accumulator.

Disadvantages of the type described can be avoided with the electro-pneumatic drive being in many respects simpler. Its principle is illustrated in Fig.3-37: The sealing flange is identical with the cylinder head, and the "OPEN" valve is connected directly to it, in order to achieve short opening times. Through the sealing flange the piston rod is directly connected to the insulating rod in the SF_6 compartment. The piston is easily detachable.



60

Figure 3-34 Breaker pole with four breaks

The inlet for the driving air for the "CLOSE" operation is placed in the base of the cylinder. The "OPEN" and "CLOSE" control valves are constructed as two way valves which, after tripping, vent that compartment actually filled with pressure. The valves are grouped into a valve block (Fig.3-38). The vent holes of the valves can be equipped with silencers which reduce the noise emission to permissible values; for example, the noise emission of a 123 kV breaker (breaking current 25 kA) lies below that of a breaker with hydraulic drives.

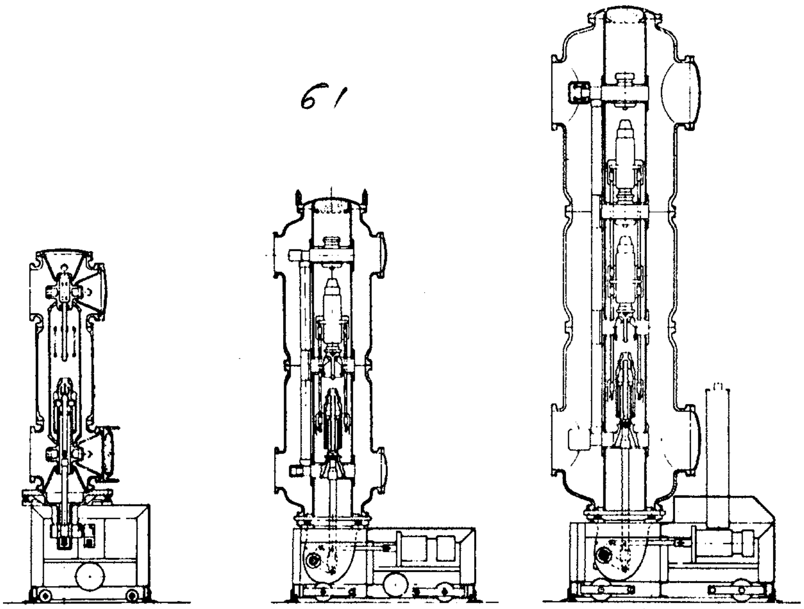


Figure 3-35 Circuit-breakers for SF$_6$-insulated substations 170, 300 and 525 kV

The drive is subject to pressure only temporarily during the switching operation so the piston does not have to satisfy and particular sealing requirements and the components of the drives can therefore be manufactured without the precision needed for hydraulic elements. The driving pressure lies between 8 and 35 bar, depending upon the rated voltage and the breaking capacity. This comparatively low pressure gives great freedom in the arrangement of the compressor unit (Fig.3-29).

The drive unit, having only small leakage rates, less than 0.1/hr, and a small air consumption, permits - when each breaker has its own compressed-air supply - two-stage compressor with an output capacity of about 100 /min. The air is not dried by expansion but in adsorption filters filled with aluminium silicate, a material also used to keep dry the SF$_6$ compartments. The driers are regenerated automatically and therefore remain maintenance-free.

3.6.1.4 CIRCUIT-BREAKERS AS SAFETY ELEMENTS

AUTO-PNEUMATIC breakers to a great extent allow the realisation of a device transferable from aircraft to the manufacturing of circuit-breakers as safety elements: the principle and design of a circuit-breaker should be such that as far as possible over-stressing or faults cannot expand into severe damage. This is realised by the following measures:

- The internal dielectric strength of a porcelain-insulated breaking chamber is greater than the external one.
- On a reduction in pressure within the SF$_6$ compartment to 1 bar the dielectric strength of the open break is still high enough for safely withstanding the line to ground voltage. At rated voltages up to 245 kV it even holds the line voltage. Therefore immediate closing of the breaker is not necessary even on such a severe pressure loss.
- AUTO-PNEUMATIC breakers for rated voltages above 245 kV are also dimensioned for the unlikely case of an unearthed three pole short-circuit. Therefore they are tested under terminal fault conditions with a first pole to clear factor of 1.5.
- The contact position remains unchanged even on loss of the driving energy.
- The low driving pressure excludes danger to personnel even in the event of defective pipes or pipe connections.

- During commissioning, the electro-pneumatic drive permits a progressive increase in pressure as a contribution to safety.
- A leakage in the energy storing device only leads to an extension of the working intervals of the compressor.
-

3.6.1.5 QUESTIONS OF ECONOMY

From the user's point of view the economy is first determined by the price of the breaker. The reduction in the weight per power ratio reveals cost reductions; however not proportional to the weight reduction stated in Fig.-36. so the cost for erection and commissioning of the breaker also enter the economy calculation, and by this the advantages for the AUTO-PNEUMATIC breaker in comparison with breakers of other principles become obvious. For example, site erection of a 245 kV breaker with one break per pole is possible in a few hours, because the pole column, factory tested together with the drive, is one transport unit (Fig.-40). Considerable savings can be achieved also for the foundation of the circuit-breakers (Fig.-41 and 3-42).

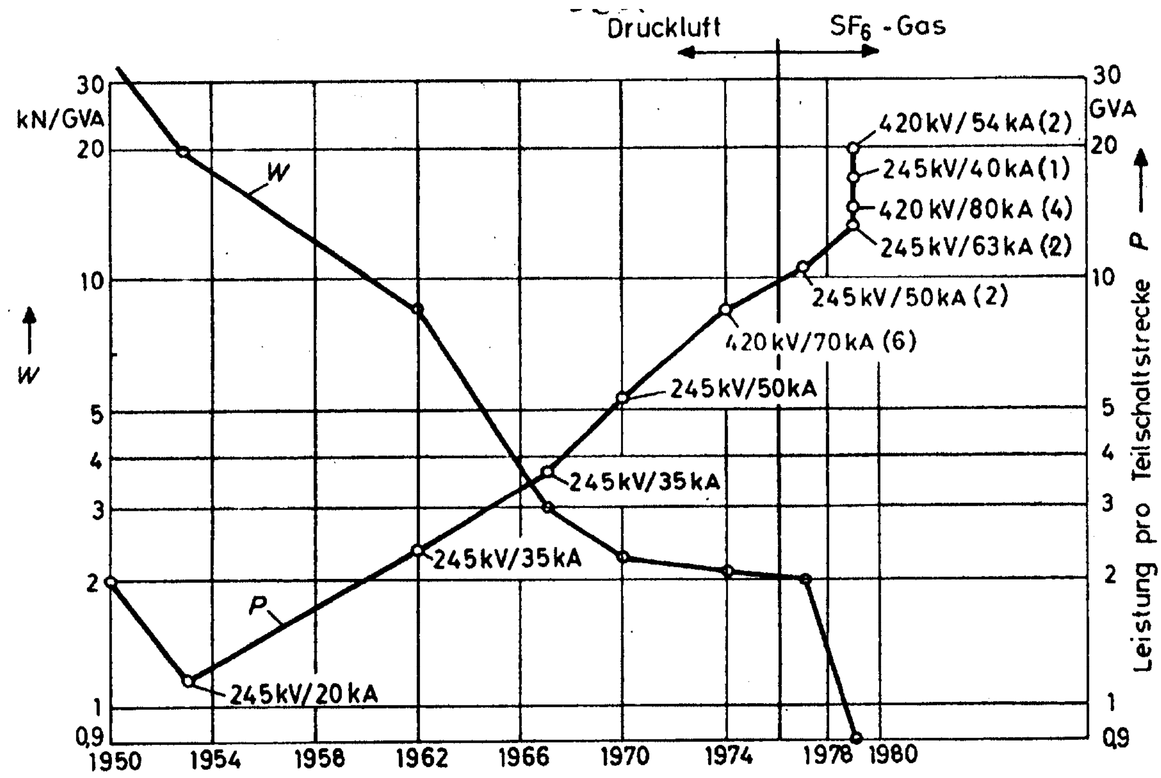
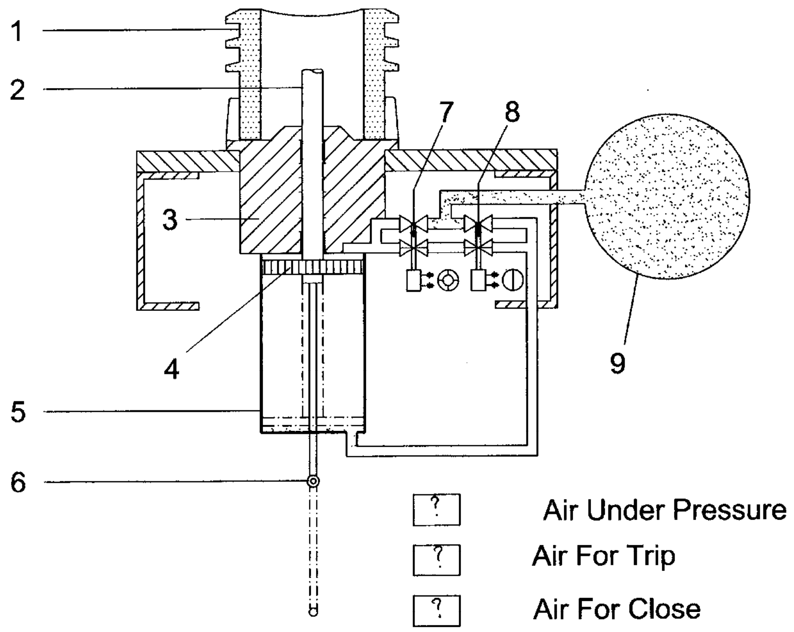


Figure 3-36 Specific weight W and specific power P of circuit-breakers from AEG-TELEFUNKEN.

Numerical dates on the power curve: Rated voltage/breaking current. The numbers in brackets indicate the number of breaks per pole Druckluft = compressed air SF_6-gas = SF_6 gas, Leistung pro Teilschaltstrecke = power per break



1. earthing insulator
2. piston rod
3. sealing flange
4. driving piston
5. drive cylinder
6. operating rod of auxiliary switch
7. opening valve with vent
8. closing valve with vent
9. air receiver

nstehende Druckluft = stored air pressure
usschaltluft = opening air
inschaltluft = closing air

Figure 3-37 Electro-pneumatic drive ELNUMATIC

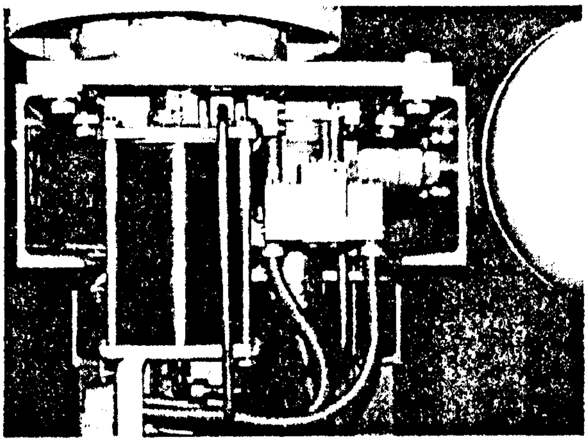


Figure 3-38 Drive with valve block of an AUTO-PNEUMATIC circuit-breaker

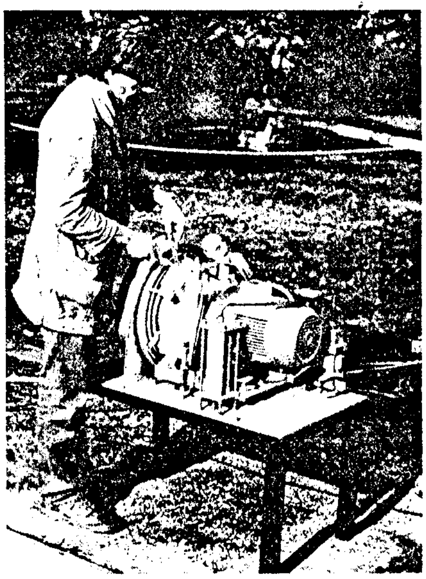


Figure 3-39 Individual Compressor Unit

Figure 3-40

a. Transport units of an AUTO-PNEUMATIC circuit-breaker for 245 kV
b. Erection of a 245 kV breaker in single-pole arrangement

3.6.1.6 QUALITY ASSURANCE IN SERVICE

Of quite considerable importance for the consideration of economy is the cost of quality assurance in service. The AUTO-PNEUMATIC SF_6 breakers has by design good preconditions for constancy of its electrical performance, i.e. switching operating, particularly fault clearances, do not alter the characteristics within the limits for permissible contact erosion of long-life materials, such as self-lubricating bearings, high-load , stale elastomers for the sealing elements. For AUTO-PNEUMATIC breaker employed in the normal networks service of an electricity supply authority without particular switching duties, such as switching of pumped-storage power stations, switching of shunt reactors or the frequent clearance of short-circuits the inspection interval can be extended to about 10 years. Longer periods between inspections are also quite realistic, since the necessity for an inspection can be determined by simple measurements. Arrangements are provided for this purpose; for instance, for measuring the pressure and movement of the drive. Since nowadays these quantities are easily measurable even in the switchyard using photo recorders, the records taken after a service period of several years can be compared with the original ones taken in the test field.

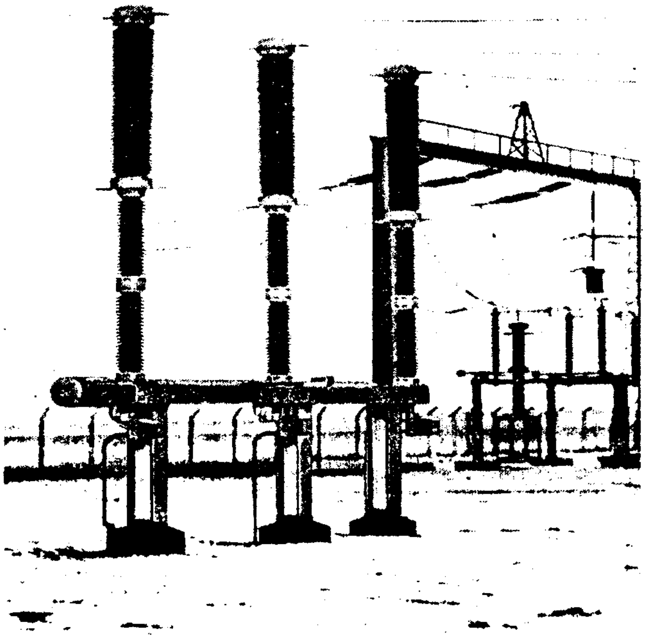


Figure 3-41 AUTO-PNEUMATIC circuit-breaker 245 kV, 40 kA (pole columns mounted on a common base).

Together with the measurement of the resistances of the closed breaks and the gas quality in the SF_6 compartments, these measurements provide a good means of diagnosis. Opening up of a breaker chamber, independently of the diagnoses measurements, may be desirable for a visual safety check or contact change. This is no problem if certain auxiliary apparatus, such as an SF_6 maintenance unit and protective clothing for the filters, are available. For the case of fault a vacuum pump would be sufficient in place of the maintenance.

Circuit-breakers as safety elements should be subjected to inspections at shorter intervals, about every three to four years, during which, amongst other things, the humidity in the SF_6 compartments should also be measured.

An important contribution to the availability of a breakers is to be seen in a good accessibility to its components. The time required to exchange a functional element or even a complete pole column very strongly depends upon the principle and the design. The AUTO-PNEUMATIC breaker with electro-pneumatic drive certainly warrants favourable assessment also in this respect.

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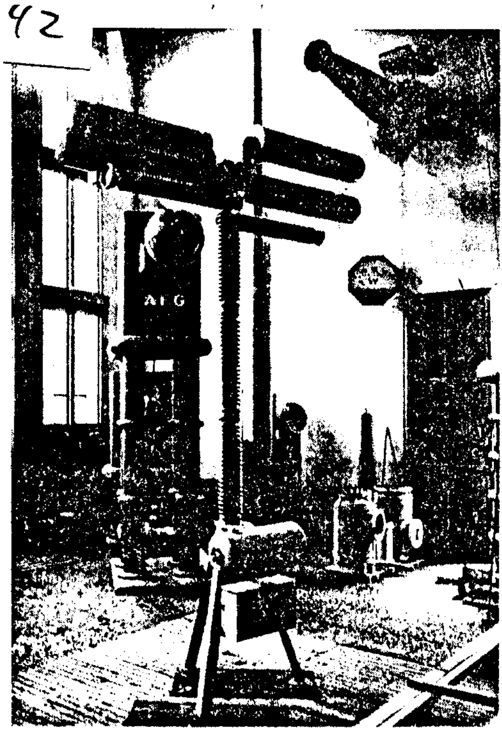

Figure 3-42 AUTO-PNEUMATIC circuit-breaker 420 kV, kA with closing resistors

3.7 MV/LV INSTALLATIONS

The MV/LV installations in a hydropower project are mainly used for supply of electrical energy to the auxiliary equipment and/or for generator buses in special types of connection.

3.7.1 GENERAL SUPPLY OF AUXILIARY EQUIPMENT

Auxiliary power for the auxiliary machinery, control and protective equipment can be supplied both as a.c. and d.c. Direct current is fed into the circuit by storage batteries, while alternating current can be obtained by various methods described later. Since the d.c. battery supply ensures the highest service reliability, its use can not be omitted for the most important part of the auxiliary equipment or for emergencies. A high-capacity battery station, however, needs much room and is rather expensive, thus an important part of electrical design is to establish the proper limits of the d.c. current load without ignoring the necessary operational safety of the power stations and outdoor switchyard.

Auxiliary a.c. power requirements of the power stations may be met by one of the following methods:

a. The transformers supplying auxiliary a.c. are branded off the main side, i.e. from the high-voltage buses of the station. In this case the auxiliary services are continuously supplied with electric power, even if operational troubles stop the station's own generators. This solution may prove especially useful in the case of unit block connection between generator and main transformer.
b. Auxiliary (station) transformers receive current from generator voltage buses and in certain cases supply current only to the electric machine assigned to them. The drawback of this solution is that if the generator fails, the auxiliary installation also remain without power.

c. Auxiliary a.c. can be supplied by auxiliary generators (station generators) mounted on the shaft extension of the main generating units. The disadvantage of this alternative is similar to that of method b.
d. If the auxiliary generator supplies only the auxiliaries pertaining to its main set (turbine and generator), and other power requirements of the station are covered by any of the other methods listed here, this solution can be considered favourably. The trouble-free generator will always ensure adequate power supply for itself and its driving turbine.
e. Since in the above mentioned cases major operational troubles paralyse auxiliary power supply in certain power stations.
f. A special auxiliary turbine and a coupled generator (auxiliary generating set) are installed to ensure auxiliary power supply or
g. The auxiliary services are connected, by means of a special supply line, to a network fed from other sources.

The optimum of safety is, of course, ensured by the installation of a special auxiliary set, nevertheless this is the most expensive solution. The power of this auxiliary unit should be from 1 to 2 percent of the total power of the plant. Under cold climatic conditions the reliability of the auxiliary generating set is questionable, since the intakes of small turbines may be blocked by frazil ice during winter. Therefore, for instance, in Sweden this method is seldom used for auxiliary a.c. supply.

With high capacity stations it is advisable to provide for at least two independent sources of a.c. supply.

The auxiliary a.c. power is, in general, a three-phase current having a voltage of 380 V. Lighting is effected by intermediate transformers of a step-down of 380/220 V.

The main devices that may be fed, in general, by the auxiliary a.c. current are:

- rotating converters (motor and d.c. dynamo) to supply exciters or booster exciters by d.c,
- motors driving the oil pumps for pressure maintenance (governor oil pumps),
- motor for oil-circulating pumps,
- motors for oil pumps lubricating the bearings,
- motors for automatic voltage regulators,
- motors for air compressors (for the circuit breakers),
- motors driving the cooling-water pumps of the transformers,
- motors of pumps feeding pressure oil into the hoists of the head gates,
- motors of drain pumps on turbine head cover,
- motors of drain pumps of the powerhouse substructure.

In emergency cases, i.e. if interruption occurs in the auxiliary a.c. supply, the above motors are switched over automatically to the d.c. circuit described later.

The hoists of the gates of the adjacent weir or spillway may also be supplied from the a.c. circuit of the station. In case of failure, reserve power is not ensured for this purpose by the d.c. resources of the station, since energy required for gate operation considerably exceeds the possibilities of an economical d.c. supply. (Reserves for gate control are: separate connection to the grid, emergency diesel generator or even manual lifting devices.

3.7.2 MIDDLE VOLTAGE SWITCHGEARS

Basically two different types are used:

1. Indoor : metalclad or open (in building)

2. Outdoor : overhead or metalclad (outside)

Basic Parts:
Bus with sufficient current carrying capacity adequate insulation level, mechanical resistance in case of short circuit.

Single Bus
Double Bus
Breaker :
- Load Breaking
- Load Connecting
- Generation Connection
- Sectionalising
- Short Circuit Breaking

Buses and Capacities
Typical Characteristics:
- Nominal voltage
- isolation level
- Nominal current
- Bus conductor size
- Rated short circuit cap
- mechanical constr.

These three main characteristics are determined by the project.

Generation output voltage distribution voltage.

3.7.3 SELECTION OF SPECIFICATION

Power Breaking: Nominal current (rated)
Depends on contacts
in specifications given for new equipment.

Type: Determined by ARC extinguishing
- Vacuum
- Small amount of oil
- Air blast
- Magneblast
- SF_6 - GAS

Application:

- Vacuum breaker
  up to 40 kV and 50 kA (TNT) 10,000 operations with nominal current or 25 years life-time.

  use in medium voltage distribution systems and in frequently used hydropower plants installations.

- Small amount of oil breaker
  from middle voltage to 250 kV and 20,000 k interrupting current, after 2,000 operations oil exchange.

- Air blast/Gas pressure) breaker
  for all ranges of voltages not used in middle voltage level, compressed air needed.

- Magneblast breaker
  for middle to low voltage levels, ARC interrupting in air and magnetic field. ARC chamber, breaking current 15,000.

- SF_6 - GAS breaker
  normally used for high and middle. Voltage level, capsuled and classical constructions. First with only 20% of need for space compared to conventional constr. Tendency lately towards SF_6 capsulated. Breaking currents 25,000 A (up to 30,000 A).

Banking for application in hydropower projects:

-	Small amount of oil	Low costs
-	Vacuum	Frequent operation
-	SF_6 conventional	Reliability
	capsulated	limited space

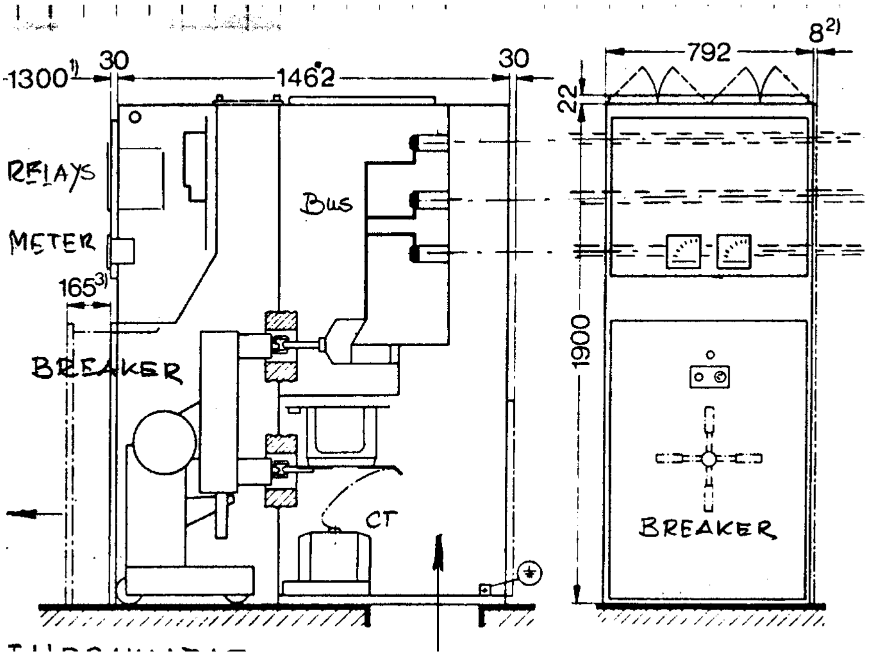

Figure 3-43

3.8 CONTROL AND PROTECTION

3.8.1 GENERAL

Contained under the heading of protection and control are all the technical aids and facilities necessary of the actuation, supervision, protection and optimum operation of all equipment in high and medium voltage networks.

The subject's scope extends from signalling relays on a high voltage breaker to complex management systems for networks and load dispatching duties.

The purpose of the secondary systems is together information at the high and medium voltage apparatus in the switching stations and to effect their on-site operation including the maintenance of secure power supplied. Additional contacts establish the interface with the tele-control system and hence with the network control facility.

The simplify normal routine operation make more efficient use of existing equipment and localise faults quickly the event of trouble, modern automation offers a variety of methods for processing and compressing information at the switching stations themselves so easing the burden on the network control centres.

Protective devices are required to safeguard the expensive equipment and transmission lines against overloads and damage by very quickly, and selectively isolating defective parts of the supply network e.g. in the event of line or earth faults. they are thus a major factor in ensuring consistent operation of the network.

Network management as a subdivision of network control systems helps to sustain the distribution of energy in evermore complex supply systems by providing each control centre with a continually up to date general picture of the entire network. All essential information is sent via tele-control links from the switching stations to the control centre, where it is instantly evaluated and corrective measures are taken. The growing flood of information means that conventional control rooms with minimised displays are increasingly being replaced by control systems using process computers and video terminals.

Load management consists in influencing the system load, possibly with the aid of ripple control which acting via the normal power network can easily disconnect and re-connect consumers or consumer categories. On the basis of current figures and forecasts it is possible to even out the generating plants load curves and make better use of available power reserves.

3.8.2 PROTECTION

Various protection devices are available for protecting generators, transformers, lines and power consuming equipment in networks with rated voltage > 1 kV. The purpose of the devices is to detect faults and isolate them selectively and quickly from the network as a whole so that the consequences of the fault are limited as much as possible. With today's high fault levels and highly integrated network, faults have far-reaching consequences both direct (damaged equipment) and indirect (loss of production).

Protection relays must therefore act very fast with the greatest possible reliability and availability.

Relays can be divided into various categories. A basic distinction is made with respect to the function in contractor relays and measuring relays. Other distinguishing characteristics are:

- The relay's construction. (e.g. circuit board relays, reed relays, miniature relays, mercury wetted relays)
- The relay's operating principle (e.g. attracted armature relays - immersed armature relays, moving coil relays)
- The relays location (e.g. telephone relays, antenna relays, generator protection relays, network protection relays)
- The relay's specific function (e.g. signalling relays, time delay relays, control relays, DSc relays)

The relays require performance (e.g. heavy current relays, high/low temperature relays, DSc relays)

The relays used for protection purposes together with the supervisory relays, fall into the category of measuring relays and, as electric relays become more wide spread, of solid state measuring relays. All the types of relays mentioned are used to transmit clearly defined fast and carefully isolated indication and control signals from low energy electronic circuits to external circuits.

3.8.2.1 PROTECTION RELAYS AND PROTECTION SYSTEMS

The protection relays and systems commonly used today are increasingly of the solid state type, though electro-mechanical examples still exist.

3.8.2.1.1 OVER CURRENT RELAYS

Currents above an adjustable threshold value are detected in one or more phases and interrupted after a presentable time. The release time is the same, no matter how much the threshold has been exceeded by. Over current relays are used in radial networks with single in feed.

Depending on the system's fault power, the relays are incorporated directly into the circuit (primary relays) or coupled through current transformers (secondary relays).
With a direction sensing element that measures current and voltage the relay can be made to provide directional time-over-current protection. Such relays are used mainly on parallel lines.

3.8.2.1.2 OVERHEAD RELAYS

The temperature conditions at the protected object are simulated with the same time constant in the relays. Any load bias is taken into account by the thermal replica in the relay in accordance with the heating and cooling curves. Alarm signals or tripping commands are given if a set temperature is exceeded. The relays are built as primary or secondary relays. Secondary relays usually operate in two or more stages. Over load relays are used on machines that can overheat, such as transformers and motors but occasionally on cables too.

3.8.2.1.3 DIFFERENTIAL RELAYS

The currents measured at the beginning and end of the protected object are matched in phase angle and magnitude and compared in a measuring element. If a set ratio of difference current to through current is exceeded, the relay emits a tripping demand.

Modern relays contain all the components needed for differential protection.

- Matching transformer
- Signally and tripping devices
- Inrush stabilisation

Differential relays are available for transformers or generators. Differential relays for lines have a measuring element at each end. The relays are linked by pilot wires. These require supervision to ensure that protection system operates correctly.

3.8.2.1.4 DISTANCE RELAYS

The distance of a fault from the relay is assigned to a tripping range by measuring the resistance with reference to the fault current and voltage. In accordance with an adjustable distance/time characteristics set on the relay, the relay trips the appropriate circuit breaker or serves as back-up protection. Distance relays operate selectively and extremely quickly in meshed networks with multiple in feed and need no auxiliary link.

3.8.2.1.5 AUTO RECLOSE RELAY

An auto reclose relay interrupts once or three phases of the energy supply registered by the time over current relay or distance relay, and then reconnects it after an adjustable intervals of about 300 ms. The arc across the fault is able to de-ionise during this time and operation can resume without interruption. Failure to reclose results in 3 phase lock out.

3.8.2.1.6 BUSBAR PROTECTION

The quantities from a number of measuring points which respond in different ways to faults on the branch lines or in the busbar system are evaluated in a measuring circuit. Owing to the difficulty of obtaining measurements (transformer saturation) and the high speed needed to limit damage in the case of high short circuit powers. It is preferable to use electronic protection systems. Busbar protection systems often include back-up in the form of breaker failure protection.

3.8.2.1.7 DIRECTIONAL EARTH FAULT RELAYS

An indication of direction is obtained from the relative vectorial position of neutral current and neutral voltage. The site of the fault is identified by comparing the values measured in the network. Other methods of measurement are also possible.

3.8.2.1.8 FREQUENCY RELAYS

If the frequency goes above or below set limits or fluctuates at an un-acceptable rate (dl/dt), this is detected, resulting in disconnecting or load rejection. With measuring accuracy and reproducibility of 0.6%, solid state relays are vastly superior to mechanical systems.

Voltage deviations are indicated allowing the system load to be reduced as necessary. Other protective devices used specifically with certain system components include interim fault relays, negative sequence relays, reverse power relays for generators, buchhoz relays, temperature monitors, oil level indicators, oil and air flow indicators for transformers and insulation monitoring for conductors.

3.8.3 BATTERIES AND CHARGERS

Batteries are used in switchgear installations for supplying power to control, protection, regulation and signal circuits etc. independently of the main power system.

The d.c voltage from the battery is used directly or via inverter to produce source a.c. voltage. In installations with modern secondary systems the source a.c. voltage is fed to the power inputs of computers and electronic protection facilities.

The voltage rating and capacity of a storage battery are determined by the permitted voltage tolerance of the individual loads (switchgear and protection devices), the power consumption of the various loads, the length of time they are in operation and the manner in which they draw power. Two main types of batteries are used for switchgear installations.

1. Lead-acid batteries with electrodes of lead and lead compounds and dilute sulphuric acid as the electrolyte. They are employed in switchyard, transformer stations and power plants to cover even relatively high power demands for considerable length of time.

Nickel-cadmium batteries with positive electrodes of nickel compounds, negative electrodes of cadmium and dilute potassium hydro-oxide as the electrolyte. They are used mainly in small to medium size switchgear installations where space is limited. Compared with lead acid batteries they have certain advantages and disadvantages such as.

- Greater mechanical strength (2) Easy to maintain (3) Longer life (4) space requirement and weight significantly smaller.
- Higher consumption of distilled water, electrolyte must be changed every two years.
- Much more expensive
- Sensitive to temperature.

If acid batteries are to be used in warm-dry or warm-wet climates, the ambient temperature must be taken into account at the planning stage, and appropriate measures agreed with the manufacturer. Information concerning soaking charge, maintenance charging and changing the electrolyte must also be obtained well in advance.

3.8.3.1 RATED VOLTAGE

The rated voltage (UN) of a cell is fixed value. For lead acid batteries it is 2.0 v, for nickel cadmium batteries is 1.2 v.

The rated voltage of a battery is the product of the number of series-connected cells and the rated cell voltage.

3.8.3.2 BATTERY RATING

The normal rating (KN) of a battery is its capacity to discharge for a specified time (nominal discharge time tn) at its rated current (IN) with the electrolyte at its nominal temperature, density and level) without the voltage falling below the final discharge voltage (USN).

The formula is KN = IN x tN

The rating of a battery is specified in a number (n) of ampere-hours if it discharges at currents other than the nominal current.

3.8.3.3 FINAL DISCHARGE VOLTAGE

The final discharge voltage (USN) is a defined value below which the voltage must not fall when discharging at the specified current.

The nominal final discharge voltage (USN) is used to determine the nominal rating kN when power is drawn at the nominal discharge current IN=kN/tN.

3.8.3.4 GASSING VOLTAGE

The gassing voltage (UG) is the charging voltage above which gas formation becomes clearly apparent in the battery, with lead acid batteries 1.40 to 1.45 v per cell, with nickel cadmium batteries 1.55 to 1.60 v per cell.

3.8.3.5 FACTOR OF CHARGING & DISCHARGING

Storage batteries require a controlled current source for recharging them. Depending on the application, it must also be able to supply the load direct. The quantity of charge needed for a lead acid battery is 110%, for a nickel cadmium battery approximate 140% of the Ah previously discharged. The self discharge current of a lead acid battery is roughly 0.2% of the three hour discharge current or daily about 1% of the ten hour capacity.

The value is stated by the manufacturer. With lead acid batteries, the charging current is usually equal to the discharge current at the three or five hour rate, when the gassing voltage has been exceeded it should be reduced to approximately one-third of the charging current stated above, and then reduced further until charging is complete. Fully charged batteries must be disconnected from the charging source to avoid damage due to continued gassing and increasing temperature. The charging time with the charging current. The higher charging current must nevertheless remain limited to the range of charging voltage of 2.1 to 2.4 v per cell. Here one must check where the connected loads are designed for the higher voltage. If batteries are unused or on standby for prolonged periods, they must be brought up to full charge at intervals as instructed by manufactures, otherwise harmful sulphating of the plates occurs which increases the internal resistance and reduces the capacity.

3.8.3.6 TYPE OF BATTERY OPERATION

If loads are fed direct from battery and the battery is disconnected form the loads for charging purposes, this is termed pure battery operation. If loads also have to be supplied with power during charging than another battery is required.

With parallel operation, load, rectifier and battery are permanently connected in parallel. Here a distinction is made between floating operation (battery is used to maintain voltage and cover peaks) and standby parallel operation (battery supplies power only if wreckage and cover peaks) and standby parallel operation (battery supplies power only if rectifier fails) standby parallel operation is the most common method. With changeover operation the battery is disconnected from the load, it is kept fully charged. The battery is connected to the load if the normal power source fails.

3.8.3.7 IMPORTANT NOTE

When planning station service system in which the source a.c voltage is produced by series connected rectifiers and inverter, the characteristics of both converters must be matched to each other for all load conditions. The selectivity of the two voltage feeding devices must be able to supply at least 5 times the rated current for a short time while adhering to the voltage reduction.

3.8.3.8 BATTERY SELECTION

The design of battery facilities is governed by the load conditions occurring in the switching installation. Here it is important to identify all the d.c users and the maximum required time on standby power if the main supply fails.

Battery selection is based on the manufacturers literature, the appropriate time being chosen in relation to current, capacity, discharge time and voltage range.
With parallel operation, the number of cells in a battery is calculated from the maximum trickle charge voltage and the maximum permitted continuous demand voltage.

n < {UV max + DELTA Umin} / {UZLE\ max}

Where

n = number of cells
UVmax = Max. permitted continuous voltage
Umin = Smallest possible voltage drop between battery and consumer
UZLE max = Max. trickle charge voltage per cell
UZLE max = UZLE + 1%

Static or dynamic loading must at no time during the discharge period allow the battery voltage to drop below the minimum value demanded by the consumers UVmin. The minimum cell voltage is defined as

UZmin Z > {UV min + DELTA Umax}/ {n}

where

UZmin = Minimum voltage of an individual cell
UVmin = Minimum permitted continuous voltage
Umax = Largest possible voltage drop between battery terminals and consumer
n = Number of cells

The battery rating is selected by reference to the capacity curve at 20 c of the chosen cell type such that the voltage according to the current/time discharge diagram does not fall below the minimum value Umin while power is being drawn.

3.8.3.9 INSTALLATION OF BATTERIES

3.8.3.9.1 TYPE OF INSTALLATION

1. Each cell container must be insulated individually with respect to earth.
2. Batteries may be mounted on

a. wooden floor frames
b. stepped wooden frames in two rows one behind the other
c. wooden racks
d. floor mounted insulators with no frame.

As regards maintenance, it is most convenient to have the cell arranged on one level. Stationary batteries are available as screwed or welded types. Here it must be noted, however, that with large batteries the bolted type is possible only up to a capacity of k10=504 Ah. Larger batteries are available only in welded form, as the voltage drop across screw terminals would be too great.

3.8.3.9.2 BATTERY ROOMS

Battery rooms must be built in accordance with J31 of the AGI.

Battery rooms are restricted access rooms of normal walking height containing batteries for supplying power to electrical installations. They are treated as electrical premises, if the installation is designed for rated voltage up to 220 v, and as locked electrical premises if the installation is designed for rated voltage above 220 v.

Figure 3-44 & 3-45 shows selection curves for lead-acid batteries type GroE and Nicd type T/tp. The curves represent the nominal capacity in percent as a function of constr. discharge current, with final discharge voltage and discharge times as parameters.

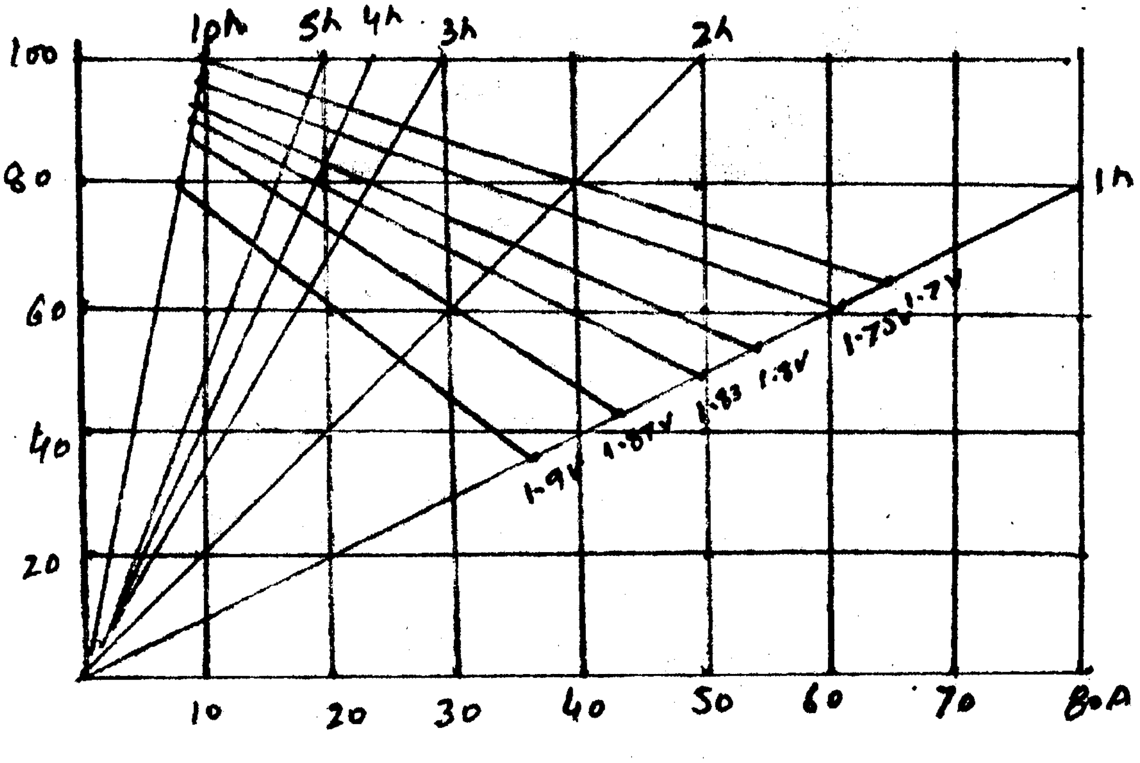

Figure 3-44 Selection curve for lead acid batteries referred to k10 = 100 Ah.

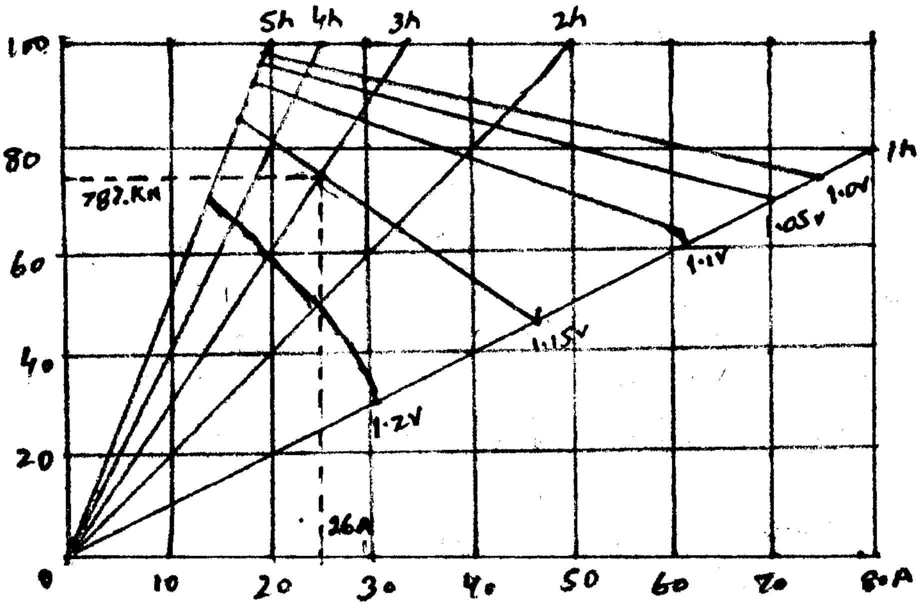

Figure 3-45 Selection curves for Nicd batteries referred to k5 = 100 Ah.

3.9 EARTHING (GROUNDING)

3.9.1 GENERAL

The general purpose of earthing system is to protect life and property in the event of

a. 50 Hz faults (short circuit)
b. Transient phenomena (Lighting, switching operations).

The most important terms relating to earthing systems are summarised below.
Earth refers both to the earth as a place and to earth as a substance e.g. humus, clay, sand, gravel, rock.

Reference earth (neutral earth) is that part of the earth, particularly the ground surface outside the sphere of an earth electrode or earthing system, between two random points in which there occurs no perceptible voltage resulting from the earthing current. Earth electrode is a conductor which is embedded in the ground and electrically connected to it, or a conductor embedded in concrete which is in contact with the earth over a large area (e.g. foundation earth.). Earthing conductor is a conductor connecting a piece of equipment to an earthing electrode provided it is not in the ground or in the ground but insulated.

If the connection between a neutral or outside conductor and the earth electrode includes an isolating link, a disconnector or an earth fault coil, only the connection between the earth electrode and the earth side terminal of the nearest of such devices is deemed to be an earthing conductor.

Main earthing conductor is an earthing conductor to which a number of earthing conductors are connected.

However it does not include:

- Earthing conductors joining the earthed parts of the separate items of 3-Phase assemblies 3 instrument transformers, 3-potheads, 3 post insulators etc.

- In compartment type installations, earthing conductors which joint together parts of several pieces of apparatus in a compartment and are connected within this compartment to a (continuous) main earthing conductor.

EARTHING system is the located delimited sum total of consecutively interconnected earth electrodes or metal parts acting in the same manner (e.g. tower feet, armouring, metal cable sheaths) and earthing conductors.

To earth means to connect an electrically conductive part to earth by way of an earthing system. Earthing is the total of all means and measures employed for this purpose. Earth resistivity (PE) is the specific electrical resistivity of the earth. It is usually expressed in m^2/m = m and then denotes the resistance of a cube of earth with sides/m long between two adjacent cube faces.

Dissipation resistance (RA) of an earth electrode is the resistance of the earth between the electrode and the reference earth.

Earthing Impedance (ZE) is the a.c. impedance between an earthing system and the reference earth operating frequency. The value of the earthing impedance is found by paralleling the dissipation resistance of the earth electrodes and the impedances of connected conductor strings, e.g. earth wires and cables acting as earth electrodes.

Impulse earthing resistance (Rst) is the resistance presented to the passage of lightning/currents between a point of an earthing system and the reference earth.

Protective earthing is the earthing of a conductive component not forming part of the normal electrical circuit in order to protect people from unacceptable touch voltages.
System earthing is the earthing of a point in the normal electrical circuit in order that apparatus or systems can be maintained properly.

It is termed.

- Direct, if it contains n resistances other than the earthing impedance.
- Indirect: if it is established by way of additional Ohmic, inductive or capacitive resistance.

Lightning protection earthing is the earthing of a conductive part not forming part of the normal electrical circuit in order to avoid as far as possible flash-over to the normally live conductors as a result of lightning stroke (back flash-overs').

Earthing voltage (VE) is the voltage occurring between an earthing system and reference earth surface potential is the voltage between a point on the earth's surface and reference earth.

Touch voltage (VB) is the part of the earthing voltage which can be shunted through the human body, the current path passing from hand to foot (horizontal distance from touchable part about 1 m) or from hand to hand.

Step voltage (VS) is that part of the earthing voltage which can be shunted by a person with a stride 1 m long, the current path passing from foot to foot. Potential control consists in influencing the earth potential, in particular the earth surface potential by earth electrodes.

Earth fault is electrical connection between one conductor of the normal electrical circuit and the earth or an earthed part due to a defect. The electrical connection can also be way of an a.c.

Earth fault current I_F is the current passing to earth or to earthed parts when an earth fault exists at only one point at the site of the defect. It is:

- The capacitive earth fault current I_C in networks with isolated neutral.
- The earth fault residual current I_{Rest} in networks with earth fault neutralisation.
- The short circuit current to earth I_{K1pol} in networks with low resistance neutral earthing.

Earthing current I_E is the total current flowing to earth by way of the earthing impedance.
The earthing current is the component of the earth fault current I_F which causes the rise in potential of an earthing system.

3.9.2 TYPES OF EARTH ELECTRODES

Classification by location.

- Surface earth electrodes are generally placed at shallow depths of up to about 1 m. They can be of strip, bar or stranded wire and be arranged as radial, ring or meshed electrodes or a combination of these.
- Deep earth electrodes are generally sunk vertically to greater depths. They can be of tubular, round or sectional material: Classification by form and cross-section strip, stranded wire and tube electrodes.

Natural earth electrode is a metal part in contact with the earth or water, directly or by way of concrete, whose original purpose is not earthing, but which acts as an earth electrode. Example include pipes, caisson walls, concrete pile reinforcement, steel parts of buildings etc.

Cable with earthing effect is a cable whose metal sheath, shield or armouring provides leakage to earth of a magnitude similar to that of strip type earth electrodes.

Foundation earth electrodes are conductors embedded in concrete which is in contact with the earth over a large area. Foundation earth electrodes may be treated as though the conductor were laid in surrounding soil.

Control electrodes are earth electrodes which by their form and arrangement serve more for voltage grading than for maintaining a particular dissipation resistance.

Rod electrodes of any significant length usually pass through soil layers of different conductivity's. They are particularly useful where lower layers conduct better and the rods penetrate sufficiently into such layers (about 3m). On site measurement of the soil's resistivity will show whether more conductive deeper layers are present.

3.9.3 MATERIALS FOR EARTHING SYSTEM

Earth electrodes (under ground) and earth conductors above ground must conform to certain minimum dimensions for mechanical strength and must withstand possible corrosive attack.

With regard to corrosion where there is no connection to other materials, the following points should be born in mind when selecting the metals for earth electrodes.

a. Hot galvanised steel is very durable in almost all kinds of soil. Hot galvanised steel is also suitable for embedding in concrete. Contrary to foundation electrodes, earth conductors embedded in concrete, equipotential bonding conductors and lightning conductor. Leads of galvanised steel can be connected to reinforcing steel if the junction points are not exposed to prolonged temperatures higher than 40 C.
b. Copper is suitable for earthing electrodes in power installations with high fault currents because its electrical conductivity is much higher than that of steel.

c. Bare copper under the soil is generally very durable.
d. Copper coated with tin or zinc-like bare copper is generally very durable under the soil. In electro-chemical terms tin-plated copper has no particular advantages over bare copper.
e. Copper with lead sheath: lead tends to form a good protective layer underground and is therefore durable in many kinds of soil. However in strongly alkaline surroundings there is a risk of corrosion. Lead must therefore not be embedded directly in concrete. Underground there is a risk of the sheath corroding if it is damaged.

The area risk means that the ratio of the anodic area F.A. (e.g. steel) to the cathodic area F.k. (e.g. copper) is crucial to the formation of corrosive elements. As the area ratio FA/Fk decreases, the rate of corrosion at the anode surfaces rises sharply. Coated steel tube conductors are therefore at risk at the junction with an earthing system or copper because the area ratio of steel to copper becomes unfavourable at defects in the pipe coating, giving rise to rapid corrosion (puncture), therefore does not allow pipes of this kind to be joined to earth electrodes of copper.

3.9.4 DIMENSIONING OF EARTHING SYSTEMS

The cross-section of earth electrodes and earthing conductors must be such that the material's strength is not reduced in the event of a fault current I_F (I_{KIP} for systems with low resistance neutral earth). The necessary cross-section can be calculated as follows:

$$\mathrm{A} = l_F \frac{\sqrt{t_F}}{k}$$

Where

I_F = Fault current
t_F = Duration of fault current
K = Coefficient of material

The material coefficient for copper is

$$\mathrm{k} = 226 \frac{\sqrt{l_n (1+g_t-g_i)}}{234.50^\circ C + l_l} A \sqrt{S/mm^2}$$

Where

gi = initial temperature in C
gt = max. permitted final temperature

For the earthing grid of a switchgear installation the dissipation resistance can be calculated as follows:

$$\mathrm{RA} = \frac{P}{4}\sqrt{\frac{\pi}{4}}$$

Where

P = specific resistivity of soil
A = Area covered by earthing grid

Measurements for earthing systems: The specific resistance P_E of the soil is important for calculating earthing systems. Wherever possible, therefore P_E should be measure before construction on a switchgear installation begins.

It is also possible to determine the earthing impedance of the installation by measuring the potential gradient area.

3.9.5 PROTECTION

3.9.5.1 PROTECTION AGAINST DIRECT CONTACT

The danger of touching their live parts is particularly great in switchgear installations because in locked electrical premises the equipment does not have any shock protection or the protection can become ineffective on opening the cubicle doors.

Protection against direct contact is always necessary, regardless of the voltage. An exception is when the voltage is produced according to the regulations for low voltage safety protection (e.g. safety isolating transformers) or motor generator as does not exceed 25 v a.c. or V d.c.

A distinction is made between full and partial protection against direct contact. Full protection is obtained by insulating, enclosing or covering the live parts and is essential if equipment is operated by electrically untrained personnel. This kind of protection should be chosen wherever possible. With switchgear, however, intervention is occasionally necessary to restore things to the normal condition e.g. actuating line protection switches, changing indicating lamps in which case there is only partial protection against direct contact. Such operations must be undertaken only by at least electrically instructed personnel.

3.9.5.2 ADDITIONAL PROTECTION IN CASE OF DIRECT CONTACT

The purpose of additional protection is that if direct contact with live parts does occur, no potentially fatal current can flow though the body. This protection is provided by using highly sensitive residual current operated circuit breaker or earth leakage circuit breakers. Additional protection in case of direct contact is not permissible as the sole form of protection. The conditions for protection against direct contact must also be satisfied.

3.9.5.3 PROTECTION IN CASE OF INDIRECT CONTACT

Dangerous touch voltage must be prevented from occurring or persisting in the event of a fault. The limit values for touch voltages are 50 V a.c and 120 V d.c. The measures of safety extra low voltage, functional extra low voltage with and without definite isolation ($\leq$ 50 V a.c, $\leq$ 120 V d.c) and limitation of discharge energy ($\leq$ 350 mj) satisfy the requirements for protection against direct contact and also in case of direct & indirect contact.

In case of extra low voltage, not only must the voltage be generated safely, but also neither live nor dead parts may be earthed.

With functional extra low voltage, earthing is not forbidden. Depending on how the voltage is produced, a distinction is made between functional extra low voltage with or without definite isolation.

.

Table 3-18Minimum dimensions for earth electrodes and earth conductors.

Material	Form	Dimensions	Dimensions
Copper			
a.	Strip	50 mm^2 (Min. thickness 2 mm)	25 mm^2
b.	Stranded wire	16 mm^2 (only for earth conductors above ground 35 mm^2	16 mm^2 (for corrosion protected conductors)
c.	Copper bar	16 mm^2 (only for earth conductors above ground	
Steel			
a.	Strip	100 mm^2 (Min. thickness 3 mm) 50 mm^2	16 mm^2 (for corrosion protected conductors)
b.	Steel bar	78 mm^2 (Eqt. to 10 mm dia) with made up driven electrodes at least 20 mm^2 dia 50 mm	
c.	Tube	25 mm (Min. wall thickness 2 mm)	
Copper coated steel	Steel sections	15 mm^2 (Min. wall thickness 2 mm)	No Data
	Steel bar	100 mm^2 (Min. thickness 3 mm) 50 mm^2 (For copper coating 20% of steel cross-section min. 35 mm^2), made up driven electrode at least	
Aluminium		25 mm^2	No Data

3.10 SHORT CIRCUIT CURRENTS CALCULATION

3.10.1 DEFINITION

Short circuit current is the current which flows across the point of the fault for the duration of the short circuit.
In three phase network a distinction is made between the following kinds of fault.

a. Three phase fault
b. Phase to phase fault clear or earth
c. Two phase to earth fault
d. Phase to earth fault
e. Double earth fault

A 3-phase fault affects the three phase network symmetrically. All three conductors are equally involved and carry the same r.m.s. short circuit current. All other short circuit conditions on the other hand incur asymmetrical loadings. Calculation need therefore be for only one conductor.

The formula for calculating initial short circuit current and short circuit powers is developed below:

a. Three phase fault with or without earth fault (Fig 3-46)

$$I''_{K3p} = \frac{1.1 * 100\%}{\left|\sqrt{3} * \underline{z}_1\right|} * \frac{1}{U_N}$$

Where

I''_K = short ckt. current
Z_1 = positive sequence impede
U_N = system operating voltage

$$S''_K \frac{\left[\sqrt{3}*1.1*100\%\right]}{\underline{z}_1}$$

b. Phase to phase fault clear of earth: (Fig 3-47)

$$I''_{KE2pE} = \frac{\sqrt{3}*1.1*100\%}{\left|\underline{z}_1+\underline{z}_o+\underline{z}_o\dfrac{\underline{z}_1}{\underline{z}_2}\right|}*\frac{1}{U_N}$$

Where
Z_o = Zero sequence impede
Z_1 = positive sequence impede
Z_2 = Negative sequence impede

c. Two phase to earth fault(Fig 3-48)

$$I''_{K2p} = \frac{1.1*100\%}{\left|\underline{z}_1+\underline{z}_2\right|}*\frac{1}{U_N}$$

d. Phase to earth fault(Fig 3-49)

$$I''_{K1p} = \frac{\sqrt{3}*1.1*100\%}{\left|\underline{z}_1+\underline{z}_2+\underline{z}_o\right|}*\frac{1}{U_N}$$

Note:
I''_K is in KA
S''_K is in MVA
U''_N is in kV
Z is in %/MVA

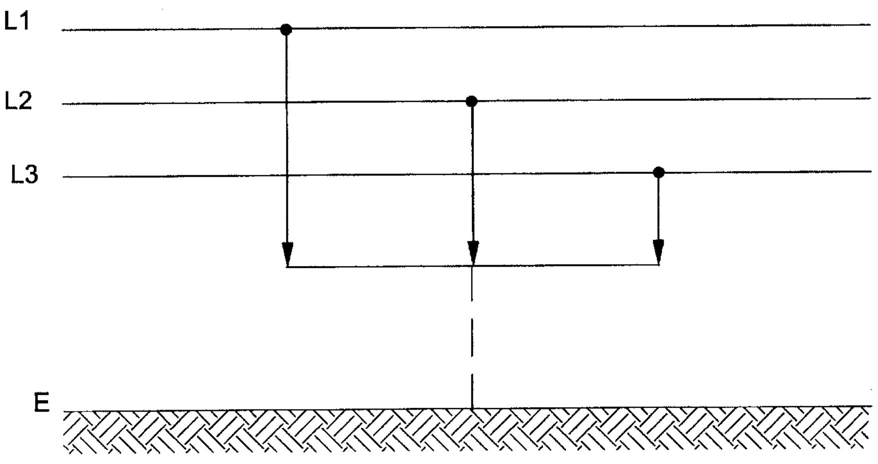

Figure 3-46 Three phase fault with or without earth fault

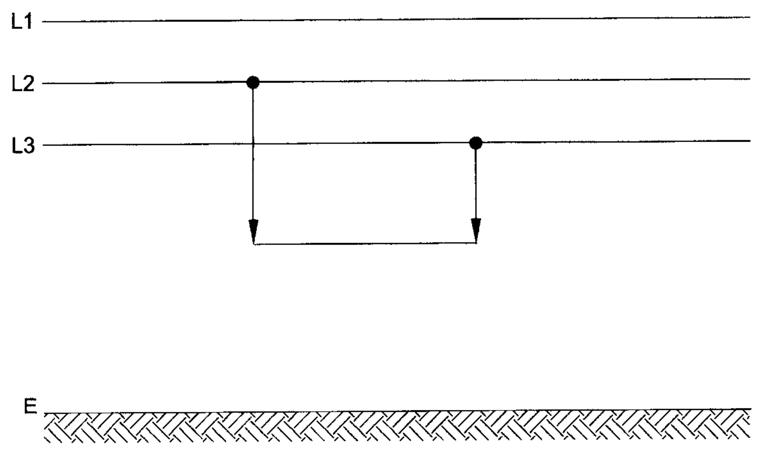

Figure 3-47 Phase to phase fault clear of earth:

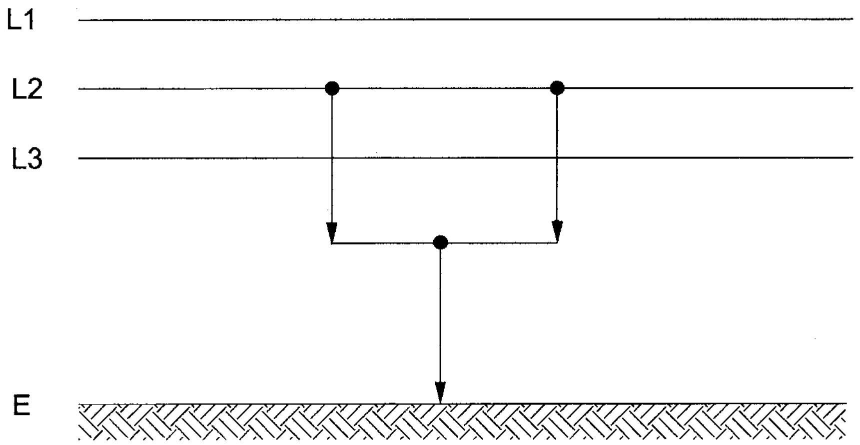

Figure 3-48 Two phase to earth fault

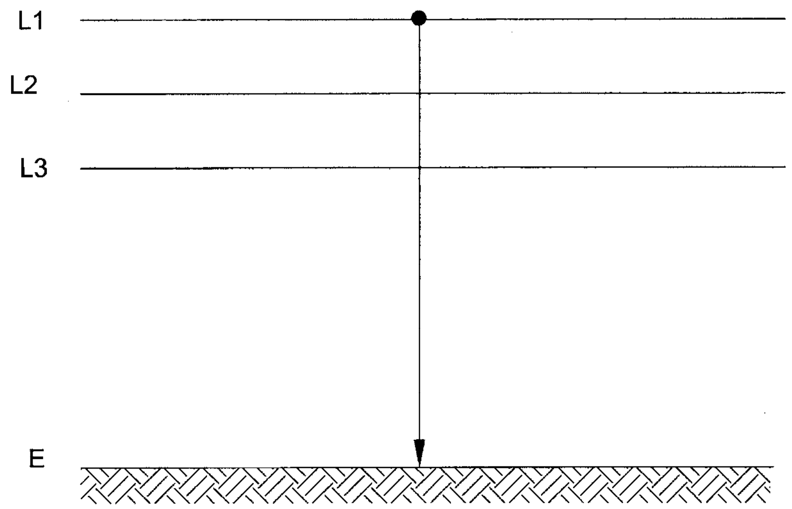

Figure 3-49 Phase to earth fault

Example of Calculation

When calculating S.C.C. in high voltage installations, it is often sufficient to work with reactance because reactance is generally much greater in magnitude then the effective resistance. The ratio of the rated system voltages are taken as the TRF ratios instead of the operating voltages of the faulty networks with the rated system the same as the rated system voltage at their respective locations.

Example

To calculate the short circuit power Sk", the peak short circuit current Is. This example concerns a fault with more than one indeed and partly common current paths.

$$\mathrm{X_Q} = \frac{1.1*100}{S''_{KQ}} = \frac{110}{8000} = 0.0138\%\ MVA$$

$$\text{Transformer 1}\quad \mathrm{X_{T1}} = \frac{U_K}{S_{NT1}} = \frac{13}{100} = 0.1300\%\ MVA$$

$$\text{Generator}\quad \mathrm{X_G} = \frac{X_d}{S_{NG}} = \frac{11.5}{93.7} = 0.1227\%\ MVA$$

$$\text{Transformer 2}\quad \mathrm{X_{T2}} = \frac{U_K}{S_{NT2}} = \frac{7}{8} = 0.8750\%\ MVA$$

$$\text{Induction Motor}\quad \mathrm{X_{M1}} = \frac{I_{NM}\ I_{start}}{S_{NM}}*100 = \frac{1}{5*2.69}*100 = 7.4349\%\ MVA$$

$$\text{Induction Motor}\,Group\quad \mathrm{X_{M2}} = \frac{I_{NM}\ I_{start}}{S_{NM}}*100 = \frac{1}{5*8*0.46}*100 = 5.4348\%\ MVA$$

For the location of the fault one must determine the total reactance of the network. This is done by step by step system transformation until there is only one reactance at the terminals of the equivalent voltage source. This is then the short circuit reactance.

3.11 PANELS

If specially stated the control panels can have location of instruments, switches, semaphores, enunciators and mimic as indicated in drawing No. PDW/TS-1924 or alternatively as advised by Engineer/WAPDA.

3.11.1 CONTROL PANELS

CP10 - It is a control panel for isolator controlled line.

There are three versions of control panels for breaker controlled lines without P.T. arrangements. More versions may be added subsequently in this series.

a) CP-20 - It is the basic control panel of this series.
b) CP-21 - Same as CP20 but with inverted mimic bus.
c) CP22 - Same as CP20 but with mimic for double bus.

There are three versions of control panel of this series.

a) CP30 - It is the basic control panel of this series.
b) CP31 - Same as CP30 but with inverted mimic bus.
c) CP32 - Same as CP30 but with mimic for double bus.

CP40 - It is a control panel for a bus coupler.

There are two versions of control panels for two-winding power transformer. More versions may be aided subsequently in this series.

a) CP50 - It is the basic control panel of this series.
b) CP51 - Same as CP50 but with mimic for double bus.

There are two versions of control panels for three winding power transformers. More versions may be adopted subsequently in this series.

a) CP60 - It is the basic control panel of this series.
b) CP61 - Same as CP50 but with mimic for double bus.

3.11.2 RELAY PANELS

a) RP1 - It is a line relay panel without any distance protection.
b) RP2 - It is a line relay panel with distance protection without carrier facility.
c) RP3 - It is a line relay panel with distance protection and carrier facility.
d) RP4 - It is a relay panel for 2-winding power transformer.
e) RP5 - It is a relay panel for -winding power transformer.

The following dimensions of the panels and face sheet have been standardised:

Control Panel	...	600	X	600	X	2200	mm
Relay Panel	...	800	X	600	X	2200	mm
Face Sheet	...	600	X	2200			mm

3.11.3 EQUIPMENT LOCATION

The audio system, that is, hooters, siren and bell shall be mounted inside the transformer control panels only.

The terminal block assembly shall be mounted on the inner side of the panels at an angle of 45 degree to the horizontal towards the door to facilitate working.

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