31 An isolated phase bus system

Contents

31.1 Isolated phase bus (IPB) system

In this construction the conductors of each phase are housed in a separate non-magnetic metallic enclosure to isolate them completely from each other with the following objectives:

1 It eliminates phase-to-phase faults.
2 It eliminates the proximity effect (extra forces and heating) by providing a magnetic shielding to the supporting and metallic structures in the vicinity.
3 It reduces the proximity effects between the main current-carrying conductors of the adjacent phases to almost zero due to magnetic shielding and large centre spacing.
4 It provides complete protection for operating personnel from high touch or step voltages (for details see Section 22.9) across the enclosure and the metallic structures caused by parasitic (electromagnetic) currents.
5 The bus system is easy to handle, bend and instal.

This is used for HV systems of very large ratings. Since it is a more expensive arrangement it is normally preferred only for critical installations such as a power generating station, where it has to carry large to very large currents due to high ratings of the generating units. In a thermal power plant it is used between the generating unit (G) and the generator transformer (GT) and the unit auxiliary transformers (UATs) and sometimes between the UAT and the unit HV switchgear as illustrated in Figure 13.21 (redrawn in Figure 31.1 for more clarity). A typical layout of such a bus system in a thermal power plant is illustrated in Figure 31.2(a) and (b). It may comprise sections noted in Section 31.1.1.

Gas insulated busbars (GIB) The above features would be easily possible in an SF_6 bus systems also but that being a costlier arrangement is usually not adopted. However, when required at locations having space constraints or other hindrances such as within a power generating station, such bus systems are an immediate solution. Also see Section 19.10.

31.1.1 Main run and auxiliary feed lines

1 From generator phase terminals to the lower voltage side of the GT. This section may partly be indoors, connecting the generator inside the turbine room and partly outdoors, connecting the GT in the transformer yard.
2 A generator neutral bus to form the generator star point.
3 Tap-offs with tee joints from the main run to the two UATs.
4 Sometimes from UAT secondaries to the unit HV switchgears.
5 If the GT is made of three, single-phase transformers, an inter-connecting IPB will be required to form the delta as illustrated in Figure 31.2(b).

31.1.2 Instrumentation and protection connections

Since an IPB forms an important integral part of a power-generating station, with it are associated a number of metering and protective devices such as CTs, VTs and generator grounding system. Below we identify inter-connections that may be required to connect these CTs and VTs while installing an IPB system.

1 Removable links for easy mounting and maintenance of CTs for metering and protection, typically as follows. For each phase in the main lines between the generator and the GT,
   • 1 CT for metering

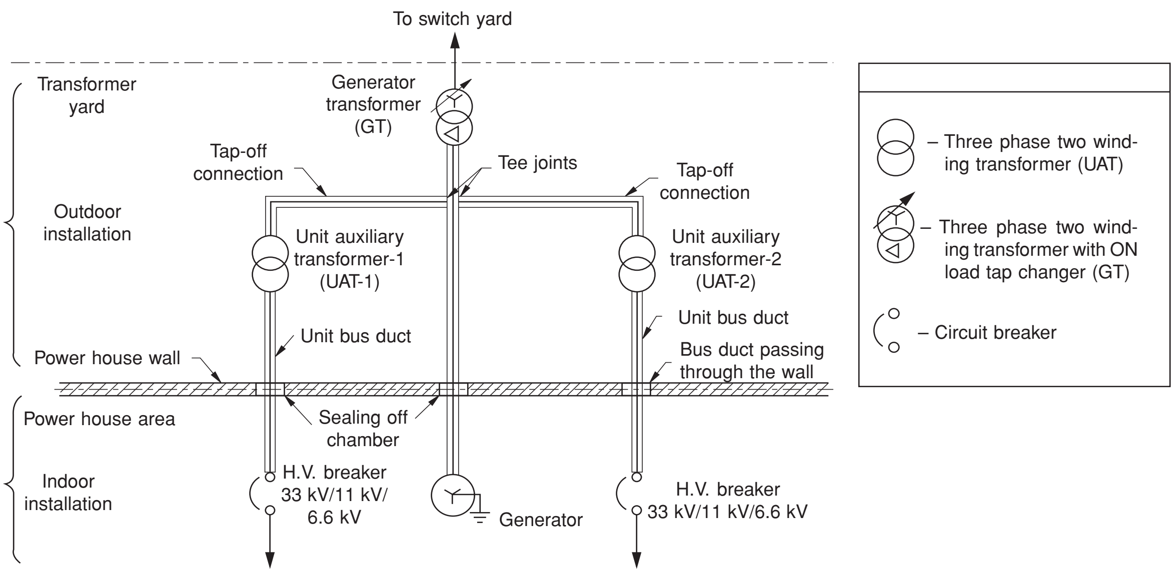


Figure 31.1 Application of an IPB

- 1 CT for protection
- 1 CT for AVR (automatic voltage regulator)
- 1 CT for differential protection

Note
For measuring purposes non-conventional Rogowski coils (Section 15.11) can be employed.

For each phase on the neutral side, 1 CT for differential protection, two sets of three CTs each for metering, in the tap-offs for the two UATs and two sets of three CTs each for protection in the tap-offs for the two UATs.

2 Tap-offs with a neutral CT, from star point of the generator, to the neutral grounding transformer (NGT).
3 VTs and surge protection tap-offs for each phase from the main run, for metering and surge protection.

Any other connections, that may be necessary at site or additional CTs for protection.

31.1.3 Shorting of phase enclosures

For continuous enclosure IPBs, the following ends of the enclosures are shorted to ensure continuous flow of induced currents:

- At the generator end, as near to the generator terminals as possible.
- GT ends, as near to the transformer flanges as possible.
- UAT ends.
- Both sides of the neoprene or EPDM rubber or metallic expansion bellows (Figure 31.2(a)).
- Near the generator neutral terminal.
- Any other section, where it is felt that it is not properly bonded and the induced currents may not have a continuous path.

The enclosure, however, should be insulated at all such locations, where the IPB terminates with another equipment, such as at the generator, GT, UATs, VTs, and the NGT to avoid longitudinal currents through such equipment as shown in Figure 31.2(b). These equipments are grounded separately.

31.2 Constructional features

As discussed later, the enclosure of an IPB may carry induced currents up to 95% of the current through the main conductors. Accordingly, the enclosure is designed to carry longitudinal parasitic currents up to 90–95% of the rated current of the main busbars. The cross-sectional area of the enclosure is therefore maintained almost equal to and even more than the main conductors to account for the dissipation of heat of the main conductors also through the enclosure only, unless an additional forced cooling system is adopted. The outdoors part of the enclosure exposed to atmospheric conditions is also subjected to solar radiation. Provision must be made to dissipate this additional heat also, from the enclosure.

The main bus and its enclosure is normally in a tubular form, in view of the inherent advantages of a tubular

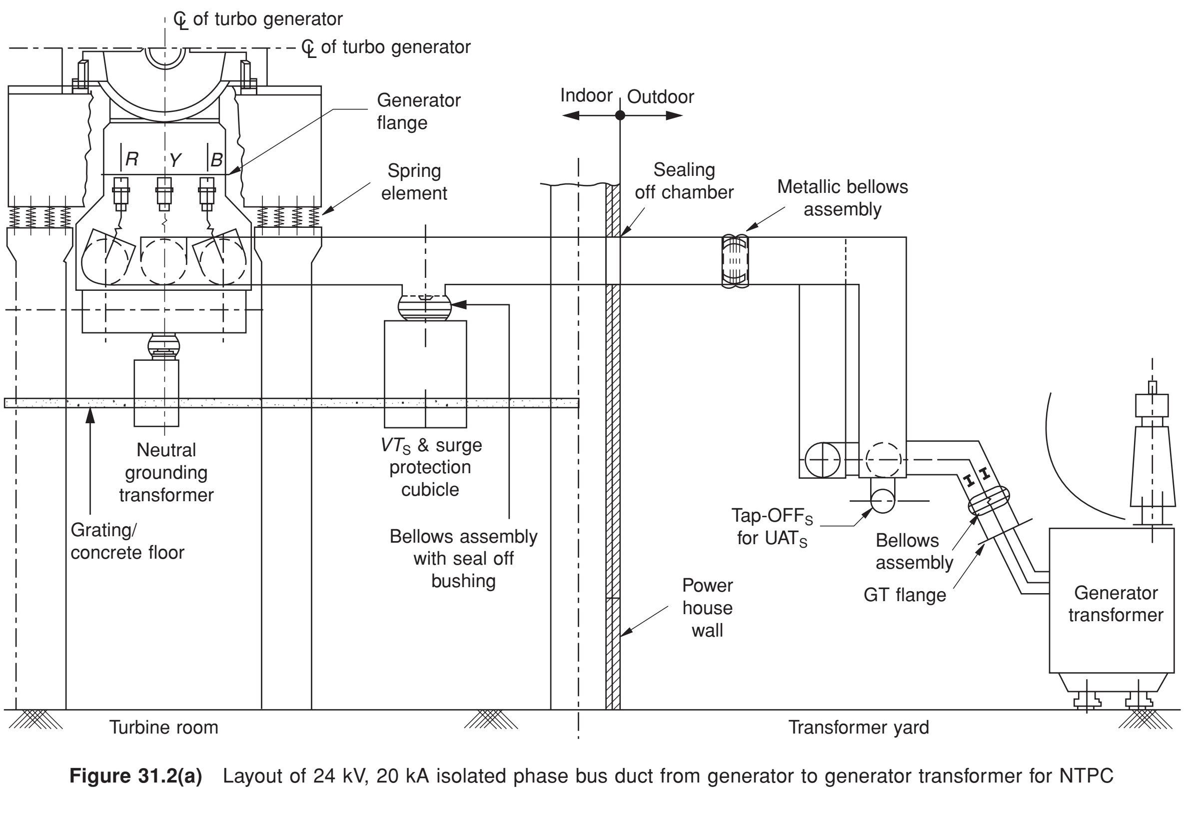
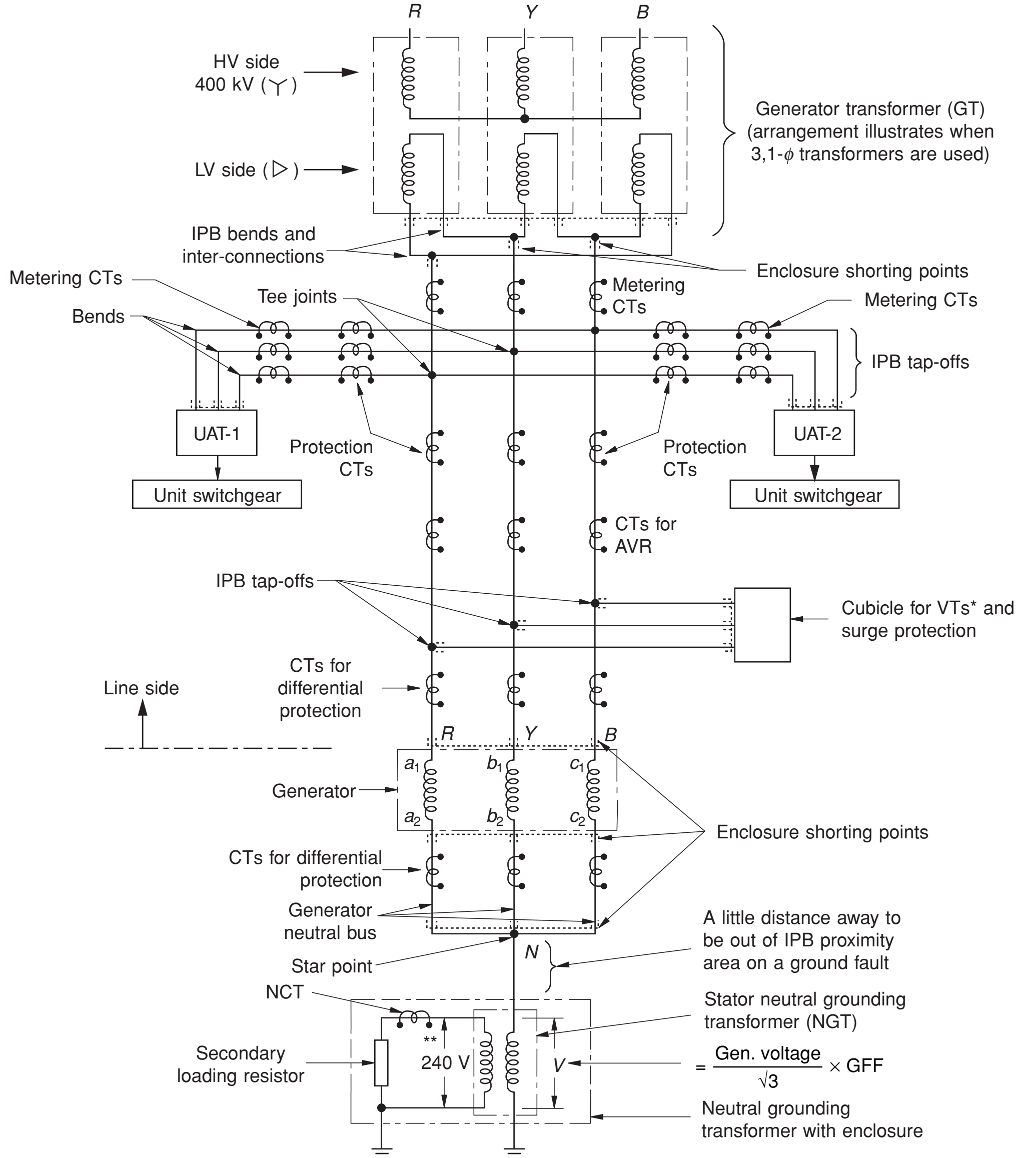


Figure 31.2(a) Layout of 24 kV, 20 kA isolated phase bus duct from generator to generator transformer for NTPC



*It may be supplemented with a surge capacitor, to suppress the steepness of a t.r.v. and diminish its r.r.r.v. (Section 17.10.1)
**Typical

Figure 31.2(b) Typical layout of an IPB system in a thermal power station, illustrating enclosure end shortings for continuous enclosures

section, as discussed already (concentration of current in the annulus, Section 28.7). One more advantage of a tubular section is that it exerts equal forces at all points of the enclosure and relieves it and the conductor from any undue stresses. Octagonal and hexagonal sections are also used as they also have near-symmetry.

- **Insulating medium:** Dry air or SF_6 gas
- **Insulators:** The conductors are resilient mounted on post insulators, to hold them in the centre (Figure 31.3) and dampen the forces, during normal operation or on fault. The conductors are held in position to have free movement axially but they have almost no movement radially. The thermal effects of the conductors are taken care of by the expansion joints (Figure 31.4(a)) and those of the enclosure by the bellows (Figure 31.4(b) and (c)). For termination see Figure 31.4(d).
- **Nominal current ratings:** Some typical current ratings for the stator voltages considered in Table 13.8 are 10 000 A for a 250 MVA generator to 40 000 A for a 1000 MVA generator. (See item 3 of the table for the normal current ratings for different MVA ratings and stator voltages of generators.) The preferred ratings may follow series R-10 of IEC 60059 as in Section 13.4.1(4).

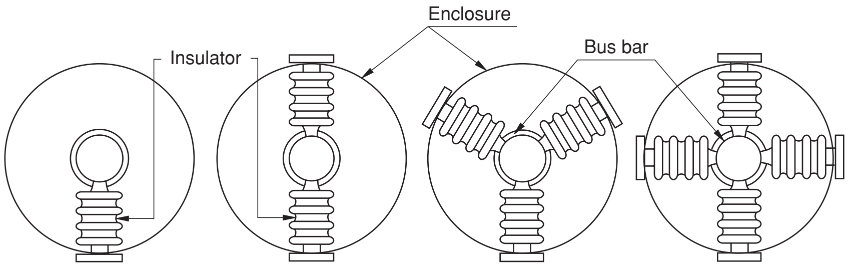


Figure 31.3 Arrangements of insulators to hold the busbars

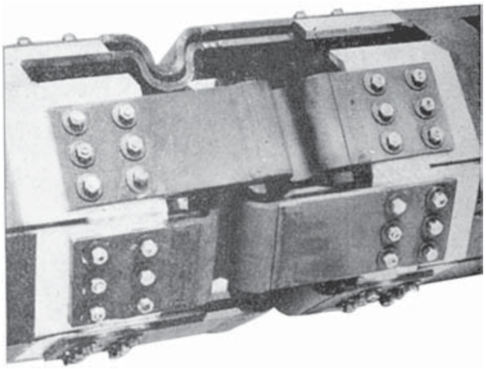


Figure 31.4(a) An expansion joint

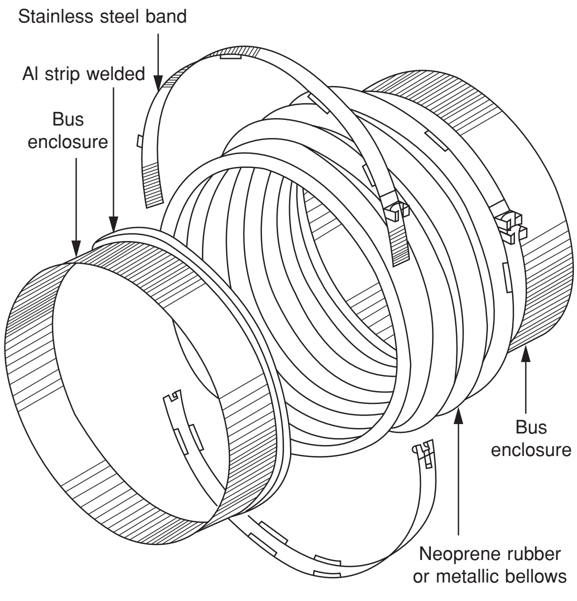


Figure 31.4(b) Rubber or metallic expansion bellows for enclosure jointing and end terminations (Courtesy: Best & Crompton)

- ***Types of enclosures:*** These may be of two types, i.e. Non-continuous, and continuous.

31.2.1 Non-continuous or insulated enclosures

These were used until the early 1960s and have since been discontinued in view of the inherent advantages of a continuous enclosure. In non-continuous enclosures the individual sections that are added together to obtain the required length and configuration of the bus layout are electrically insulated from each other. They are also insulated from their mounting structures by rubber or fibre-glass or similar insulating pads, as illustrated in Figures 31.5(a) and (b). This is to prevent the longitudinal flow of current from one section of the bus system to the other as well as from one phase enclosure to the other. There is no external return path for the induced currents. But local induced currents do flow through each insulated section and may cause nominal step and touch voltages. Each section is grounded at one point (only) to its own separate ground bus which in turn is connected to the station ground bus at one point only to make the induced current flow in one direction only. The ground bus is of the continuous type. Layout of a non-continuous IPB with grounding arrangement is shown in Figure 31.6. This system of insulation and grounding minimizes the step and touch voltages (Section 22.9) across each section of the enclosure. The induced voltage across each section is kept as low as possible, preferably below 2 V, when operating at the rated current. The ground bus which may be of copper or aluminium (only of non-magnetic material and not of GI) for each phase is continuously running and capable of carrying the momentary peak current (Table 28.1) of the main bus system for two seconds as in ANSI C-37/20C.

Such an arrangement, although adequate in some respects, has some disadvantages as noted below:

(a) There are higher losses in the enclosure due to the higher proximity effect as the induced current is not continuous throughout the enclosure.
(b) It provides negative magnetic shielding to the outside metallic structures in the vicinity. Magnetic shielding is an extremely important requirement to minimize the eddy currents ($\propto B^2$) and hysteresis losses ($\propto B^{1.6}$) in all such metallic structures and to reduce the electrodynamic forces developed between them and the main bus conductors.

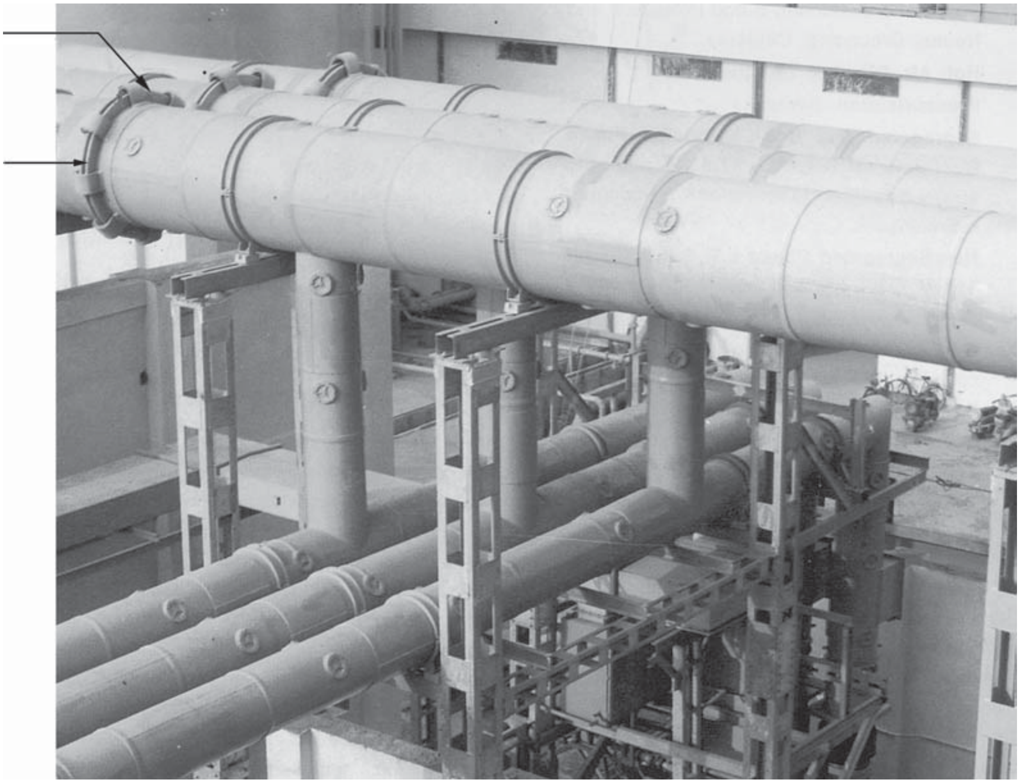


Figure 31.4(c) 24 kV, 20 kA, IPB straight run and tap-offs (Courtesy: Controls and Switchgears)

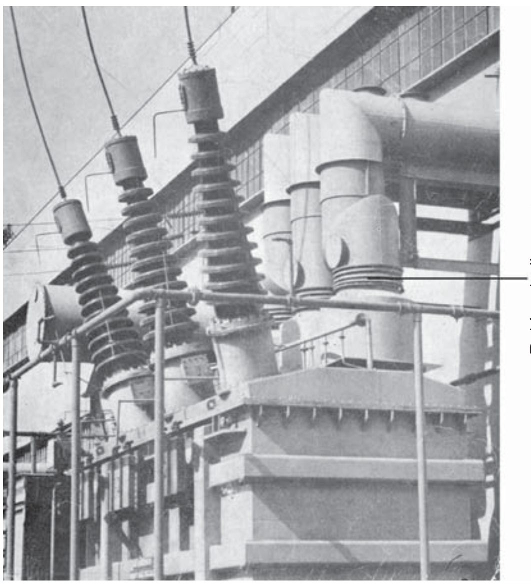


Figure 31.4(d) Termination of an isolated phase bus system at a transformer (Courtesy: Best and Crompton)

31.2.2 Continuous or bonded enclosures

The system is called electrically continuous when the individual sections (enclosures) of the IPB joined together to obtain the required length and configuration of the bus layout are also electrically bonded to each other. Each enclosure is then cross-connected with the enclosure of the other phases at the extreme ends of the installed bus duct. The bonding permits longitudinal flow of induced currents through the length of the enclosure and return through the enclosure of the other phases, as shown in Figure 31.8. This arrangement provides the required magnetic shielding between the phases, as the induced currents flowing through them adjust among themselves and make it an almost balanced current system. The magnitude of such current is almost equal to that of the main conductors while the direction is the opposite. Similar bonding is practised while laying EHV XLPE cables, Section A16.10 (Figure A16.6).

These balanced enclosure currents also induce electric fields into nearby structures, RCC beams and columns in the same way as the main conductors, and hence nullify most of the space magnetic fields. These space fields (fields outside the enclosure) are otherwise responsible for causing eddy current and hysteresis losses

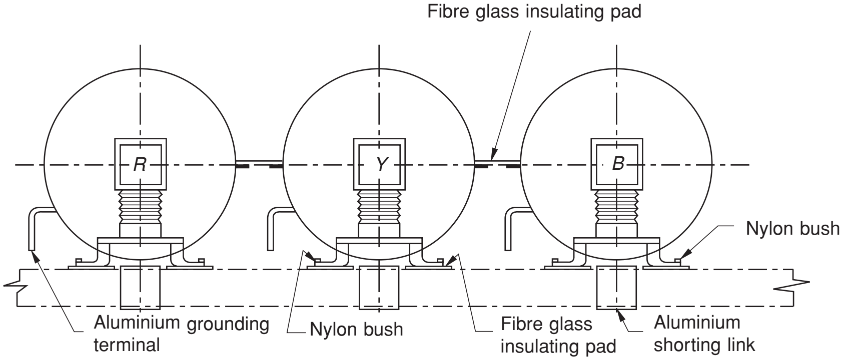


Figure 31.5(a) Typical insulating practice to isolate enclosure of a discontinuous IPB system (Courtesy: Best & Crompton)

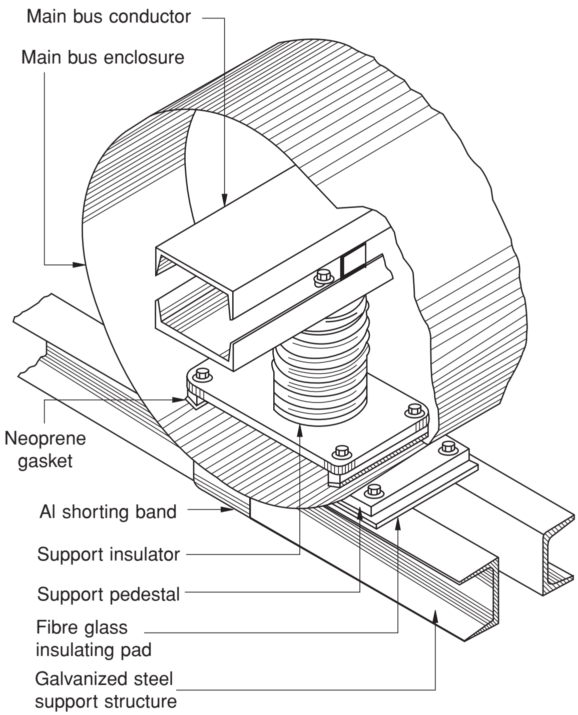


Figure 31.5(b) Cross-sectional view of an IPB with insulated (discontinuous) enclosure illustrating busbar-supporting arrangement (Courtesy: Best & Crompton)

in the metallic (magnetic) structures, RCC beams and columns in the vicinity. The electrical bonding of enclosures thus nullifies the proximity effect and helps to reduce the heating of such structures to a very great extent.

The electrodynamic and electromagnetic forces between the conductors and the structures are also reduced to only 10–15% or even less. These two advantages are not available to this extent in a non-continuous enclosure. The induced current causing the magnetic field in the space is now reduced to only,

$$\phi_{\text{space}} \propto (\bar{I}_r - \bar{I}_e) \tag{31.1}$$

Figures 31.7 and 31.8 illustrate the disposition of the conductor and the enclosure fields in the space and their nullification, where
I_r = conductor current
I_e = enclosure current
I_r and I_e are almost 180° out of phase.
therefore, $\phi_{\text{space}} \propto (I_r - I_e)$

For better shielding it is essential that bonding is carried out at the farthest possible locations where the configuration of the IPB changes such as at the bends and tap-offs or where it passes through a wall. Where bonding is not possible, the supports and the enclosure must be adequately reinforced to sustain electrodynamic forces, especially during a fault. Figure 31.2(b) illustrates the shorting and grounding locations of an IPB system.

To limit the fault level, if it is likely to exceed the designed limits, or the breaking capacity of the interrupting device, or the associated equipment and to limit the induced circulating currents in the enclosure during normal operation, to contain enclosure losses in very large ratings of bus systems, say, 25 000 A and above (above 500 MW), unsaturable type series reactors (see Chapter 27) may be provided in the enclosure circuit, as illustrated in Figure 31.8 to limit such high currents to a desired level especially during a fault. The reactors should not saturate under fault conditions, as they are provided to supplement the enclosure circuit impedance to limit the high currents through the enclosure, especially during faults, and reduce the forces between the main conductors. For a better flow of circulating currents, it is also grounded only at one point. Accordingly, it is supported on non-conducting supports to keep the ground path continuous and completely isolated. The enclosure must also be insulated electrically from the rest of the plant by rubber bellows.

A continuous enclosure provides a high degree of magnetic shielding for metallic objects and structures located in the vicinity and generates only nominal eddy current or hysteresis losses. Magnetic shielding also significantly reduces the electrodynamic stresses caused by short-circuits on the structures and between the enclosures of the other phases. For details on the thickness and size of enclosure to provide magnetic shielding up to a required level, refer to the sample calculations in

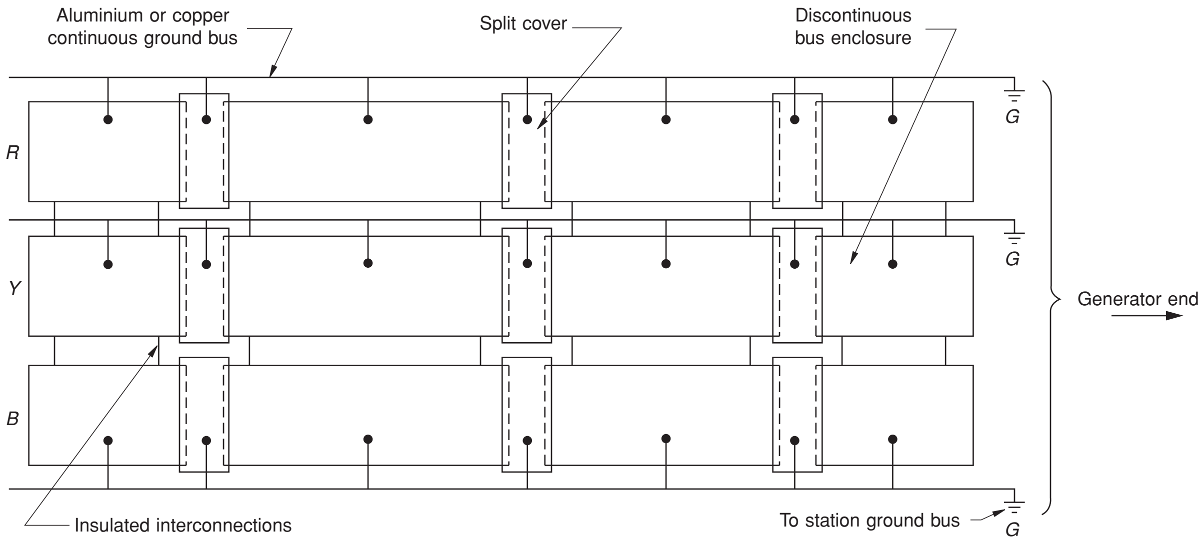


Figure 31.6 Grounding arrangement of a noncontinuous isolated phase bus (IPB) system

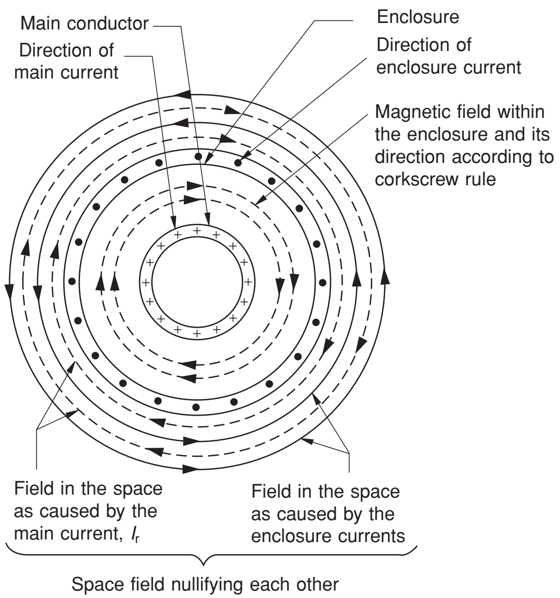


Figure 31.7 Nullifying of magnetic field in space in continuous enclosures

Example 31.1 and Further Reading at the end of this chapter.

Grounding

The system is grounded only at one point as discussed above. It is also insulated from the ground as well as the rest of the plant along its length by being supported on insulated foot mountings. The minimum clearance of the bus from the ground will depend upon the voltage of the IPB system. The ground bus is not screened through the enclosure but is provided some distance away from it to remain unaffected by the fault currents. Otherwise it may also develop large electric fields and be strenuous to excessive forces on a fault.

31.3 Special features of an IPB system

It is almost mandatory for such a bus system to have the following features to make it more reliable and to provide uninterrupted services over long years of continuous operation:

1 The enclosure is constructed of non-magnetic material, generally aluminium, in view of its low cost and weight as compared to copper. The nonmagnetic material eliminates hysteresis and eddy current losses in the enclosure, as a result of mutual induction.
2 To contain the proximity effect, in the metallic structures existing in the vicinity, it is essential that the IPB enclosures be at least 300 mm (surface to surface) from all structures existing parallel and 150 mm existing across the enclosures. A distance of 300 mm is sufficient to contain the proximity effect in view of the substantially reduced magnetic field in the space.
3 The enclosure must be airtight and waterproof.
4 Large generators are hydrogen (H_2) cooled. H_2 forms a highly explosive mixture with air and may leak through the generator terminals to the bus enclosure. Suitable sealing-off chambers must therefore be provided between the generator and the IPB enclosure with ventilation to allow gases to be vented to the atmosphere in the event of a leakage.
5 The termination of the conductor at the generator, transformer and the switchgear ends are made through flexible connections (Figure 31.4(a)).

Jointing of the enclosure sections is carried out with a rubber or metallic (mostly aluminium thin

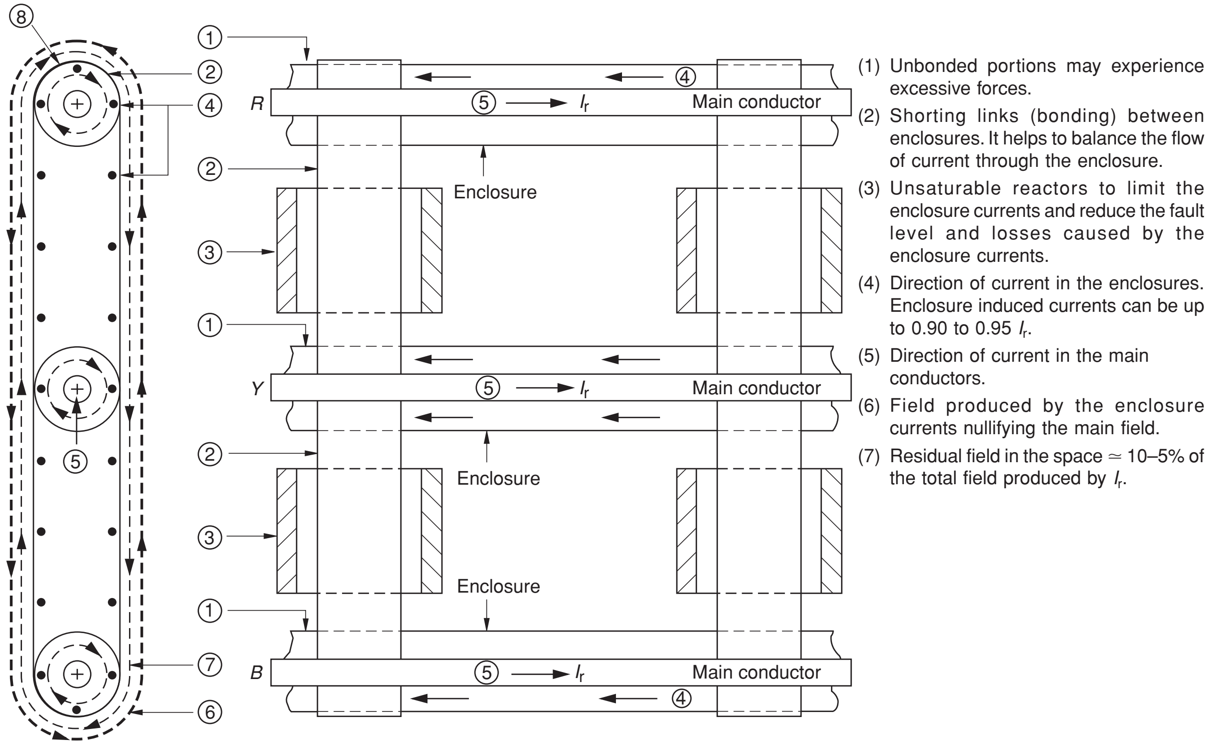


Figure 31.8 A continuous IPB system with phase reactors

sheets) expansion bellows assembly, as shown in Figure 31.4(b). Besides absorbing the enclosure expansion, the bellows assembly takes care of minor mismatches between the flanges of the IPB and the generator or the transformers and also prevents transmission of generator and transformer vibrations through the enclosure. The expansion bellows, when they are metallic, are insulated with the housing as they are made of thin sheets and are incapable of carrying excessive enclosure currents. They are clamped to the housing with the help of an insulating pad and metallic bands as shown in Figure 31.4(b). To maintain the continuity of enclosure currents, the bellow assemblies are superimposed with enclosure shorting flexibles, sufficient to carry the full enclosure currents (see Figure 31.4(c)).

However, they should remain insulated when terminating with an equipment or a device such as at the ends of generators, GTs, UATs or VTs. It is essential to avoid IPB longitudinal currents through the terminal equipment. Now the bellows necessarily should be of rubber. Figure 31.4(d) shows a rubber bellows but in this small part of the bellows the conductor field will not be nullified and occupy the space affecting the metallic structures, beams and equipment/devices in the vicinity. This needs to be taken into account at site and it should be ensured that the nearest structure, beam or equipment is at least 600 mm away from the IPB enclosure.

6 The terminal ends are provided with terminal palms or tap-off palms, as required, to bolt them to the other sections.

7 The structures supporting the IPB, at bends and tee-offs particularly, are adequately reinforced to sustain the excessive forces that may arise on a fault and tend to shear off such joints and structures. Even in a continuous type of enclosure it may not always be possible to fully bond all such parts electrically. Should such a situation arise, current limiting unsaturable reactors may be provided at the bends and the tee-off joints to contain the excessive enclosure currents at such locations, particularly during faults.

8 The exterior of the conductor and the interior of the enclosure are painted with non-magnetic matt finish black paint to improve the heat transfer due to radiation.

9 (a) Provision of space heaters is made to prevent condensation of vapour during a shutdown.
  (b) Shorting links may also be provided to short-circuit the buses for the purpose of generator drying when required, after a long shutdown, due to a fall in insulation level.

10 Locations having low ambient temperature or high humidity may adversely affect the insulation level of the bus system. In this case an ordinary space heater may not be adequate and a separate anti-condensation arrangement may become imperative to dry the condensate and maintain a high dielectric strength. This may be achieved by:

- Blowing hot air: A typical arrangement is shown in Figure 31.9. The bus duct enclosure is provided

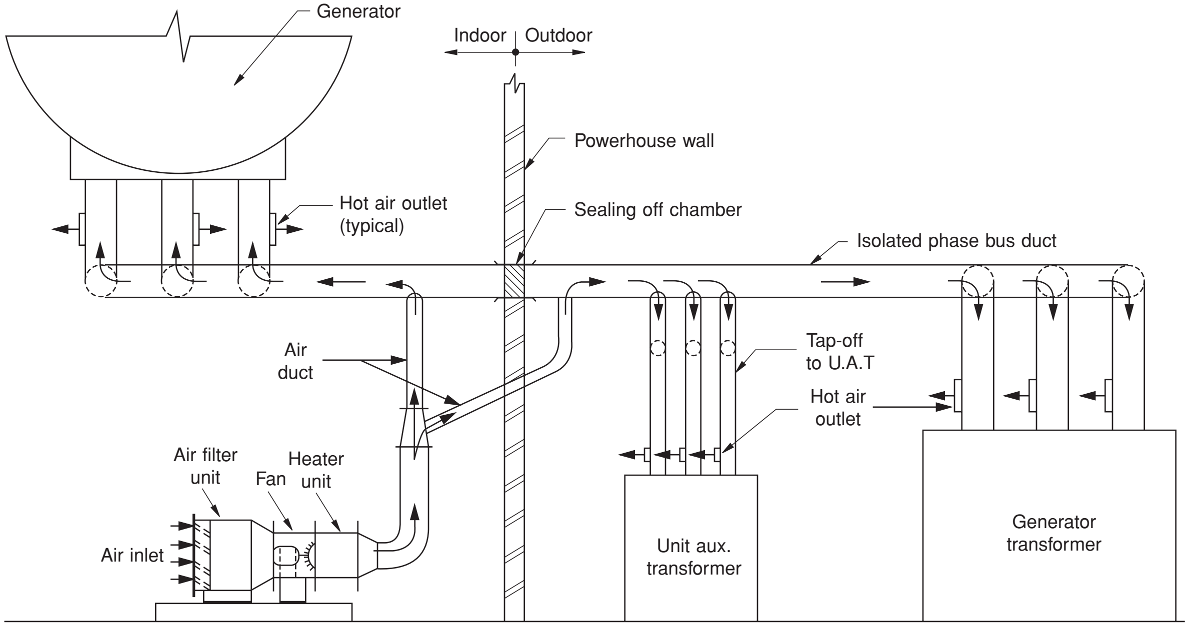


Figure 31.9 A typical arrangement illustrating drying of enclosure through hot air blowing

with inlet and outlet valves at suitable locations. Hot air is supplied through the inlet valve until the interior of the enclosure is completely dry. The blowing equipment comprises an axial flow fan, a heater unit, an inlet air filter unit, pressure valves, required controls and interlocks and air ducts.

- Pressurizing the bus enclosure: A typical arrangement is shown in Figure 31.10. In this case the enclosure is maintained at slightly positive pressure by continuously supplying it with dry and clean air or SF_6 to prevent vapour condensation. Compressed air is supplied at a pressure of 5–7 kg/cm^2 and passed through the air dryer and the flow control valve. The leakage, if any, is recommended to be within 5% of the volume of the enclosure per hour. The air dryer removes the moisture present in the compressed air and leaves the air in a bone dry condition having a dew point of –25°C. The dry air is then

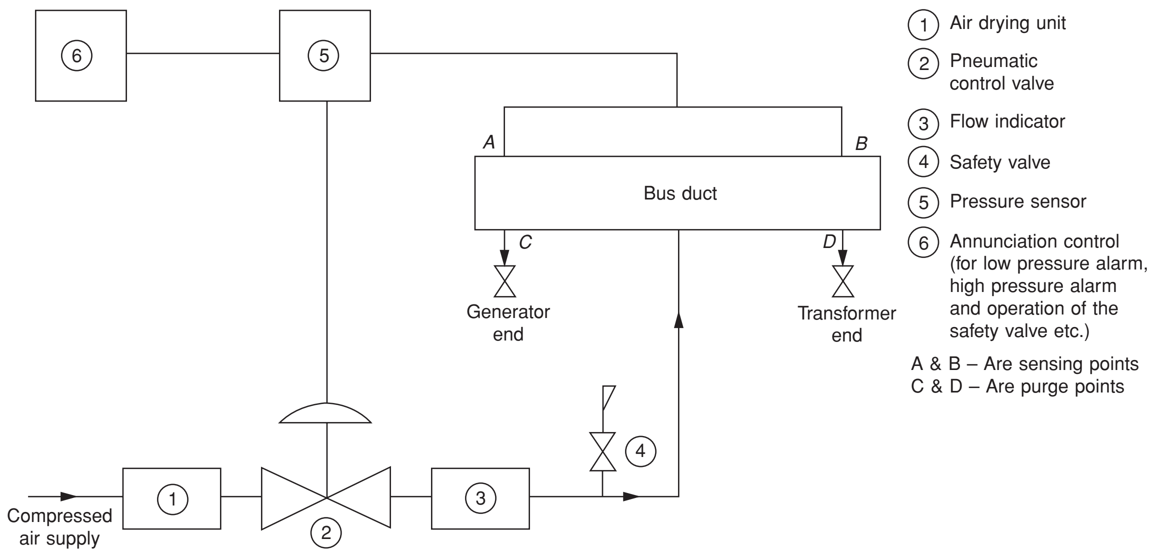


Figure 31.10 Typical layout illustrating pressurization system for an IPB bus system

passed into the enclosure through the control valve and the flow indicator. The controls are set to allow the dry-air flow to the enclosure, until the pressure inside the enclosure reaches the required level.

Note
Use of SF_6 gas for insulation purpose is usually made when SF_6 gas supply and monitoring system, which is a costly affair, is already available at site feeding a GIS system.

31.4 Enclosure heating

Heating of enclosures in bus systems of such large ratings is a deterrent to their design work. In smaller ratings (say, up to 3200 A) it has been easier to do this by increasing the size of enclosure, choosing larger bus sections, changing their configuration or using a non-magnetic enclosure or by adopting more than one of these measures, as discussed in Chapter 28. But this is not so in large ratings, where heat generated, particularly in the enclosure, is enormous due to carrying almost the same amount of induced currents as the rating of the main conductors. Therefore, dissipating the heat of the conductor and the enclosure is a major task in an IPB system. When designing such a system it is imperative to first check the adequacy of the enclosure to dissipate all the heat generated within permissible limits.

If the heat generated by induced currents (there are no magnetic losses) on load on per phase basis is;

– In the main conductor, due to $I_r = W_1 = I_r^2 \cdot R_c$,
– In the enclosure, due to $I_e = W_2 = I_e^2 \cdot R_e$
– In the outdoor portion of the enclosure, due to solar radiation = W_s*

Then the total heat generated

$$W_t = W_1 + W_2 + W_s^* \text{ in watts per unit length} \qquad (31.2)$$

(*only for the outdoor parts)

where
I_r = rated current of the main conductors in Amperes (r.m.s.)
R_c = a.c. resistance of the main conductors per unit length at the operating temperature, in Ω
I_e = Induced current through the enclosure in Amperes (r.m.s.). This will vary with the type of enclosure, the effectiveness of its electrical bonding and the impedance of the bonding links. If current limiting reactors are used in the enclosure circuit this current would be reduced substantially, as discussed above. Without such current limiters, the current may be assumed to be up to 95% of I_r. Experiments have corroborated this assumption in continuous bus systems.
R_e = a.c. resistance of the enclosure, per unit length at the operating temperature in Ω.

To determine R_c and R_e the same procedure may be adopted as discussed in Section 28.7. For a tubular conductor,

$$R_{dc20} = \frac{\rho l}{\pi \cdot d_m \cdot t} \text{ in } \Omega/\text{m or } \mu\Omega/ft \qquad (31.3)$$

(in MKS or FPS units, depending upon the system adopted)
where
ρ = resistivity of metal at 20°C in Ωm or μΩcm
d_m = mean diameter of the tube in m or cm
t = thickness of the tube in m or cm
l = length of the conductor in m or cm

From similar skin effect curves, as in Figure 28.13(b), corresponding to t/d the ratio R_{ac20}/R_{dc20} can be found. Having determined R_{ac20}, it must be corrected to the operating temperature by using

$$R_{dc\theta} = R_{dc20}\,[1 + \alpha_{20}\,(\theta - 20)] \qquad (31.4)$$

where
$R_{dc\theta}$ = d.c. resistance of the conductor at the operating temperature
α_{20} = temperature resistance coefficient of the metal at 20°C per-°C (Table 30.1)

W_1, W_2 and W_s (W_s, when considering the outdoor part) can thus be determined. The total heat, W_t, so generated can be naturally dissipated through the enclosure by radiation and convection. If natural cooling is not adequate, forced cooling can be adopted through forced air or water. But precautions must be taken to ensure that the system is protected from absorbing dirt, dust or moisture from the atmosphere.

Note
For medium ratings as in a non-isolated bus system of up to 3200A little significance is attached to such heating effects because of a comparatively weaker magnetic field produced by the conductors of each phase, and cancellation of a part of it by the fields of the other phases (Figure 28.22 and Section 28.8). The enclosure currents are now a much lower percentage of the current of the main conductors and hence cause a low heating of the enclosure. The residual magnetic field in such cases is also small and is normally ignored. Yet certain installations may require magnetic shielding in such ratings also where these fields may influence the operation of the sensitive instruments or protective devices that are installed in the close vicinity.

31.4.1 Skin effect in a tubular conductor

Tubular conductors provide the most efficient system for current carrying, particularly large currents. As discussed in Section 28.7, the current density is the maximum at the skin (surface) of the conductor and falls rapidly towards the core. Experiments have been conducted to establish the normal pattern of current distribution in such conductors at different depths from the surface as shown in Figure 31.11.

At a certain depth, the current density reduces to $1/\varepsilon = 0.368$ of the value at the surface. This depth is termed the depth of penetration, δ_p. Of the total heat generated in such conductors, almost 80% occurs within this depth (annulus). In other words, around 90% of the total current (heat generated $\propto 0.9^2 \simeq 0.8$) is concentrated in this area alone. This depth in mm can be represented by

$$\delta_\rho = \frac{1}{2\pi}\sqrt{\frac{\rho}{\mu f}} \qquad (31.5)$$

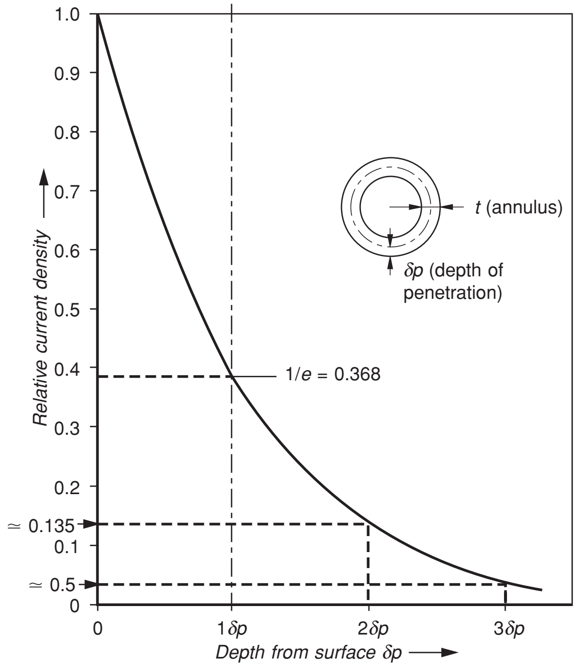


Figure 31.11 Skin effect in tubular isolated conductors in terms of depth of penetration δp

where

ρ = resistivity of the metal in e.m.u.
= $10^9 \times$ (ρ in Ω cm) as in Table 30.1

f = frequency of the system in Hz

μ = effective permeability of the medium in which the field exists (aluminium in the present case), and will depend upon the electric field induced in the enclosure
= 1 for non-magnetic materials

δ_p will thus vary with the material of the conductor and the enclosure and the operating temperature. For aluminium, grades EIE-M and E-91E, we have worked out the likely values of δ_p at an operating temperature of 85°C as follows:

1 For grade EIE-M

$$\rho_{20} = 2.873 \times 10^{-6}\ \Omega\ \text{cm}$$

$$\alpha_{20} = 4.03 \times 10^{-3}\ \text{per °C}$$

$$\therefore \rho_{85} = \rho_{20}\,[1 + 4.03 \times 10^{-3} \times (85 - 20)]$$

$$= \rho_{20} \times 1.26195\ \Omega\ \text{cm}$$

Therefore depth of penetration at 20°C

$$\delta\rho_{20} = \frac{1}{2\pi}\sqrt{\frac{2.873 \times 10^{-6} \times 10^{9}}{1 \times 50}}$$

$$= 1.207\ \text{cm or } 12.07\ \text{mm}$$

and at 85°C

$$\delta\rho_{85} = 12.07\sqrt{1.26195}$$

$$= 13.56\ \text{mm}$$

(The suffix refers to the temperature.)

2 For grade E-91E

$$\rho_{20} = 3.133 \times 10^{-6}\ \Omega\ \text{cm}$$

$$\alpha_{20} = 3.63 \times 10^{-3}\ \text{per °C}$$

$$\therefore \quad \rho_{85} = \rho_{20}\,(1 + 3.63 \times 10^{-3} \times 65)$$

$$= \rho_{20} \times 1.236\ \Omega\ \text{cm}$$

$$\therefore \quad \delta\rho_{20} = \frac{1}{2\pi}\sqrt{\frac{3.133 \times 10^{-6} \times 10^{9}}{1 \times 50}}$$

$$= 1.26\ \text{cm or } 12.6\ \text{mm}$$

and $\delta\rho_{85} = 12.6\sqrt{1.236}$

$$= 14.01\ \text{mm}$$

Since most of the current will flow through δ_p, a thicker conductor will only add to the bulk and cost of the tube without proportionately raising its current-carrying capacity. A greater thickness does not assist in heat dissipation, as the heat is dissipated more quickly from the outside than the inside surface of a body.

31.4.2 Thickness of enclosure

For a near-total shielding of the field produced by the main conductors (i.e. for $I_r - I_e$ to be very low), it is essential to have the thickness of the enclosure as near to δ_p as possible. But this too may prove to be a costly proposition. In addition, a higher induced current in the enclosure will also mean higher losses. This has been established by computing the cost of the enclosure and capitalizing the cost of losses for minimum losses in the enclosure

$$\frac{\text{Thickness of tubular conductor } (t)}{\text{Depth of penetration } (\delta_p)} = \pi/2$$

or

$$t = \frac{\pi}{2}\,\delta_p \qquad (31.6)$$

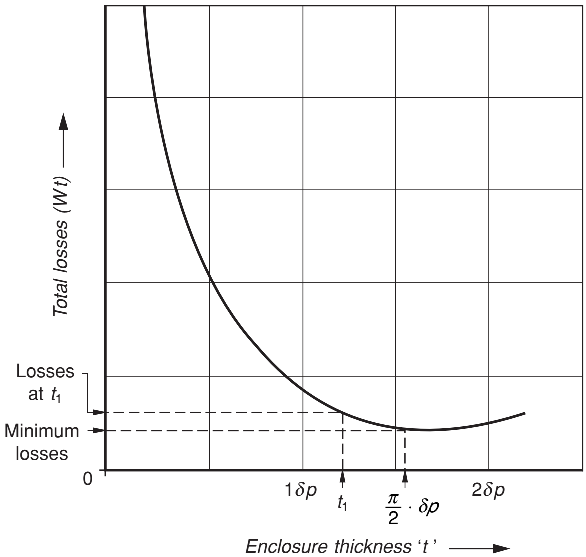
But this will also prove to be a costly proposition.

A smaller surface area may require forced cooling and an extra cost for the same while a larger enclosure would mean a higher cost for the enclosure itself. Considerations of cost will thus determine a larger enclosure or a forced cooling. Two factors have been considered relevant here:

- **Loss factor:** This is a function of losses (W_t) in the main conductor (W_1) and the enclosure (W_2). A curve as illustrated in Figure 31.12 can be established between the losses versus thickness (t) of the enclosure by experiments.
- **Optimization factor:** This is a function of the cost of enclosure for different thickness, t the cost of the cooling system (if cooling is considered necessary)

and the capitalized cost of the losses at different thickness *t*. A curve as shown in Figure 31.13, rather similar to that in Figure 31.12, can be established theoretically between the total cost of the IPB system versus *t*.

The above two curves will help optimize the thickness, *t* of the enclosure for a total minimum cost of the system. Enclosure losses may not be lowest at this thickness as shown in Figure 31.12, but they would maintain the temperature rise of the enclosure within limits. The magnetic field in the space, being already very low, would require no other measure. Moreover, a small field in the space may cause only a small amount of heat in nearby structures, which may be acceptable. Therefore, to choose a thinner enclosure is common practice to economize on the total cost, allowing part of the magnetic field to occupy the space.



t_1 = Thickness of enclosure for minimum cost of IPB system (Figure 31.13)

Figure 31.12 Variation in losses with thickness of enclosure

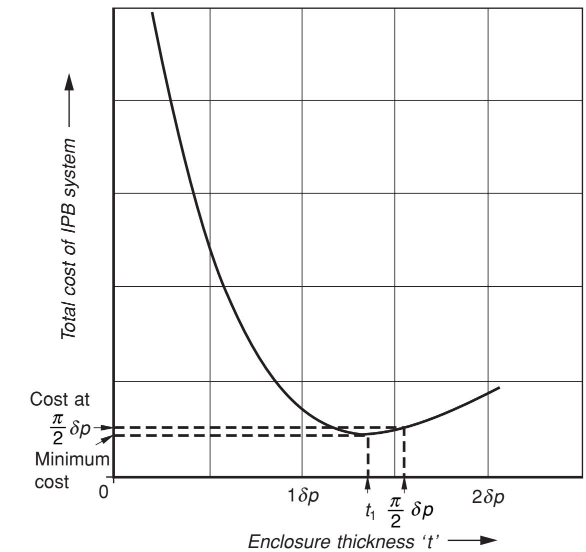


Figure 31.13 Optimization curve between thickness of enclosure and the total cost of the IPB system

31.4.3 Proximity effect in an IPB system

The three phases are now completely isolated and adequately spaced. They are thus hardly under any influence of proximity. The forces are now greater between the conductor and the enclosure rather than between two phases due to an almost negligible or only moderate magnetic field in the space (Figures 31.7 and 31.8). The emphasis is now more on the losses in the enclosure and the metallic structures outside the enclosure and their consequent heating, rather than the derating of the current-carrying conductors.

To arrive at the most appropriate and economical design of the enclosure is a complex subject and requires detailed study. For brevity, in our present attempt, we have derived inferences from the established work in this field by engineers and authors (see Further Reading) and have underlined briefly the basic approach to design such a system. For smaller ratings, up to 3200 A, the discussions in Chapter 28 will generally suffice to design a good bus system. There we have assumed the content of proximity on the conductors and exercised care while selecting the size and material of the enclosure, spacings between the enclosure and the busbars and between the busbars of two adjacent phases etc. In an IPB system, however, the space occupied by the electric field is large may cause excessive parasitic currents within the enclosure and in the metallic structures in close proximity outside the enclosure and excessive heating in both. The assumptions made earlier may not suffice now for its effect on the enclosure, supports and the structures in the vicinity.

To provide magnetic shielding within the enclosure will require the enclosure to be made of non-magnetic material at the first instance to eliminate magnetic losses and a cross-section sufficient to carry a near full load current on the other. It is also essential to allow a nil or only a moderate field in the space outside the enclosure to limit the parasitic currents in the supporting and other metallic structures so that they do not require any special treatment or insulation and protect the operating personnel from excessive touch or step voltages. The main emphasis to design such a system is therefore to optimize the thickness of the enclosure and its overall size to obtain the required magnetic shielding and a temperature rise within desirable limits.

31.4.4 Solar radiation

The part of the bus enclosure installed outdoors is exposed to solar radiation which is a cause of additional heat gain by the enclosure. ANSI C-37.24 has provided a basis to determine its effect in terms of heat generated as follows:

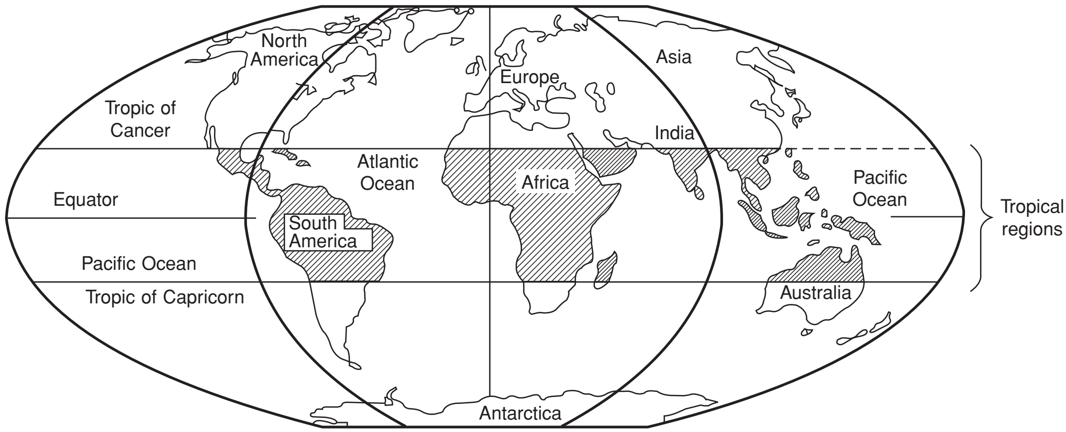


Figure 31.14 World map showing Tropical regions (Source: World Book Encyclopaedia)

during winter – 670 W/m^2
during summer – 990 W/m^2
for tropical areas* – 1100–1200 W/m^2

By simulating these effects in a test laboratory it has been established that solar radiation may raise the temperature of the external surfaces by up to 15°C, depending upon the colour and the condition of the surface.

Surfaces with light colours absorb less heat than dark surfaces. But light colours may fade with the passage of time. The outer surfaces may also collect soot and dirt with passage of time and hence lose the benefit of being light-coloured to some extent. The heat generated by solar radiation per foot length can be estimated by

$$W_s = k_a \cdot G \cdot A \text{ W/ft} \qquad (31.7)$$

where

k_a = coefficient of absorption. When a canopy is provided on the outdoor part of the enclosure the coefficient, k_a, may be reduced.

G = global solar radiation
= 1100 W/m^2 (for tropical areas)

A = area of the enclosure that is exposed to the sun. We have assumed about 50% of the surface area falling outdoors which is exposed to direct solar radiation.

During heat dissipation by radiation the colour and condition of the surface plays a similar role. Dark-coloured bodies dissipate more heat than the light-coloured ones. The amount of heat absorption and emission for the same body may therefore be assumed to be almost the same. Accordingly, Table 31.1, for selected colours, may be considered for the coefficients of absorption and emission of heat due to solar radiation and natural radiation respectively.

* Tropics are the regions of the earth that lie about 2570 km north and 2570 km south and parallel to the equator (Figure 31.14). These regions signify the areas that generally have a warm to hot climate throughout the year, as the sun reaches its greatest altitude.

Table 31.1 Coefficients of absorption (of solar radiation) and emission (natural radiation) for a metallic surface located outdoors

Colour of the surface when new	*Coefficient of absorption, K_a and emission, e*	*Approximate temperature rise of the surface, °C*
White	0.14	2.2[a]
Light grey	0.50	7.7
Medium grey	0.75	11.6
Dark grey	0.95	14.7
Black	0.97	15

[a] Example: $\frac{0.14}{0.97} \times 15 = 2.2$°C

In our sample calculations (Example 31.1) we have chosen the colour of the outdoor surface as light grey and taking the weathering effect into account, have considered the coefficient of both absorption and emission as 0.65. The manufacturer, depending on the colour and site conditions, may choose a suitable coefficient. It is, however, advisable to be conservative when deciding the temperature rise due to solar radiation to be on the safe side.

The normal practice of all leading manufacturers is to keep the same bus and enclosure sections for the outdoor and indoor parts of the bus system. This is to retain simplicity in design and ease of jointing and interconnections. But this may prove to be a costly arrangement, as now the indoor section of the bus system will have to be designed for outdoor conditions. The practice to economize on conductor and enclosure sizes is to provide a shade or a canopy over the outdoor part of the bus system to protect the enclosure from direct sunlight and hence mitigate the solar effect.

31.5 Natural cooling of enclosures

Heat dissipation from a hot body to the surroundings can occur in two ways:

1 **By Radiation (W_r)** This heat loss is expressed by the difference of the fourth power of the absolute temperatures and the emissivity of the enclosure, and is represented by the Stefan-Boltzmann law expressed by (see Dwight *et al.*, 1940)

$$W_r \simeq \frac{36.9}{10^{12}} \cdot e \cdot A_s \, [T_1^4 - T_2^4] \text{ W/ft} \tag{31.8}$$

where

e = coefficient of emissivity, expressed by the condition of the surface of the hot body (Table 31.1)

A_s = effective surface of radiation per foot of enclosure length in square inches

T_1 = absolute temperature of the hot body
= $(\theta_s + 273)$°C (θ_s = enclosure surface temperature in °C)

T_2 = absolute ambient temperature
= $(\theta_a + 273)$°C (θ_a = ambient temperature in °C)
(For conductors, the enclosure temperature will become their ambient temperature)

2 **By convection (W_c)** (from the external surface of the enclosure): For a hot body installed indoors and reasonably ventilated this can be expressed by (Dwight *et al.,* 1940)

$$W_c \simeq 0.0022 \cdot A_s \cdot \frac{\rho^{0.5} \cdot \theta^{1.25}}{h^{0.25}} \text{ W/ft} \tag{31.9}$$

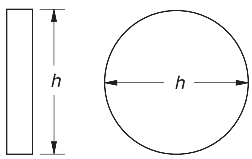
where

A_s = effective surface area per foot of enclosure length in square inches

ρ = air pressure in atmospheres
= 1 at sea level

θ = temperature rise of the enclosure above the ambient temperature in °C

h = width of flat or bar mounted in a vertical plane, or the diameter of a round conductor in inches.



3 **By forced convection** The factors that can influence the temperature of the enclosure, installed outdoors are wind and snow, other than forced cooling. But their effect on actual cooling may be small. Sometimes this happens and sometimes not. It is better to ignore this effect when estimating various thermal effects. Natural convection and radiation will take account of this.

31.6 Continuous rating

The continuous current rating of a bus system is then defined by the current at which a steady-state thermal condition is reached within permissible limits. It is a balance between the enclosure and the conductor's heat gain and heat loss. If this temperature is more than the permissible steady state thermal limit, then it must be reduced to the desired level by increasing the size of the conductor or the enclosure or both, or by adopting forced cooling. Otherwise the rating of the bus system will have to be reduced accordingly.

31.7 Forced cooling

For ratings up to 20 000 A natural cooling is found to be generally adequate to maintain all temperatures within limits. Where this is not possible, as when the size of the enclosure cannot be increased for whatever constraints (generator termination being one), to dissipate the required heat, then forced cooling may be adopted. The general practice is to eliminate forced cooling as far as possible to avoid the piping network and the associated equipment and accessories and their regular maintenance and upkeep. This is one major factor against forced cooling. A breakdown of cooling system will not result in a shutdown of the bus system but will require its deration and lead to an under-utilization of the generating unit. Forced cooling (by air, gas or liquid) is more relevant when the total length of the bus system is sufficient to justify initial investment in the external cooling arrangements and their regular upkeep and also when one can economize on the cost of conductor and the enclosure in lieu of forced cooling.

For 25 000 A and above, heat dissipation through natural cooling alone may not be sufficient. It may require a larger enclosure. But this may become too large to terminate at the generator end and be a limiting factor, besides becoming more expensive. In this case one can opt for forced cooling.

31.8 Influence of space field on metallic structures

The influence of an induced field on a metallic (magnetic) structure is in the form of closed magnetic loops, which cause hysteresis and eddy current losses. These closed loops cannot be broken by insulating magnetic structures at bends or joints or any other locations. (Refer to Figure 28.32 for more clarity.) There is thus no treatment that can be applied to such structures or bodies in the vicinity of an IPB to protect them from the magnetic effects of the field if present in the space.

The IPB system must therefore be designed so that it allows only a moderate field in the space. The field should be incapable of heating structures in the vicinity beyond a reasonable limit, or cause step and touch voltages. These voltages are undesirable and may become dangerous to a human coming into contact with them.

31.9 Fault level

As discussed in Section 31.2.2, in continuous enclosures there is a near-magnetic shielding between any two phases. The space field between the enclosures is also of the order of 10–15% or even less ($\propto (I_r - I_e)$) than that of the field in the enclosures. As a result, the electrodynamic and electromagnetic forces generated between the enclosures during a fault are also only nominal ($F_m \propto (I_{sc}^2 - I_{sce}^2)$, where I_{sc} is the fault level of the system and I_{sce} the corresponding fault current through the enclosure). One therefore need to deal only the forces between the conductor and the enclosure, which will remain as high as in a non-segregated bus system ($F_m \propto I_{sc}^2$) rather than the forces between the enclosures.

When such large generating units are connected to a power grid the bus system connecting the generator and the generator transformer will be subject to a higher fault level commensurate with the fault level of the power grid limited up to the fault level of GT (Section 13.4.1.(5) and Figure 13.21). Similarly, the tap-offs connecting the UATs will be subject to a cumulative fault level, one of the generator and the other of the power grid (grid fault limited up to GT). Generally, therefore such large ratings of bus systems are subject to a high fault level. (For a few large ratings of bus systems these levels are shown in Table 13.8.)

For ratings of 25 000 A and above it is possible that the fault level of the system may exceed the rupturing capacity of the available interrupting devices. To reduce the fault level in such cases, current limiting unsaturable type series reactors can be provided with the bus system, as noted earlier and illustrated in Figure 31.8.

31.10 Voltage drop

As discussed earlier, this has no relevance in HV systems.

31.11 Forming sections for IPB system

It is not possible to extrude large sections in full circular, hexagonal or octagonal shapes. These are normally produced in smaller extruded sections as illustrated in Figure 31.15. Circular sections may, however, also be rolled from sheets in two halves to obtain the desired size. Moderate sizes of circular sections are also available in extruded form. For hexagonal and octagonal shapes, the thickness and lengths of such sections will depend upon the practices adopted by the manufacturer of the extruded sections. The desired size of conductor and enclosure can then be shop fabricated out of these sections, choosing the nearest next available size, to form them into the required size of conductor and enclosure.

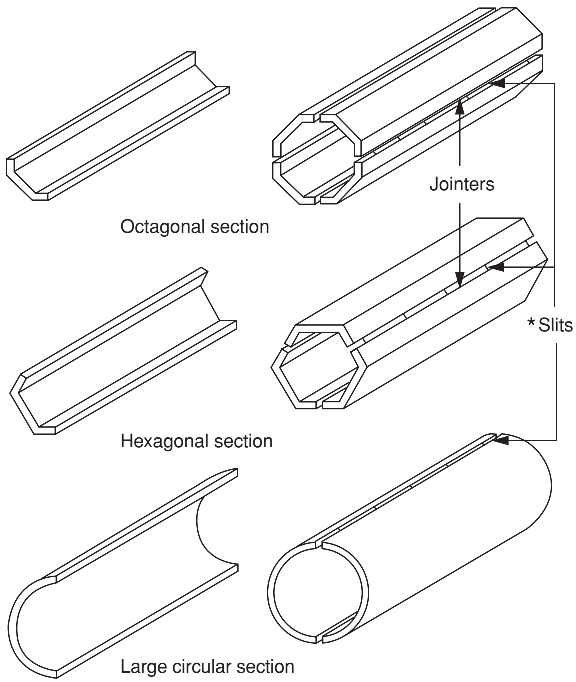
Enclosures

Small margins are added in enclosures for inspection and maintenance windows and tap-offs, which may affect their current ratings. These sections are welded circumferentially to give them the required shape (circular, hexagonal or octagonal). They are welded longitudinally to shape them into the required length and configuration. Extreme care must be taken when making such joints, to make them airtight and to ensure maximum continuity of current.

Conductor

The conductor may not have any inspection or maintenance windows, but may be provided with surface openings, as illustrated in Figure 31.15 to dissipate its interior heat into the enclosure for onward dissipation by the enclosure's surface to the atmosphere. This facility, however, may not be available in smaller circular conductors if they are extruded as one piece (which is possible in smaller sections).

Since the aluminium sections are formed to individual designs, there are no ready reckoners available from aluminium manufacturers of extruded sections to quickly determine their current ratings. This may be established only by conducting shop tests. It is not recommended to assign the rating on the basis of per unit area in view of a number of factors that may influence the rating, such as the surface area, the thickness of the enclosure or the conductor sections and ambient conditions. The design of a bus section is a matter of experience of the design engineer. As a rough guide, however, to establish the basic parameters, a rating around 350 to 400 A/in.^{2} may be considered which will also take account of all possible deratings. (Refer to the sample calculations in Example 31.1.) The normal practice is to do it with a computer aided programme, which can provide a number of alternative designs.



* Slits are left (≃ 50 mm wide) to facilitate heat dissipation from the inside surface of the conductors [enclosures are totally closed]

Note

Number of sections would depend upon the dimensions of the conductor or the enclosure.

Figure 31.15 Forming a conductor or enclosure from the available extruded sections

The cross-sections of the conductor and the enclosure are then checked for their adequacy to dissipate the heat generated. The cross-section is then adjusted suitably by permutations and combinations to arrive at the most appropriate size, keeping in mind the available extruded sections, accounting for all such factors that may affect the rating or the fault level of the enclosure and the conductor, such as tap-offs, which may be subject to a cumulative fault level, openings in the conductor for heat dissipation or the enclosure for inspection windows that can influence their ratings. A calculation in Example 31.1 will clarify the procedure to establish the size of the conductor and the enclosure for an IPB. The final sizes attained can then be laboratory tested to establish their accuracy.

31.12 Determining the section and size of conductor and enclosure

An isolated phase bus is also a tailored system to suit a particular layout. Size and area of cross-section will vary with the manufacturer. The insulators also play an important role in determining the diameter of the enclosure and its thickness as well as the diameter and thickness of the conductor. The manufacturer of an IPB may have the insulators made to specifications (for voltage, height, clearance and creepage distances) or make a choice from what is available in the market and compromise on the enclosure's diameter. To standardize on the size of conductor and enclosure for such systems is not normal practice. A manufacturer, however, can do so for his adopted design practices and standardize on some vital parameters such as the type of section (round, hexagonal or octagonal), depending upon the current rating as well as the availability of the extruded aluminium sections produced by indigenous manufacturers, design of insulators, area of cross-section and the system of cooling, etc. Generally, natural cooling and hollow cylindrical sections are preferred.

In smaller bus systems, say, up to 3200 A, standard data for sizes of busbars and their current ratings have been long established, as noted in Section 30.2 and Tables 30.2a, b and c, 30.4 and 30.5 etc. for different metals, sections and cross-sectional areas. These data can be used in the design of a particular bus system. But an IPB has to be specially designed. Below we provide brief guidelines for designing such a system from fundamentals, i.e. by applying the theory of thermal equilibrium between the heat generated by the system (conductor and the enclosure) and that dissipated by the conductor and the enclosure surfaces.

The amount of heat generated will decide the size and shape of the main current-carrying conductor, the rating and size of the enclosure and the provision of external cooling, if necessary. As noted earlier, forced cooling, if it can economize on the cost of the bus system, can be used. The one factor against the forced cooling is the need for an elaborate water softening, circulating and cooling system, its piping network, other equipment and their regular upkeep. Cooling system breakdown will not result in a total shutdown but a reduced rating of the bus system and consequent under-utilization of the generating unit. For larger ratings, however, above 25 000 A, forced cooling may become mandatory to dissipate the great heat generated in the enclosure. In such cases the size of the enclosure which is restricted by the size of the generator terminals may prove insufficient to dissipate the heat generated.

We have estimated the likely heat that may be generated by a particular size of conductor and enclosure for a certain current rating and then have counter-checked whether the conductor and the enclosure so chosen can dissipate this heat by radiation and natural convection, and reach a state of thermal stability within permissible limits or we may have to increase the size of the conductor or the enclosure, or both, and/or augment the heat dissipation through forced cooling to meet thermal requirements. The theoretical design is then put to laboratory tests to establish its accuracy.

Current rating varies with the surface area of a conductor and its thickness (annulus). In our sample calculation, to establish the basic parameters of the conductor and the enclosure, we have hypothetically considered the current density for both as 400 A/inch^2 to begin with.

The outdoor part of the enclosure has to perform more onerous duties as it has to withstand weather conditions and also absorb solar radiation. It has also to dissipate the heat of the conductor in addition to its own. It is therefore possible that the surface area of enclosure so chosen may have to be increased, and this will be revealed during thermal calculations which are carried out to check its suitability.

With this assumption, the basic cross-section of the conductor and the enclosure can be chosen. It is then counter-checked whether the size so chosen is adequate to reach a thermal stability. When desired, the t can be suitably modified to reach thermal equilibrium. The sizes can be optimized by plotting a few theoretical graphs:

- Losses versus t (Figure 31.12) and
- Cost versus t (Figure 31.13) to optimize t and hence, the cost of the conductor and the enclosure. For this t, the diameter may be modified to arrive at a more economical design. A higher t will mean a lower diameter and vice versa, and may be modified to satisfy the conductor's current-carrying and the enclosure's heat-dissipating requirements. Since the size of a hollow conductor, for large to very large current ratings, is not standardized the cylindrical diameter (d) and the wall thickness (t) can be varied, depending upon the rating, the extruded sections available and the cooling system adopted by the manufacturer. The exact d and t are then established by trial, and optimized as noted above. Figures 31.12 and 31.13 suggest that for a more economical design, the thickness must be less than the depth of penetration (δ_p). In enclosures a more economical design is achieved by keeping t in the vicinity of 50–60% of δ_p. This may mean some field in the space, but its severity is already mitigated by arresting most of it by the enclosure. Leading manufacturers have established their own data and programmed them on computers for routine reference and designing a bus system. These data are then

checked for their accuracy by conducting heat run tests on sample lengths (Section 32.3.4). After a few initial designs it is possible to optimize and predefine the vital parameters for a particular rating.

The exercise below is purely theoretical, based on the information and the data available on the subject, with a view to providing the basic guidelines to a practising engineer to design an IPB system.

Since ANSI-C-37.23 is available in the FPS system, we have adopted this for ease of corroboration. Also, since continuous enclosures are more often used for their obvious advantages, we have also considered them in our sample calculations. For details of non-continuous enclosures, reference may be made to the work noted in IEE Committee (1968).

31.13 Sample calculations

Example 31.1

To apply what we have discussed so far we give below a brief outline of a design for an IPB system. The economics of this design would be a matter of further investigation of its performance versus cost. This will require an optimization on the thickness of the enclosure as discussed earlier.

When optimizing the natural cooling of the enclosure its diameter may have to be increased but this would add to the cost of the IPB, on the one hand and make it too large to terminate at the generator end, on the other. The total design is thus a matter of many permutations and combinations. Most manufacturers have optimized their designs, based on experience and test results, through complex computer programming. In this example we will suggest only a basic approach to establish a design. Its optimization would require an elaborate cost analysis as noted earlier although its authenticity can be verified through laboratory tests.

Assume the following parameters of a turbo-alternator (Table 13.8):

Generator size (MW)	500 at 50 Hz
Rated p.f.	0.85
Rated MVA	$\frac{500}{0.85} = 588$
Stator nominal voltage (kV)	21
Stator maximum voltage (kV)	24
Stator current (CMR) (A)	16 200
Rated current of IPB (CMR) (A)	18 000
IPB to be designed for (A)	20 000*
One-second short-time rating (kA)	122
Type of enclosure for IPB	Continuous

We limit our discussion to the main length of the generator bus. A similar exercise can be carried out to design the neutral shorting star bus, tap-offs to the two UATs, the delta bus to inter-connect the GT when it is made of three single-phase units, tap-offs for CTs, VTs and surge protective equipment and all the auxiliary buses described in Section 31.1.1. Some of these tap-offs, such as for UATs, which are low-rating bus sections, can also be made with the construction of segregated phase bus system (Section 28.2.2) or partially isolated phase bus system (PIPB, Section 28.2.6) to economize on cost.

* This is a normal safety margin ($\simeq$ 10%) for such duties. It accounts for the dip in the grid voltage to which it is connected which may require the generator to operate at a lower voltage but still cope with the full-load (MVA) demand, resulting in a corresponding rise in its current for a short period.

Requirements

Ambient temperature for enclosure (θ_{ae} in °C)	48	
Enclosure's maximum permissible temperature (θ_e in °C) for indoors	80	
for outdoors	95	
Ambient temperature for conductor (θ_{ac} in °C), for indoors	80	The same as for the enclosure
for outdoors	95	
Conductor's maximum allowable temperature (θ_c in °C) for indoors	95	Assuming welded or silver-plated joints
for outdoors	105	

Assumptions

Conductivity of conductor and enclosure (% IACS)	60 (at 20°C, Table 30.1)
Grade	EIE
Specific resistance (ρ_{20} in $\mu\Omega$ cm)	2.873 (at 20°C, Table 30.1) $= 2.873 \times 10^{-6}\ \Omega$ cm
Temperature coefficient of electrical resistance (α_{20} in per °C)	3.96×10^{-3} (at 20°C, Table 30.1)
Effect of solar radiation on the outdoor part of the bus section (°C)	10†
Factor of emissivity, for the purpose of heat dissipation for the light grey surface of the enclosure noted above (e)	0.65‡

Cross-sections of conductor and enclosure are to be the same for indoor and the outdoor parts. This is normal practice of all manufacturers to achieve simplicity in design and ease of inter-connections. We have considered a circular conductor (the enclosure is usually circular).

Establishing the size of the conductor

Approximate area of cross-section (by simple hypothesis) $= \frac{20\,000}{400}$

$= 50$ square inches

Let us assume the thickness of the conductor to be close to but less than δ_p, say, around 11 mm, to reduce its diameter and hence increase the gap between the enclosure and the conductor.

$\therefore\ t = 0.43''$

and for the conductor's outer diameter d,

$$\left(\text{Area of hollow pipes} = \frac{\pi}{4} d_1^2 - \frac{\pi}{4} d_2^2\right)$$

$$= \frac{\pi}{4}(d_1 + d_2)(d_1 - d_2)$$

$$50 = \frac{\pi}{4}(d_1 + d_2)(d_1 - d_2)$$

$$= \frac{\pi}{4}(2d - 2t) \cdot 2t$$

† Assuming the approximate absorption coefficient of solar radiation to be 0.65, for a light-grey external surface, having collected soot and dirt over a period of time, as in ANSI-C- 37-24 the approximate temperature rise on account of solar radiation

$$= \frac{0.65}{0.97} \times 15 \simeq 10°\text{C}$$

‡ We have considered the emission of heat, from the surface through natural radiation, nearly the same, as its absorption of heat through solar radiation.

$= \pi(d - t)\cdot t$

$= \pi(d - 0.43)\times 0.43$

$\therefore\ d = \dfrac{50}{\pi\times 0.43} + 0.43$

$= 37.46''$

and the conductor's outer surface area ($\pi d \ell$) per foot run

$A_{so} = \pi\times 37.46\times 12$

$= 1411.49$ square inches

(ℓ is the length of conductor in inches)
Conductor's inner surface area per foot run

$A_{si} = \pi[37.46 - 2\times 0.43]\times 12$

$= 1379.09$ square inches

Establishing the size of the enclosure
As discussed above, that thinner the section, the fewer will be the losses and the more economical will be the design. But we cannot reduce the thickness and increase the diameter of the enclosure indefinitely. A very large diameter may also become unsuitable to match at the generator end. The generator terminal dimensions, in fact, decide the size of the enclosure. For the generator rating under consideration, we are taking the outside diameter of the enclosure as 1500 mm (it should be considered according to the site requirement and adjusted for the support insulators selected). The terminal spacing of the generator between phases will also determine the centre spacing of the IPB. In our calculations we assume it to be around 68 inches (which may almost be the case in practice).

Enclosure's approximate area of cross-section $= \dfrac{20\,000\times 0.98}{400}$

$= 49$ square inches

(assuming the enclosure's current to be around 98% of the conductor's current

Enclosure's outer diameter = 1500 mm

$D = 59$ inches

$\therefore$ enclosure thickness $t \simeq 0.27$ inch (Figure 31.16)

$[49 = \pi(D - t)\cdot t = \pi(\simeq 59)t]$

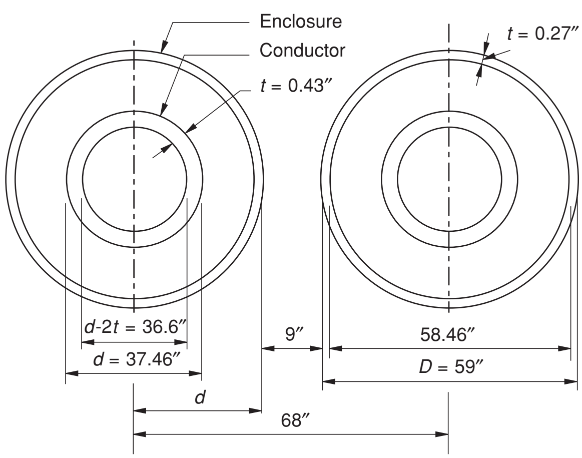


Figure 31.16 IPB conductor and enclosure for Example 31.1

$\therefore$ exact area of cross-section $= \dfrac{\pi}{4}(59^2 - (59 - 0.54)^2)$

$= 49.79$ square inches

Enclosure surface area per foot run $A_s = \pi\times 59\times 12$

$= 2223.12$ square inches

Checking the suitability of the above sections by heat balancing

Heat generated (In the outdoor part)

1 By the conductor

$W_1 = I_r^2\cdot R_{ac}$ W/ft

$= I_r^2\cdot R_{dc}\times$ skin effect ratio

$R_{dc20} = \dfrac{\rho_{20}\cdot \ell}{\pi\cdot d_m\cdot t}\ (\ell = 1')$

$= \dfrac{(2.873\times 10^{-6}\ \Omega\ \text{cm})\times(1'\times 12\times 2.54\ \text{cm})}{\pi\times[(37.46 - 0.43)\times 2.54\ \text{cm}]\ (0.43\times 2.54\ \text{cm})}$

$= 0.271\times 10^{-6}\ \Omega$/ft

and

$R_{dc105}{}^* = R_{dc20}\,[1 + \alpha_{20}\,(105 - 20)]$

$= 0.271\times 10^{-6}[1 + 3.96\times 10^{-3}\times 85]$

$= 0.271\times 10^{-6}\,[1.3366]$

$= 0.3622\times 10^{-6}\ \Omega$/ft

Skin effect ratio, from Figure 31.17 for

$\sqrt{\dfrac{f\times 10^3}{R_{dc}}} = \sqrt{\dfrac{50\times 10^3}{0.3622}}$ (R_{dc} in $\mu\Omega$/ft)

$= 371.54$

and $t/d = \dfrac{0.43}{37.46}$

$= 0.011$

$\therefore$ Skin effect ratio $\simeq 1.03$

$\therefore\ W_1 = (20\,000)^2\times 0.3622\times 10^{-6}\times 1.03$

$= 149.22$ W/ft

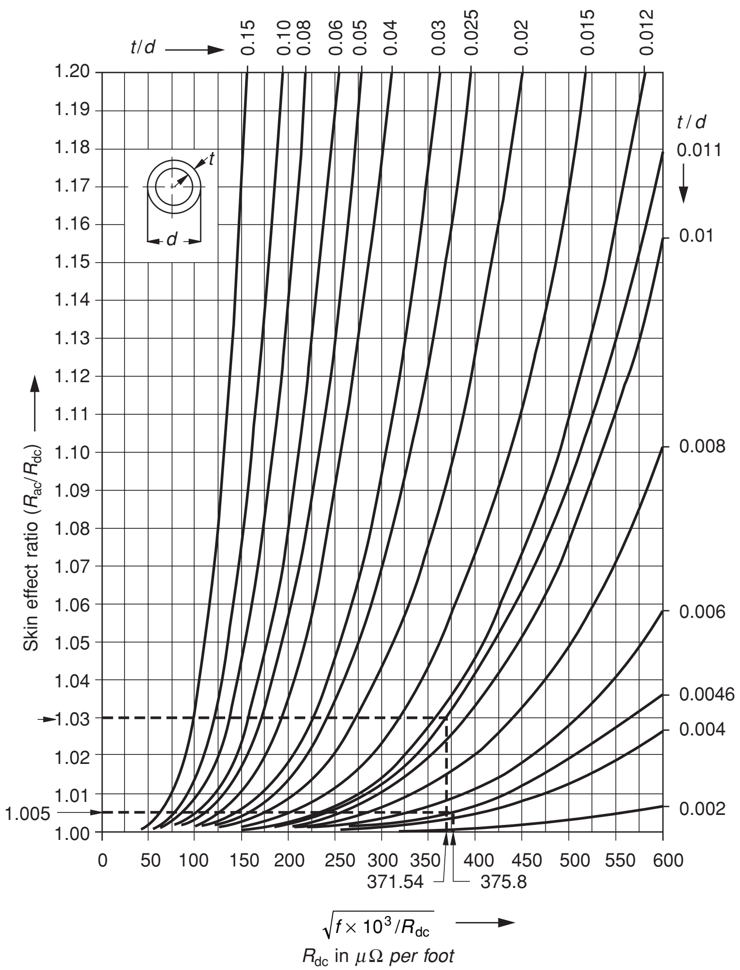
2 By the enclosure

(a) ***By current***

$W_2 = (0.98\ I_r)^2\cdot R_{ac}$

The current through the continuous enclosure is assumed to be at about 98% of that of the main conductor. The actual current may be less than this as a result of low enclosure thickness, which is considered to be less than the depth of penetration δ_p. But it may not cause a high field in the space, leading to heating of steel structures, beams, columns or other equipment installed in the vicinity or step and touch voltages higher than permissible. This is a subject for further investigation and experiments need be conducted to establish that the field in the space is within reasonable limits. Otherwise the enclosure thickness may need to be increased slightly and the diameter reduced accordingly.

*We have considered the conductor to be operating at its maximum permissible temperature, although it may be operating at less than this and generating less heat than assumed.



Note Figure 28.13(b) in Ω/1000 m is redrawn in μΩ/ft.

Figure 31.17 Curves for skin effect for isolated tubular conductors

Now, $R_{dc20} = \dfrac{(2.873 \times 10^{-6})\,(1 \times 12 \times 2.54)}{\pi \times (59 - 0.27) \times 2.54 \times 0.27 \times 2.54}$

$= 0.273 \times 10^{-6}\ \Omega/\text{ft}$

and R_{dc95}† $= 0.273 \times 10^{-6}\,[1 + 3.96 \times 10^{-3} \times (95 - 20)]$

$= 0.273 \times 10^{-6}[1.297]$

$= 0.354 \times 10^{-6}\ \Omega/\text{ft}$

and skin effect ratio from Figure 31.17

for $\sqrt{\dfrac{50 \times 10^3}{0.354}}$ or 375.8

and $t/d = \dfrac{0.27}{59} = 0.0046$

$\therefore$ skin effect ratio $\simeq 1.005$

† Here also we have assumed the maximum operating temperature though the enclosure may be operating at less than this.

$\therefore\ W_2 = (0.98 \times 20\,000)^2 \times 0.354 \times 10^{-6} \times 1.005$

$= 136.67$ W/ft

(b) ***By solar radiation (W*** $_{\mathbf{s}}$***)***

$W_s = k_a \cdot G \cdot A$ W/ft

where

$k_a = 0.65$

$G = 1100$ W/m^2 (for tropical areas)

$= \dfrac{1100}{3.28 \times 3.28}$ W/ft^2

$= 102.24$ W/ft^2

$A = 0.5 \times \dfrac{2223.12}{144}$ ft^2 (assuming only the upper 50% surface to be subjected to direct solar radiation)

$\therefore\ W_s = 0.65 \times 102.24 \times \left(\dfrac{0.5 \times 2223.12}{144}\right)$

$= 512.98$ W/ft

$\therefore$ Total heat generated (within the enclosure)

$$= 149.22 + 136.67 + 512.98$$

$$= 798.87 \text{ W/ft}$$

Suitability of the conductor

Heat dissipation by the conductor

1 By radiation

$$W_r = \frac{36.9}{10^{12}} \cdot e \cdot A_s [T_1^4 - T_2^4] \text{ W/ft}$$

where

e = 0.85 (conductor is painted matt black with non-magnetic paint)
A_s = 1411.49 square inches
T_1 = 105 + 273
= 378°C
T_2 = 95 + 273
= 368

$$\therefore \quad W_r = \frac{36.9}{10^{12}} \times 0.85 \times 1411.49 [378^4 - 368^4]$$
$$= 91.92 \text{ W/ft}$$

2 By convection

(i) **From the outer surface**

$$W_c = 0.0022 A_s \frac{p^{0.5} \cdot \theta^{1.25}}{h^{0.25}} \text{ W/ft}$$

A_{so} = 1411.49 square inches

p = 1 (near sea level)

θ = 105 – 95 = 10°C

h = 37.46 inches

$$\therefore \quad W_c = 0.0022 \times 1411.49 \times \frac{10^{1.25}}{37.46^{0.25}}$$
$$= 22.32 \text{ W/ft}$$

(ii) **From the inner surface***

A_{si} = 1379.09 square inches

h = 37.46 – 2 × 0.43 = 36.6 inches

$$W_c = 0.0022 \times 1379.09 \times \frac{10^{1.25}}{36.6^{0.25}}$$
$$= 21.93 \text{ W/ft}$$

$\therefore$ Total heat dissipated

= 91.92 + 22.32 + 21.93

= 136.17 W/ft

as against the total heat generated of 149.22 watt/ft. The conductor chosen appears to be very close to the required size. Its diameter or thickness may be slightly modified to achieve thermal equilibrium and a more appropriate size.

3 By enclosure

(a) **By radiation**

$$W_r = \frac{36.9}{10^{12}} \cdot e \cdot A_s [T_1^4 - T_2^4] \text{ W/ft}$$

*This dissipation of heat will not be applicable when the circular section is made of circular extruded sections which have no surface openings.

where

e = 0.65 (This is on a conservative side. For dull, non-magnetic matt finish painted surfaces, which such enclosures generally are, some manufacturers consider this factor up to 0.85)
A_s = 2223.12 square inches
T_1 = 95 + 273
= 368°C
T_2 = 48 + 273
= 321°C

$$\therefore \quad W_r = \frac{36.9}{10^{12}} \times 0.65 \times 2223.12 [368^4 - 321^4]$$
$$= 411.76 \text{ W/ft}$$

(b) **By convection (W_c)**

$$W_c = 0.0022 A_s \frac{p^{0.5} \cdot \theta^{1.25}}{h^{0.25}} \text{ W/ft}$$

where
A_s = 2223.12 square inches
p = 1 (near sea level)
θ = 95 – 48
= 47°C
h = 59 inches

$$W_c = 0.0022 \times 2223.12 \times \frac{1 \times 47^{1.25}}{59^{.25}}$$
$$= 217.17 \text{ W/ft}$$

$\therefore$ Total heat dissipated

= 411.76 + 217.17

= 628.93 W/ft

compared to the total heat generated of 798.87 W/ft.

Notes

1 If we assume the emissivity factor to be 0.85 the shortfall in the heat dissipation is nearly made up. However, it would be a matter of laboratory testing to establish the suitability of the enclosure section chosen. Otherwise the thickness of the enclosure may be slightly increased and the calculations repeated.
2 Add a suitable margin in the conductor's cross-section to account for the opening considered to dissipate the inside heat. Similarly, add a suitable margin in the enclosure's cross-section to account for the inspection windows.
3 In fact, it is the solar effect that is causing the maximum heat. The factors considered for the solar effect are also highly conservative. Nevertheless, a canopy over the outdoor part is advisable in the above case. This will ensure the same size of enclosure for the outdoor as well as the indoor parts and also eliminate the requirement for a thicker enclosure or a forced cooling arrangement. Now there will be no direct solar radiation over the bus system and the total solar effect can be eliminated, except for substituting the indoor ambient temperature of 48°C with the maximum outdoor temperature for the outdoor part of the bus system.
4 If we can overcome the solar effect, the size of the conductor and the enclosure can be reduced to economize their costs. Another exercise with reduced dimensions will be necessary for this until the most economical sections are established.
5 Once the required sizes of the conductor and the enclosure are established, one can choose the nearest economical sizes of the extruded sections available in the market, or have them specially manufactured if possible.

A design engineer will be the best judge of the best and the most economical design and extruded sections.

The above example is only for the outdoor part of the bus system. The indoor part, in any case, would be cooler than the outdoor one and will also provide a heat sink to the hotter enclosure and the conductor constructed outdoors. No separate exercise is therefore carried out for the indoor part of the bus system, for the sake of brevity. For a realistic design that would be essential. The above example provides a basic approach to the design of an IPB system. With some permutations and combinations, a more realistic and economical design can be achieved. A computer programming is necessary for this exercise.

Relevant Standards

IEC	*Title*	*IS*	*BS*	*ISO*
60059/1999	Standard current ratings (based on Renald Series R-10 of ISO-3).	–	–	3/1973

Relevant US Standards ANSI/NEMA and IEEE

ANSI/IEEE-C37.23/1992	Metal enclosed bus and guide for calculating losses in isolated phase bus.
ANSI/IEEE-C37.24/2003	Guide for evaluating the effect of solar radiation on outdoor metal enclosed switchgear.

Notes

1 In the table of relevant Standards while the latest editions of the Standards are provided, it is possible that revised editions have become available or some of them are even withdrawn. With the advances in technology and/or its application, the upgrading of Standards is a continuous process by different Standards organizations. It is therefore advisable that for more authentic references, one may consult the relevant organizations for the latest version of a Standard.
2 Some of the BS or IS Standards mentioned against IEC may not be identical.
3 The year noted against each Standard may also refer to the year it was last reaffirmed and not necessarily the year of publication.

List of formulae used

Constructional features

Continuous or bonded enclosures

Magnetic field in space

$$\phi_{\text{space}} \propto (\overline{I_r} - \overline{I_e}) \tag{31.1}$$

ϕ_{space} = magnetic field in space
I_r = conductor current
I_e = enclosure current

Enclosure heating

$$\text{Total heat generated} = W_1 + W_2 + W_s^* \tag{31.2}$$

in watts per unit length. (*only for the outdoor parts)

W_1 = heat generated in the conductor in watts
W_2 = heat generated in the enclosure in watts
W_s^* = heat generated due to solar radiation in watts

For tubular conductors

$$R_{\text{dc20}} = \frac{\rho l}{\pi \cdot d_m \cdot t} \text{ in } \Omega/\text{m or } \mu\Omega/\text{ft} \tag{31.3}$$

(in MKS or FPS units, depending upon the system adopted)

ρ = resistivity of metal at 20°C in Ω m or in μΩ cm
d_m = mean diameter of the tube in m or cm
t = thickness of the tube in m or cm
l = length of the conductor in m or cm

$$R_{\text{dc}\theta} = R_{\text{dc20}}[1 + \alpha_{20}(\theta - 20)] \tag{31.4}$$

$R_{\text{dc}\theta}$ = d.c. resistance of the conductor at the operating temperature
α_{20} = temperature resistance coefficient of the metal at 20°C per °C

Skin effect in a tubular conductor

$$\delta_\rho = \frac{1}{2\pi}\sqrt{\frac{\rho}{\mu f}} \tag{31.5}$$

δ_ρ = depth of penetration in mm
ρ = resistivity of the metal in e.m.u.
f = frequency of the system in Hz
μ = effective permeability of the medium, in which the field exists and will depend upon the electric field induced in the enclosure
= 1 for non-magnetic materials

Thickness of enclosure

For minimum losses,

$$\frac{\text{Thickness of tubular conductor } (t)}{\text{Depth of penetration } (\delta_p)} = \pi/2$$

or

$$t = \frac{\pi}{2}\delta_p \tag{31.6}$$

Solar radiation

$$W_s = k_a \cdot G \cdot A \text{ W/ft} \tag{31.7}$$

k_a = coefficient of absorption
G = global solar radiation
A = area of the enclosure, that is exposed to the sun

Natural cooling of enclosures

By radiation

$$W_r \simeq \frac{36.9}{10^{12}} \cdot e \cdot A_s\ [T_1^4 - T_2^4]\ \text{W/ft} \tag{31.8}$$

e = coefficient of emissivity, expressed by the condition of the surface of the hot body
A_s = effective surface of radiation per foot of enclosure length in square inches
T_1 = absolute temperature of the hot body
= $(\theta_s + 273)$°C (θ_s = enclosure surface temperature in °C)
T_2 = absolute ambient temperature
= $(\theta_a + 273)$°C (θ_a = ambient temperature in °C) (For conductors, the enclosure temperature will become their ambient temperature).

By convection

$$W_c \simeq 0.0022 \cdot A_s \cdot \frac{\rho^{0.5} \cdot \theta^{1.25}}{h^{0.25}}\ \text{W/ft} \tag{31.9}$$

A_s = effective surface area per foot of enclosure length – in square inches
ρ = air pressure in atmospheres
= 1 at sea level
θ = temperature rise of the enclosure above the ambient temperature in °C
h = width of flat or bar mounted in a vertical plane, or the diameter of a round conductor in inches

Further Reading

1 Albright, R.H., Bates, A.C., Conanagla, A. and Owens, J.B., 'Isolated-phase metal enclosed conductors for large electric generators', *Trans. IEEE*, **81**, February, 1067–72 (1963).
2 Ashdown, K.T. and Swerdlow, N., 'Cantilever-loaded insulators for isolated phase bus', AIEE paper, April (1954).
3 Buchanan, G.E., 'Lab field test experience with high capacity isolated-phase bus', *Trans. IEEE*, **78**, October, 925–931 (1959).
4 Conangla, A.C., 'Heat losses in isolated phase enclosure', *AIEE Trans.* June, 309–313 (1963).
5 Conangla, A. and White, H.E., 'Isolated-phase bus enclosure loss factors', *Trans. IEEE*, **87**, August, 1622–1628 (1968).
6 Dwight, H.B., 'Theory for proximity effects in wires, thin tubes and sheaths', *AIEE Trans*. **42** (1923).
7 Dwight, H.B., 'Some proximity effects formulae for bus enclosures', *Trans. IEEE*, **83**, December 1167–1172 (1964).
8 Dwight, H.B., 'Proximity effect formulae for bus enclosures', *Trans. IEEE*, **87**, August, 1622–1628 (1968).
9 Dwight, H.B., Andrews, G.W. and Tileston Jr H.W., 'Temperature rise of busbars', *General Electric Review*, May (1940).
10 Elgar, E.C., Rehder, R.H. and Sverdlow, N., 'Measured losses in isolated-phase and comparison with calculated values', *Trans. IEEE,* **87**, August, 1724–1730 (1968).
11 Gupta, C.P., and Prakash, R., *Engineering Heat Transfer*, Nemchand Bros, Roorkee, India.
12 IEEE Committee, 'Proposed guide for calculating losses in isolated phase bus', *Trans. IEEE*, **87**, August, 1730–1737 (1968).
13 Jain, M.P., *Proximity Effects of Busbars*, ME thesis, Electrical Engineering Department. University of Roorkee, Roorkee, India (1969).
14 Jain, M.P. and Ray, L.M., 'Field pattern and associated losses in aluminium sheet in presence of strip busbar', *Trans. IEEE*, **89**, September/October, 1525–1539 (1970).
15 Jain, M.P. and Ray, L.M., 'An experimental study of proximity effects of busbars', *Journal of Institution of Engineers (India),* **51**, No. 12, Part EL–6, August, 341–350 (1971).
16 Mankoff, L.L., Sverdlow, N. and Wilson, W.R., 'An analogue method for determining losses in isolated-phase bus enclosures', *Trans. IEEE*, **82**, August, 532–542 (1963).
17 Niemoller, A.R., 'Isolated-phase bus enclosure currents', *Trans. IEEE,* **87**, August, 1714–1718 (1968).
18 Paulus, C.F. and Bellack, J.H., 'Progress in generator leads: Economical application of forced cooling', *Trans. IEEE*, **88**, February, 175–180 (1969).
19 Poritsky, H. and Jerrard, R.P., 'Eddy current losses' *Trans. AIEE,* Part I, **73**, May, 97–108 (1954).
20 Sebold, G.K., 'Induced current, in supporting steel for 10 000 Ampere generator open bus', *Trans. IEEE*, 642–647 (1960).
21 Skeats, W.F. and Sverdlow, N., 'Minimising the magnetic field surrounding isolated phase bus by electrically continuous enclosures', *AIEE Trans.* No. 62 (1962).
22 Skeats, W.F. and Sverdlow, N., 'Minimising the magnetic field surrounding isolated phase bus by electrically continuous enclosures', *Trans. IEEE*, **81**, February, 655–657 (1963).
23 Stratton, J.A., *Electromagnetic Theory*, McGraw-Hill, New York (1941).
24 Sverdlow, N. and Buchta, M.A., 'Practical solution of induction heating problems resulting from high current buses', *Trans. IEEE*, **78**, 1736–1742 (1959).
25 Wilson, W.R. and Mankoff, L.L., 'Short-circuit forces in isolated phase buses, *AIEE Trans.,* April (1954)