Part V

Busbar Systems

28 Carrying power through metal-enclosed bus systems

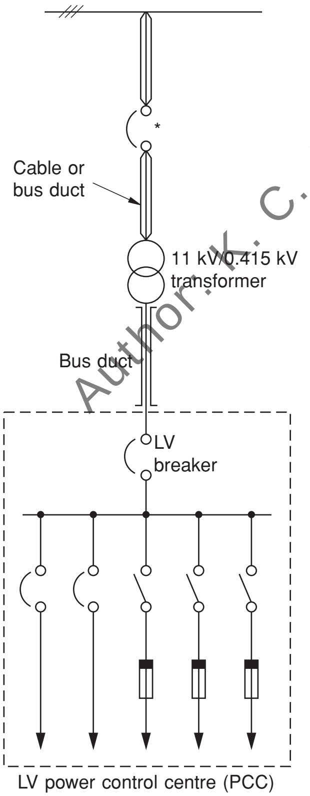
Contents

28.1 Introduction

In a power-generating station power is carried from the generator to the power transformer, to the unit auxiliary transformer (UAT) or to the unit auxiliary switchgear as illustrated in Figure 13.21 through solid conductors (HV bus systems). This is due to large capacity of the generators (up to 1000 MW). The transmission of such large amounts of power over long distances is then through overhead lines or underground cables.

Similarly, for a distribution system of 3.3, 6.6 or 11 kV and even higher such as 33 or 66 kV, feeding large commercial or industrial loads, the distribution of power on the LV side (Figure 28.1) may be through cables or solid conductors (LV bus systems), depending upon the size of the transformer. The HV side of the transformer may also be connected through cables or the HV bus system as illustrated.

For moderate ratings on LV system, say, up to 600/800 A, cables are preferred, while for higher ratings (1000 A and above), the practice is to opt for solid conductors (LV bus systems), on the grounds of cost, appearance, safety, ease of handling and maintenance. For larger ratings, more cables in parallel may become unwieldy and difficult to maintain and present problems in locating faults. The busbar conductors may be of aluminium or copper. The use of copper may be more appropriate at corrosive areas (such as humid, saline or chemically aggressive locations). In humid and corrosive conditions, aluminium erodes faster than copper.



* 11 kV breaker for isolation and protection of transformer and interconnecting cables

Figure 28.1 Application of a bus system

These solid or hollow conductors connect the supply side to the receiving end and are called bus ducts. They may be of the open type, such as to feed a very high current at very low voltage. A smelter unit is one such application. But normally they are housed in a sheet metal enclosure, Figures 28.2(a) and 28.33(b).

Our main concern here will be dealing with large to very large currents, rather than voltages. Currents are more difficult to handle than voltages due to mutual induction between the conductors and between the conductor and the enclosure. Here we briefly discuss the types of metal-enclosed bus systems and their design parameters, to select the correct size and type of aluminium or copper sections and the bus enclosure for the required application, current rating and voltage system. More applications, illustrations are provided for aluminium conductors rather than copper, as they are more commonly used on grounds of cost, but adequate data and tables are provided to design a copper busbar system also.

28.2 Types of metal-enclosed bus systems

A bus system can be one of the following types, depending upon its application:

- Non-segregated
- Segregated
- Isolated phase
- Rising mains (vertical bus systems)
- Overhead bus (horizontal bus system)
- Non-conventional bus systems

  (1) Compact and sandwich type
  (2) Partially isolated phase bus (PIPB) type
  (3) Gas (SF_6) insulated busbars (GIB)

28.2.1 A non-segregated phase bus system

In this construction all the bus phases are housed in one metallic enclosure, with adequate spacings between them and the enclosure but without any barriers between the phases (Figure 28.2(a)).

Application

Being simple and economical, it is the most widely used construction for all types of LV systems. The latest trend now is to go in for compact bus systems where possible, in view of their inherent advantages noted later.

Nominal current ratings

The preferred current ratings may follow series R-10 of IEC 60059 and as discussed in Section 13.4.1(4). They may increase to 6000 A or so, depending upon the application like when required to connect a large LV alternator or the LV side of a large transformer to its switchgear. The preferred short-time ratings may be one of those indicated in Table 13.7.

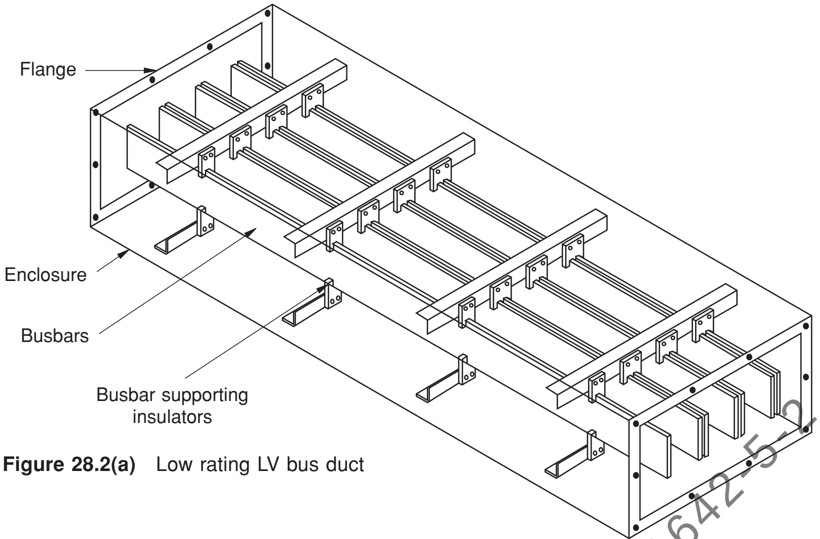


Figure 28.2(a) Low rating LV bus duct

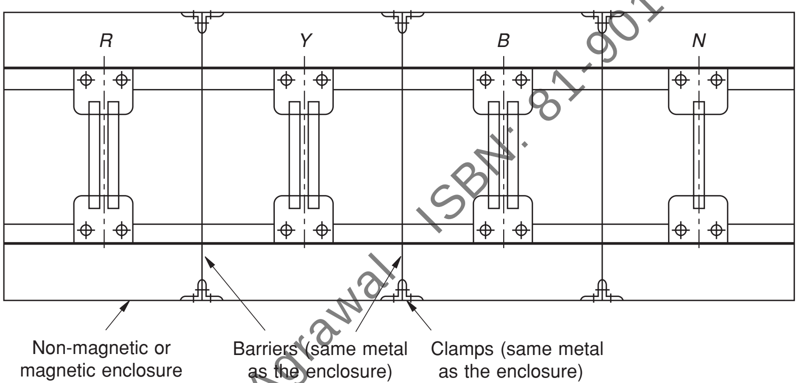


Figure 28.2(b) A segregated phase bus system

28.2.2 A segregated phase bus system

In this construction all the phases are housed in one metallic enclosure as earlier, but with a metallic barrier between each phase, as illustrated in Figure 28.2(b). The metallic barriers provide the required magnetic shielding and isolate the busbars magnetically from each other, like an isolated phase bus system (IPB). The metallic barriers transform the enclosure into somewhat like Faraday Cages (Section 23.18). For more details see Section 31.2. The enclosure can be of MS or aluminium and the barriers also of the same metal as the enclosure to provide uniform distribution of field. The purpose of providing a metallic barrier is not only to shroud the phases against short-circuits but also reduce the effect of proximity of one phase on the other by arresting the magnetic field produced by the current carrying conductors within the enclosure itself. It now operates like an enclosure with an interleaving arrangement (Section 28.8.4) balancing the fields produced by the conductors to a great extent and allowing only a moderate field in the space, as in an IPB system (Section 31.2). The enclosure losses with such an arrangement may fall in the range of 60–65% of conductors in case of m.s. (mild steel) and 30–35% in case of aluminium enclosures for all voltage systems 3.3–11 kV and current ratings above 3000 A and up to 6000 A or so. Only aluminium enclosures should be preferred to minimize losses and enclosure heating. The effect of proximity is now almost nullified as also an imbalance in the phase reactances. An unbalance in the reactance is otherwise responsible for a voltage unbalance between the three phases as discussed in Section 28.8.2 and enhance the electrodynamic forces that may lead to a phase-to-phase fault at higher rated currents.

Applications

They are generally used for higher ratings, 3000 A and above, on all voltage systems. They are, however, preferred on an HV rather than an LV system, such as between a unit auxiliary transformer (UAT) and its switchgears and a station transformer and its switchgears as in a power-generating station and shown in Figure 13.21, for reasons of safety and also cost of an isolated phase bus system (IPB) (Chapter 31) over a segregated system.

With the availability of compact and partially isolated bus systems as discussed later, this type of bus system can be easily replaced with the non-conventional bus systems.

Note
For such ratings, enclosure of non-magnetic material alone is recommended due to high iron losses in a magnetic material.

Nominal current ratings

These will depend upon the application. The preferred ratings may follow series R-10 of IEC 60059, as described in Section 13.4.1(4). They may increase to 6000 A or so depending upon the application.

28.2.3 An isolated phase bus (IPB) system (for very large ratings 10 000 A and above)

The design criteria and construction details of this system are totally different from those of a non-isolated phase bus system discussed above. This type of enclosure is dealt separately in Chapter 31.

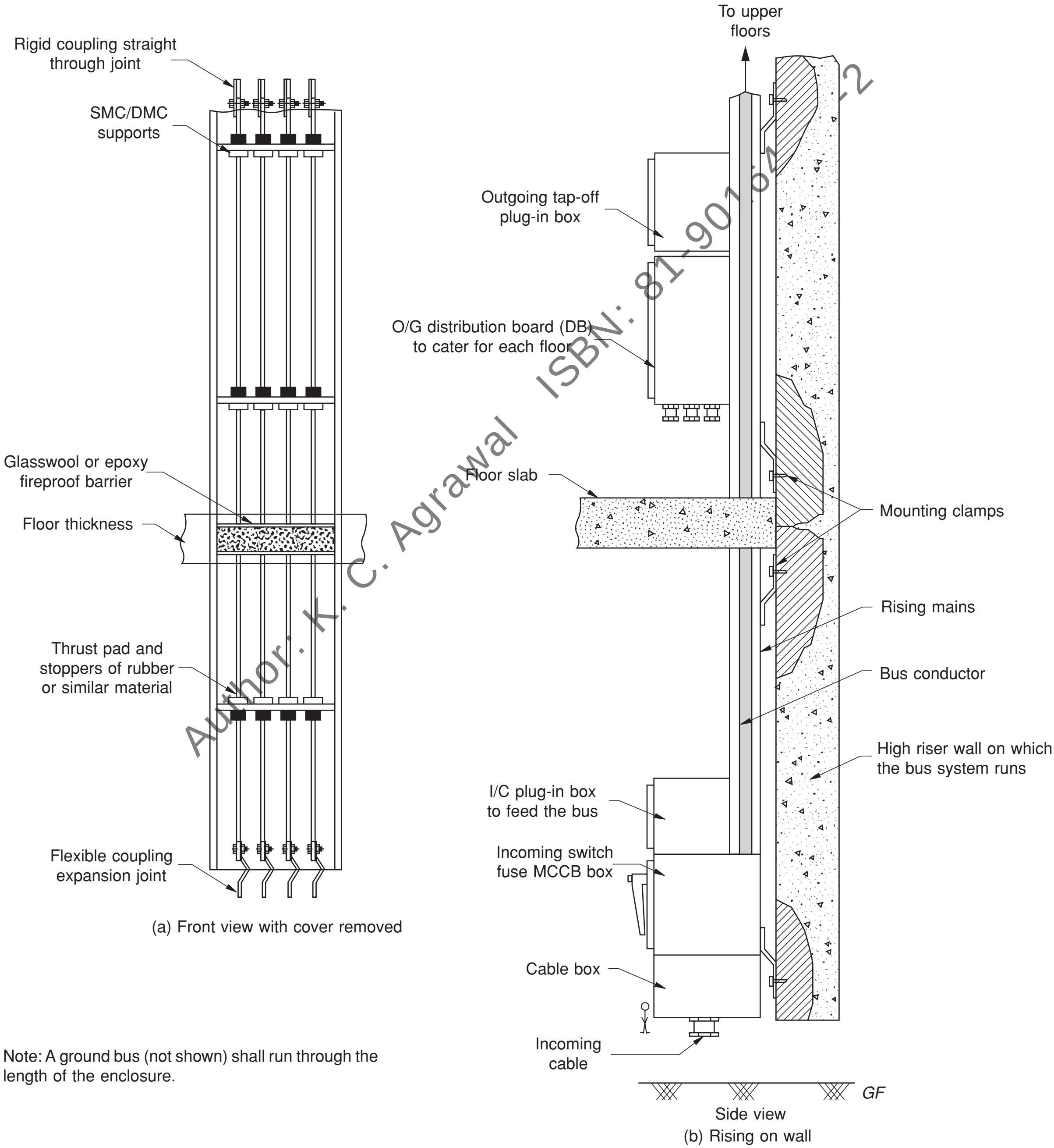


Figure 28.3 Rising mains mounting arrangement

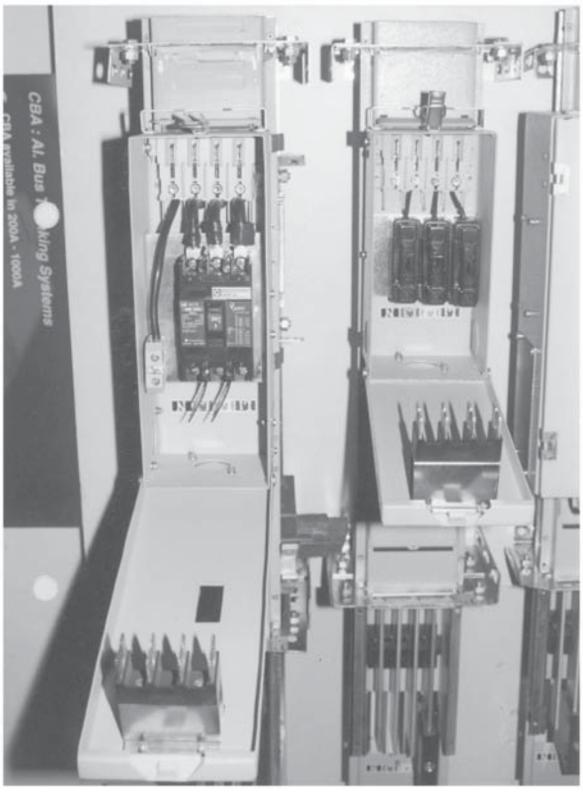
28.2.4 A rising mains (vertical bus system)

For power distribution in a multi-storey building

This is another form of a bus system and is used in vertical formation to supply individual floors of a high-rise building (Figures 28.3(a) and (b)). This is much neater arrangement than using cables and running numerous lengths of them to each floor which may not only be unwieldy but also more cumbersome to terminate and to locate faults. Such a system is the normal practice to distribute power in a high-riser. It rises from the bottom of the building and runs to the top floor. To save on cost, the ratings may be in a decreasing order after every three or four floors, as after every floor the load of that floor will be reduced. The rating can be grouped for three or four floors together, depending upon the total load and the number of floors. A smaller rating of, say, 200–400 A need not be further stepped for it may not be of any economic benefit.

Special features of rising mains

1 They are manufactured in small standard lengths, say, 0.45–3.0 m, and are then joined together at site to fit into the layout.
2 Wherever the rising mains cross through a floor of the building, fireproof barriers are provided as shown in Figure 28.3(a) to contain the spread of fire to other floors.
3 On each floor opening is provided in the rising mains to receive a plug-in box (Figures 28.3(b) and (c)) to tap-off the outgoing connections and to meet the load requirement of that floor. The plug-in box can normally be plugged in or withdrawn from the live bus without requiring a shutdown.
4 To take up the vertical dynamic load of busbars and to prevent them from sliding down, two sets of thrust pads are generally provided on the busbars in each standard length of the rising mains, as illustrated in Figure 28.3(a).
5 Flexible expansion joints of aluminium or copper are essential after every three or four standard lengths (say, after every 7.5–10 m) to absorb the expansion of busbars on load.



DB with MCCB DB with HRC fuses

Figure 28.3(c) Rising mains

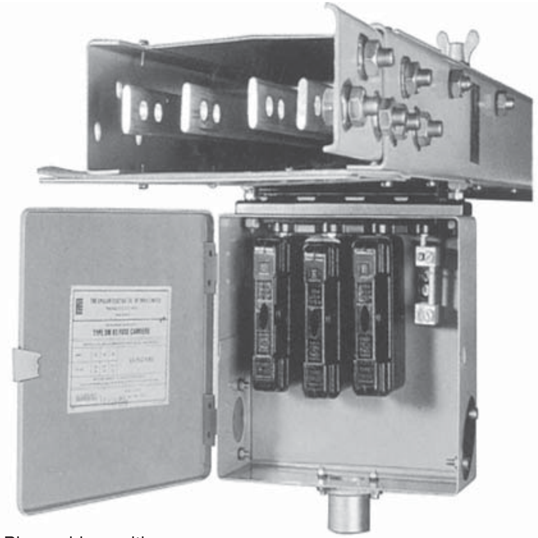
Usually compact and energy efficient bus risers that are light weight and easy to manoeuvre are preferred for such applications (Figure 28.4(f1)).

28.2.5 An overhead bus (horizontal bus system) (Figures 28.4a, b and c)

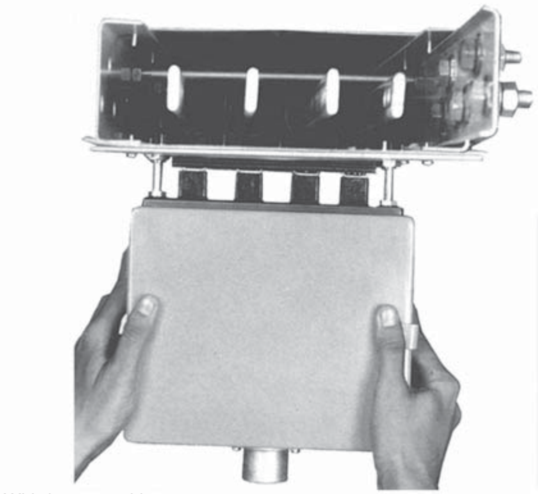
Unlike a high riser, now the overhead bus system runs horizontally, below the ceiling at a convenient height, as shown in Figure 28.4(c) to distribute power to light and small load points. Large tool room or machine shops are installations that would otherwise require a distribution system, for short distances, to meet the needs of various load points and make power distribution unwieldy and cumbersome. Moreover, it would also mean running many cables under the floor to feed each load point. In an overhead busbar system, the power can be tapped from any number of points to supply the load points just below it through a plug-in box similar to that used on a rising mains. The floor can now be left free from cables and trenches. Here also it is preferred to use a compact and energy efficient bus system.

28.2.6 Non-conventional compact and low loss bus systems

Cables are too compact (Appendix 16). If we can create similar conditions in a bus system also, so as to be able to place the conductors together, we can achieve similar compactness in busbars also. This technique is effectively and meticulously developed and utilized by some manufacturers by providing adequate insulation to the current carrying conductors and making it possible to place them together to produce very compact sizes of busbars for LV and HV systems. The concept behind these bus systems has revolutionized the power transfer technique through bus systems. Placing the busbars together reduces the inductance of the busbars 'Xa', impedance (Z), voltage drop (I.Z) and so also the magnetizing losses to a very great extent. Lesser the spacing between the phase busbars lesser is the 'Xa'. Figure 28.24 and Tables 28.0(1) and 28.0(2) elucidate this. Since there being little scope for the movement of busbars higher EM forces are of no consequence like in cables.

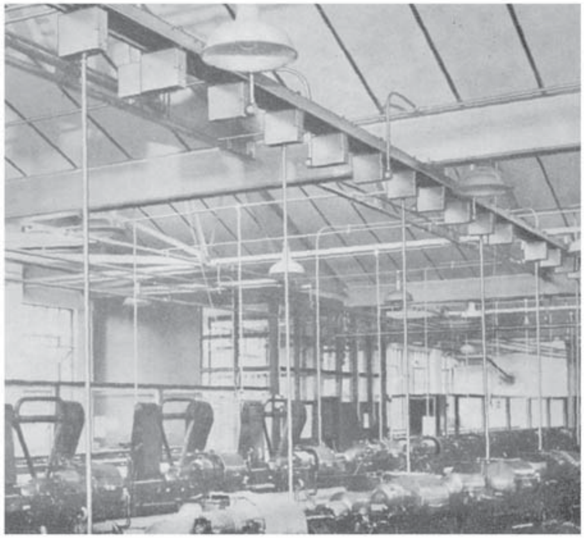


Plugged in position

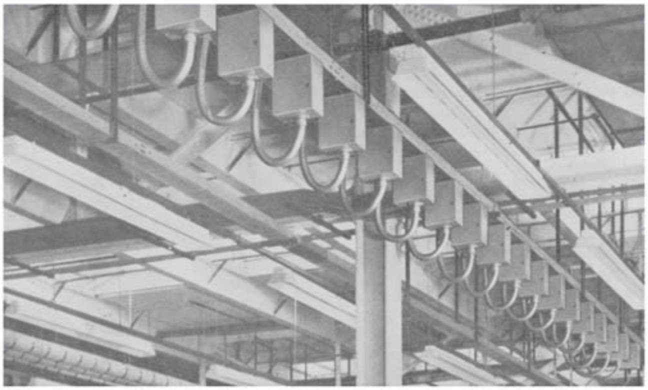


Withdrawn position

Figure 28.4(a) Plug-in tap-off box



Overhead busbar system in a machine shop



Installation of overhead bus system with tap-off boxes in a large assembly shop

Figure 28.4(c)

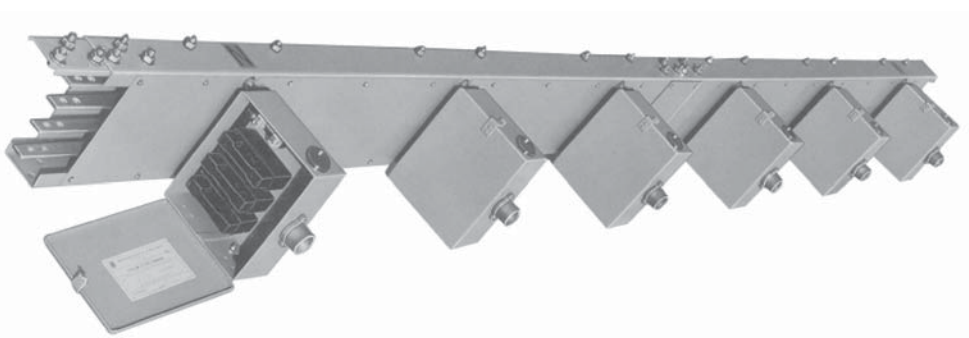


Figure 28.4(b) An overhead bus system shown with tap off boxes (Courtesy: GE Power)

These systems therefore save space and energy. The important feature of such bus systems is their insulation technique. The heat transfer now is usually through conduction rather than convection. In a conventional bus system the heat dissipation is through conductor to air, air to metallic enclosure and enclosure to surroundings. And air being a poor medium of heat transfer by natural convection. A conventional bus system therefore calls for larger cross-section of conductors and the enclosure to dissipate the heat generated, more so in larger ratings 2000A and above (see Ex 28.12, Figures 28.33 and 28.34). We can therefore call them as energy efficient and space-saver bus systems and a preferred choice for all applications for power transmission requiring a bus system. Below we provide brief details of these bus systems:

(1) Compact and sandwich type bus systems

To achieve a good insulation the busbars may be epoxy or polyester insulated using vacuum or other effective process. Epoxy has a dielectric strength of about 35–40 kV/mm, whereas polyester, a heat resistant halogen free insulation has it of the order of 100 kV/mm and more. Both are used extensively for LV and HV sandwich busbar systems. The coating in case of polyester is usually in the form of a thin film. With thinner insulation the heat dissipation is efficient and so also the metal utilization and the bus system is even more compact.

PVC having a low dielectric strength of the order of 18 kV/mm (Table A16.2) is suitable only for LV systems but is usually not preferred for the following reasons,

- Wrapping skin tight PVC sleeve over busbars is not safe as it may bear cuts and cracks while sliding over the busbars. A perfect insulation as noted, is a pre-requisite for safe operation of sandwich busbars over long periods. Using a thicker sleeve may defeat the utility of heat transfer by conduction, the main concept behind such bus systems.
- It may also trap air to form air pockets restricting heat dissipation.

However, if it is possible to provide PVC coating than sleeving over the busbars PVC may also provide an acceptable insulation and heat dissipation system.

Similarly is coated the inside of the enclosure so that they all (conductors and enclosure) can be placed touching. Heat transfer by conduction makes it an efficient heat transfer system. Figure 28.4(d) shows a few views of such bus systems in LV and HV and a few bends. When the busbars are placed touching with each other they are termed as sandwiched and when tap-off provision is made, such as for a rising mains or an over-head bus ways and a space is left between the phase conductors to receive the plug-in contacts, they are termed as compact bus-systems.

- These busbars are usually manufactured up to 6000 A or so in LV and HV systems. They offer a good substitute to cables in larger ratings. For a general reference Tables 28.0(1) and 28.0(2) furnish the

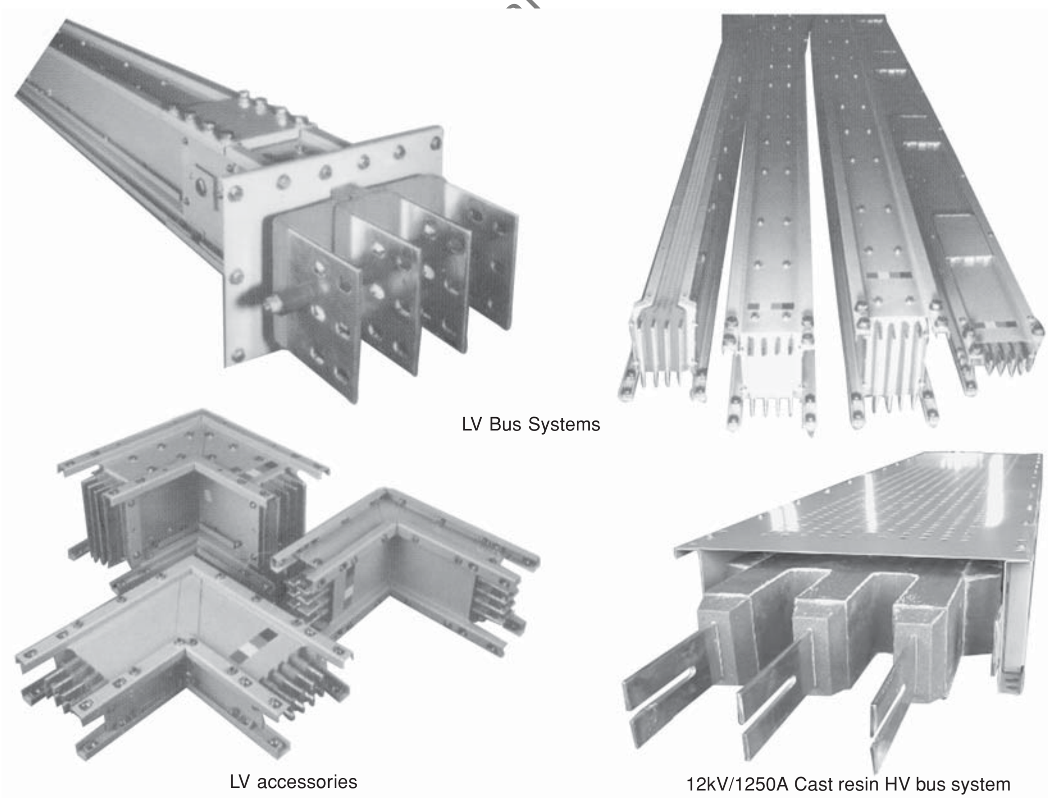


Figure 28.4(d) Sandwiched and compact bus systems and their accessories (Courtesy: Mayduct Technology SDN.BHD.)

Table 28.0(1) LV compact bus-ducts – electrical characteristics for copper conductor (frequency : 50 Hz)

Concentrated rated current Amp	*No. of bars per phase*	*Busbar size mm*	*Impedance micro-ohm per meter at 95°C*			*Line voltage drop in milli-volt per meter at rated current and at various power factors*										
			R	*X*	*Z*	*1.0*	*0.9*	*0.8*	*0.7*	*0.6*	*0.5*	*0.4*	*0.3*	*0.2*	*0.1*	*0.0*
400	1	6×25	157.75	96.31	184.83	109.29	127.45	127.47	124.16	118.96	112.43	104.87	96.44	87.24	77.32	66.73
600	1	6×40	96.62	85.48	129.01	100.41	129.10	133.63	133.73	131.31	127.14	121.58	114.86	107.12	98.43	88.83
800	1	6×50	69.64	25.40	74.13	96.50	102.20	98.31	92.68	86.05	78.73	70.86	62.52	53.78	44.67	35.20
1000	1	6×75	50.75	19.38	54.32	87.90	93.74	90.46	85.50	79.60	73.02	65.92	58.39	50.47	42.19	33.57
1250	1	6×100	37.89	14.84	40.69	82.03	87.84	84.91	80.37	74.92	68.84	62.26	55.26	47.89	40.17	32.13
1750	1	6×125	30.24	11.86	32.48	91.66	98.16	94.90	89.84	83.76	76.96	69.61	61.79	53.55	44.94	35.95
2000	1	6×150	25.15	9.80	27.00	87.12	93.21	90.07	85.23	79.43	72.96	65.96	58.52	50.69	42.49	33.95
2500	1	6×200	18.95	7.57	20.41	82.06	88.14	85.31	80.85	75.46	69.42	62.87	55.89	48.53	40.82	32.78
3250	2	6×125	15.12	6.05	16.29	78.57	84.41	81.72	77.45	72.29	66.51	60.24	53.56	46.52	39.14	31.44
4000	2	6×150	12.58	5.00	13.54	87.16	93.54	90.51	85.75	80.01	73.58	66.61	59.19	51.37	43.18	34.64
4500	3	6×125	10.08	4.15	10.90	78.57	84.41	82.26	78.10	73.02	67.30	61.07	54.43	47.41	40.04	32.35
5500	3	6×150	8.38	3.43	9.05	72.57	78.26	75.88	72.01	67.31	62.01	56.25	50.11	43.62	36.81	29.71
6300	3	6×200	7.25	2.87	7.80	75.34	80.81	78.17	74.40	69.07	63.50	57.47	51.06	44.29	3.72	2.98

Table 28.0(2) LV compact bus-ducts – electrical characteristics for copper conductor (frequency : 60 Hz)

Concentrated rated current Amp	*No. of bars per phase*	*Busbar size mm*	*Impedance micro-ohm per meter at 95°C*			*Line to line voltage drop in milli-volt per meter at rated current and at various power factors*										
			R	*X*	*Z*	*1.0*	*0.9*	*0.8*	*0.7*	*0.6*	*0.5*	*0.4*	*0.3*	*0.2*	*0.1*	*0.0*
400	1	6×25	157.75	115.57	195.55	109.29	133.26	135.48	133.69	129.63	123.99	117.10	109.17	100.31	90.60	80.07
600	1	6×40	96.62	102.58	140.92	100.41	136.84	144.29	146.42	145.53	142.53	137.87	131.82	124.53	116.11	106.60
800	1	6×50	69.64	30.48	76.02	96.50	105.26	102.54	97.71	91.69	84.83	77.31	69.24	60.68	51.67	42.23
1000	1	6×75	50.75	23.26	55.83	87.90	96.67	94.49	90.30	84.97	78.84	72.09	64.80	57.05	48.88	40.29
1250	1	6×100	37.89	17.81	41.87	82.03	90.64	88.76	84.96	80.07	71.41	68.15	61.39	54.19	46.57	38.56
1750	1	6×125	30.24	14.23	33.42	91.66	10.13	99.21	94.97	89.50	83.18	76.20	68.64	60.59	52.08	43.13
2000	1	6×150	25.15	11.76	27.78	87.12	96.17	94.14	90.08	84.86	78.84	72.19	65.00	57.34	49.25	40.74
2500	1	6×200	18.95	9.08	21.01	82.06	90.99	89.24	85.52	80.69	75.08	68.86	62.12	54.93	47.33	39.32
3250	2	6×125	15.12	7.26	16.77	78.57	87.15	85.49	81.94	77.32	71.95	66.00	59.56	52.68	45.39	37.72
4000	2	6×150	12.58	6.00	13.94	87.16	96.56	94.67	90.70	85.55	79.58	72.96	65.80	58.16	50.08	41.57
4500	3	6×125	10.08	4.98	11.24	78.57	87.63	86.14	82.72	78.19	72.90	67.00	60.60	53.74	46.48	38.81
5500	3	6×150	8.38	4.12	9.34	72.57	80.87	79.47	76.28	72.09	67.19	61.73	55.81	49.47	42.76	35.68
6300	3	6×200	7.25	3.13	7.90	75.34	81.99	79.79	75.97	71.23	65.84	59.95	53.63	46.94	3.99	3.25

Source : Mayduct Technology SDN. BHD

Note

R and *X* would vary with the size and configuration of busbars and their grade and hence from manufacturer to manufacturer. The tables provided here are only for general reference. For exact details one may contact the manufacturer.

technical data with copper conductors for LV bus ducts of a particular manufacturer for 50 and 60 Hz systems.

- The busbars so insulated are sandwiched together. They can be $3^1/_2$ or 4 conductors. They can also be five conductor-3 phases, twice the size protective neutral for clean grounding for electronic circuits (Section 6.13.3) and same size of neutral as the phases for power equipment grounding and to handle large harmonics. All these conductors are encapsulated in an epoxy or polyester insulated metallic enclosure (usually non-magnetic). To augment heat dissipation some manufacturers even provide fins in their enclosures, particularly in large ratings to provide better heat sink. There being no intentional air gap. The conductors and the enclosure thus transform into a compact enclosure. Since the busbars are almost touching (separated by thin epoxy or polyester insulation) and have little scope for movement, the proximity effect in terms of electromagnetic forces has little influence on the bus system. Because of this these bus systems are suitable for power systems having high fault levels. Since the proximity effect in terms of *X*a is only little compared to conventional busbars, the system does not call for a special enclosure treatment to dissipate excessive magnetic heat or phase transposition or insertion of an inductor in the middle phase to make up for the lost inductance (Section 28.8.2), to avoid a voltage unbalance. Nevertheless in larger ratings (3000 A and above) when the length of the bus is more, it is advisable to provide phase transposition chambers at reasonable intervals (say, 50 m or so) to balance bus inductances (for whatever little may exist), minimize conductor losses in the middle phase sharing higher current, as well as voltage unbalance. Busbars so produced therefore help in maintaining a voltage balance in the three phases unlike in a conventional bus system. It is easy to provide tap-off joints as required in such a system like in a rising mains or horizontal busways. Jointing and termination kits are also supplied by the manufacturer to facilitate easy jointing and termination. A few such kits like T-joint, phase transposition chamber and expansion joint are shown in Figure 28.4(e).
- Busbars in flats, tubes or channels in box form can also be used depending upon the current rating. It is however usual to use flat bars, being simpler to use and can meet most current requirements on an LV or HV systems. To further mitigate the skin and proximity effects in large ratings using two busbars or more, the manufacturer can choose a more efficient configuration as shown in Figure 28.14.
- To maintain current carrying capacity over long years of operations it is imperative to avoid surface oxidation. Since the busbars are totally encapsulated and sealed from atmosphere providing a direct insulation coating on its surfaces (surfaces must be free from oxidation) is quite safe and only the exposed portions (terminals) be silver plated for making connections. Nevertheless, some manufacturers adopt to tin plating the whole bus lengths (except the end

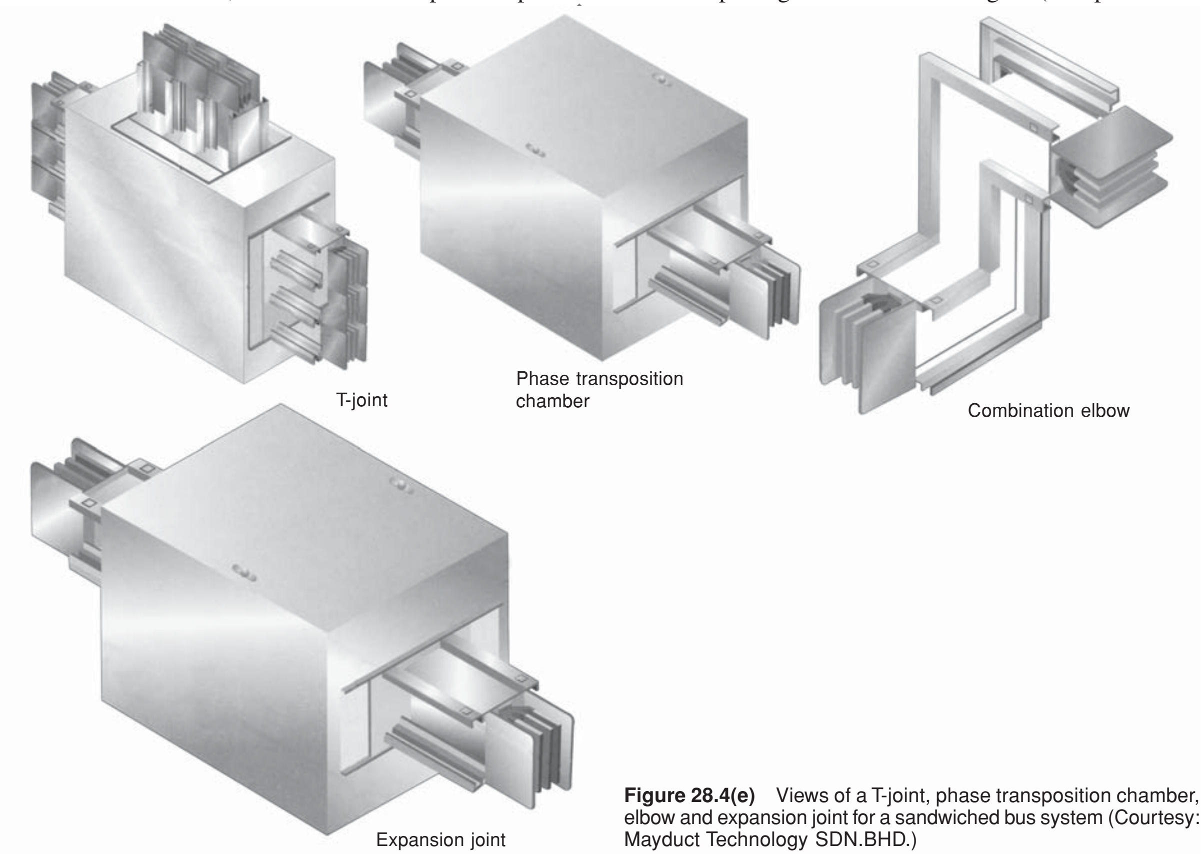
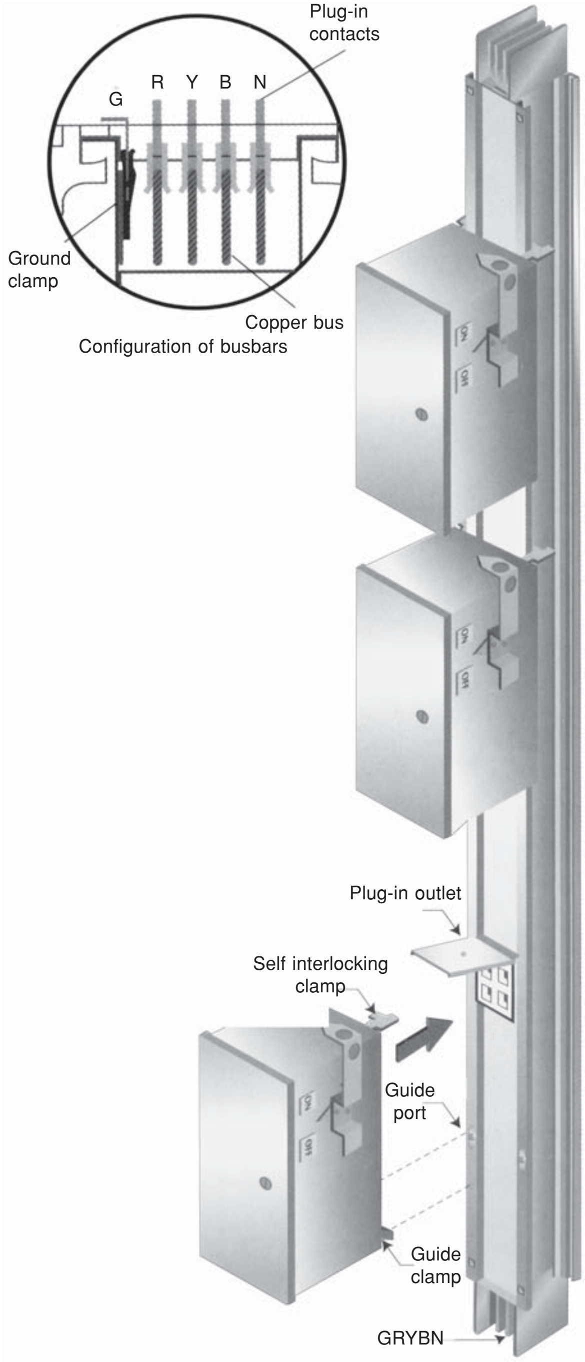


Figure 28.4(e) Views of a T-joint, phase transposition chamber, elbow and expansion joint for a sandwiched bus system (Courtesy: Mayduct Technology SDN.BHD.)



Note: Similar arrangement for horizontal busways

Figure 28.4(f1) View of a compact rising mains with 5 buses (ground, RYB and N) and plug-in boxes (Courtesy: Mayduct Technology SDN.BHD.)

terminals for reasons noted below) to safeguard against possible pin holes or weak insulation areas left out during the process of insulation, also against accidental rupture of insulation during assembly. Such miniature exposures to atmosphere may cause tracking over a period of time and render the busbars vulnerable to gradual oxidation consequently withering of its current carrying capacity.

Limitation of tin plating at the end terminals Tin also makes a good conductor of electricity and costs only one tenth that of silver plating as a rough estimate but calls for the following safeguards,

- The plating procedure calls for utmost care.
- It has high contact resistance and calls for a high derating of the terminals and hence the entire bus system (up to 20%)
- Arcing eats away tin coating. It is therefore not suitable for draw-out contacts that may wither the coating due to their movements and silver plating alone is recommended.
- At properly made straight-through joints, tin coated surfaces may be good as proper contacts cause no arcing. But it is too theoretical in view of ageing and loosening of hardwares with time that may render the joint vulnerable to failure.
- Usually therefore at straight-through joints most manufacturers adopt to silver plating only.
- For fixed busbars, however, like the straight lengths tin plating is quite suitable and economical. About 8–10 microns of tin coating is found adequate for fixed busbars.

Therefore electrical grade silver plating at joints 5–6 microns and at draw-out contacts 8–10 microns and tin plating 8–10 microns at the fixed lengths is a usual practice of most manufacturers. Silver coated portions that are exposed to atmosphere but are non-functional are usually flashed with just 1–2 micron of silver coating. Busbars so sealed can be operated at temperatures higher than 90ºC (see Section 28.5.1). It is however advisable to choose higher cross-sectional area of busbars to keep the heat loss low (loss $\alpha\ R\ \alpha$ 1/A (A – area of cross-section)) as a measure to saving energy.

- Rising mains and overhead busways can be insulated with IP55 or IP66 enclosures to make them fire retardant or self-extinguishing like fire retardant cables. Figure 28.4(f1) shows a typical rising mains and Figure 28.4(f2) shows when it is installed as overhead bus system. Epoxy or polyester encapsulated system can withstand forceful water jets during fire fighting operations and can even be submerged in water.
- These busbar systems are like standard products for a manufacturer and are not required to be custom-built for every application except for variations in ambient conditions or special site requirement like contaminated, humid or hazardous locations. Straight-through joints, bends (elbows), T-joints, flanges, transposition chambers, flexible and expansion joints are standardized and are manufactured as standard products. These busbars can be ordered as per site plan and easily assembled at site. Many leading manufacturers even stock the standard lengths in different ratings with their accessories for ready deliveries like any other standard product. Only short lengths or end connections need be manufactured as per the site plan at the last moment.

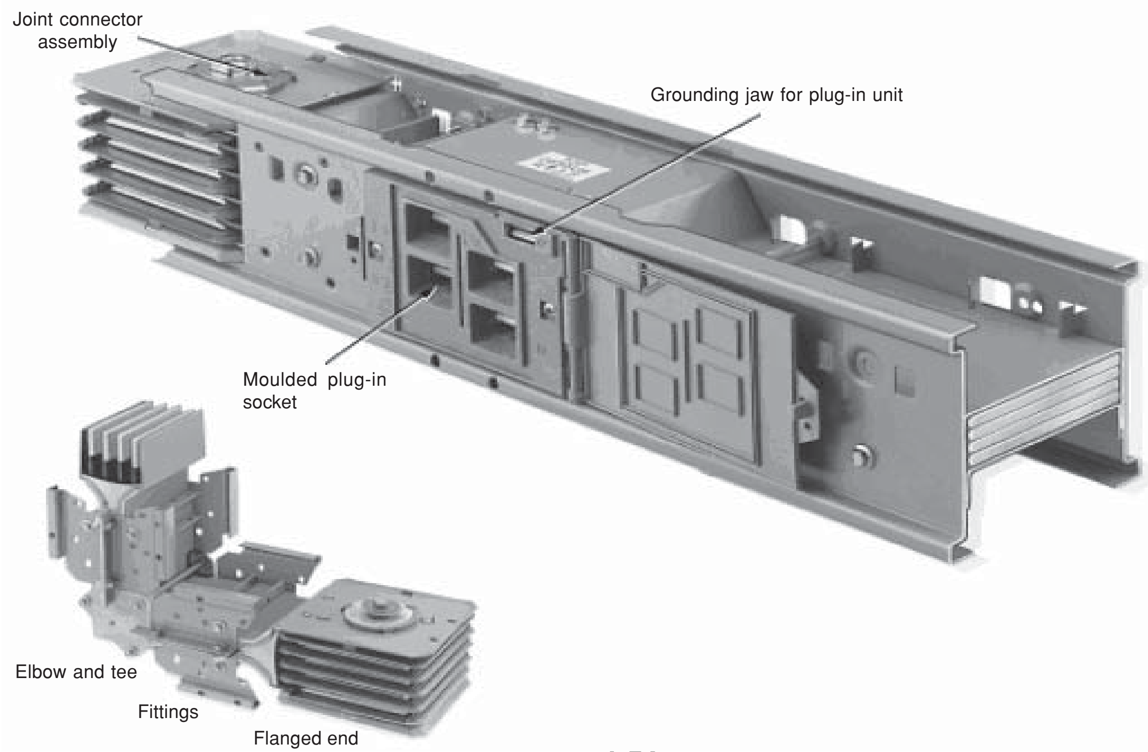


Figure 28.4(f2) Plug-in busbar trunking in horizontal formation (800A–5000A) (Courtesy: Schneider Electric)

- They conform to the same test requirements as other bus systems and also withstand fire retardant, humidity and ageing tests.
- The compact bus systems are usually fire resistant for 2 hrs as per ISO 834.

(2) Partially isolated phase bus systems (PIPBs) (for HV and MV systems)

For switchyards, large substations 15 MVA and above, medium-sized to large generating stations or large industries and captive power generations where any of the above conventional bus systems may pose a limitation either because of their bulk (large conductor spacings in segregated bus system) or cost (as for IPBs) or because of their rigidity that the PIPBs, as evolved by some manufacturers, can provide an easy alternative. The usual method that one can choose to interconnect a switchgear assembly with a transformer, transformer with a swithchyard or an over-head line with a transformer or a switchgear can be one of the following,

(i) XLPE cables – XLPE cables is an ideal method but these may not be easily available in short lengths, as they are usually produced in lengths of 1000 m or so unless the project is already using these cables. When only short lengths are required for interconnections, availability of these cables may pose a limitation and PIPBs can provide a ready answer.

Moreover, XLPE cables may not be suitable for large ratings because multiple runs of them may render them unwieldy and cumbersome to handle and terminate.

(ii) GIB (gas insulated bus system) – In GIS substations to interconnect the switchgear with the transformer through GIB is an easy way and is usually practised. GIBs can be produced compact and easily fabricated by GIS manufacturers according to the site requirements. To provide a GIB between transformer and switchyard however, is usually not practicable for obvious reasons and XLPE cables or PIPBs alone can serve the purpose.

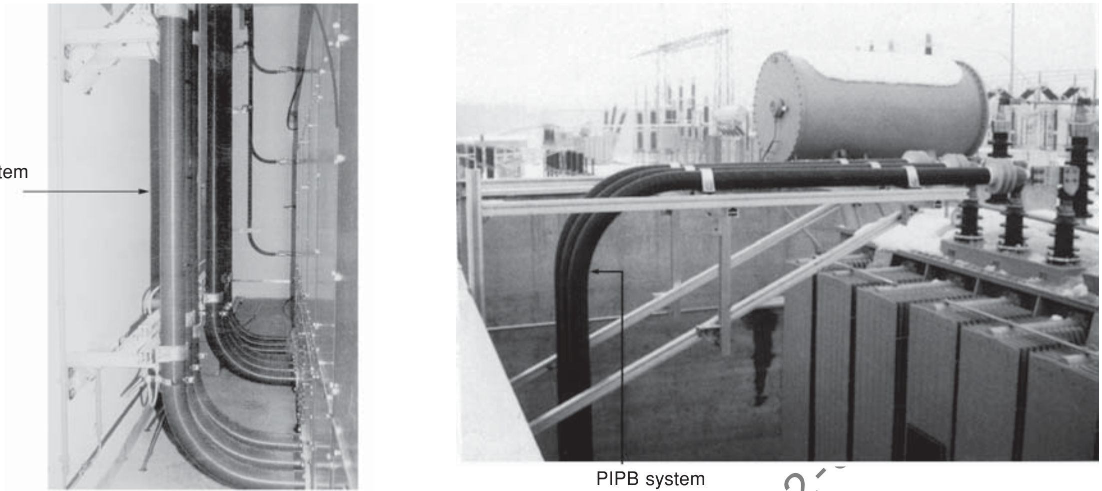
(iii) In an SF_6 air insulated substation one can use XLPE cables if available in short lengths or opt for a PIPB system. Since, XLPE cables may not always be possible as noted above unless they are being already used at the same site for transmission or distribution purposes, PIPBs provide an easy answer.

(iv) PIPBs – The basic purpose of this system is safety and security. For inter-connecting transformer and switchyard – usually bare conductors are used. In seismic areas for safety and integrity of the system it is advisable to adapt for enclosed conductors and PIPBs provide a ready solution.

Another advantage of PIPBs is that they are custom-built and can be supplied as per site requirement with built-in jointing arrangement. It is therefore easy and fast to instal and make end terminations of such a bus system at site.

A few more points in favour of PIPBs compared to XLPE cables and other bus systems are noted below,

- These bus systems are easy to handle, instal, lay and terminate and can be used as cables of much higher ratings. Here also, the basic concept is that of cables



(g1) Connecting on the 24 kV/2500A panel side (g2) Connecting on the 24 kV/2500A transformer side

Figure 28.4(g) Application of partially isolated phase bus systems (PIPBs) similar to cables (Courtesy: MGC Technologie AG)

PIPB system

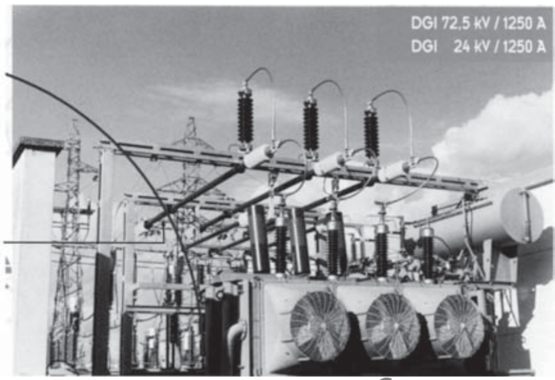


Figure 28.4(h) Layout of a 72.5 kV/1250A PIPB at a switchyard (Courtesy: MGC Technologie AG)

(Appendix 16) where XLPE cables are produced up to 550 kV in extremely compact sizes. Because of PIPB flexibility, transformer and switchgear can be placed at different locations as convenient than in the same room if that be a constraint. Figures 28.4(g1 and g2) illustrate the application of PIPBs similar to cables in a substation while Figure 28.4(h) shows its use in a switchyard. PIPBs therefore may be a preferred choice for inter-connecting switchgears to transformers and transformers to switchgears for an industry or large installation or a switchyard for further distribution.

This system is usually manufactured up to 245 kV and 8000 A or so in single phase configuration like an isolated phase system (IPB) and hence the name PIPB. For accurate details one may consult the manufacturer. Technical data of a few voltage systems and corresponding current ratings of a particular manufacturer are furnished in Tables 28.0(3) and 28.0(4), for aluminium and copper conductors respectively for a general reference. The main conductor that can be of aluminium or copper is vacuum epoxy resin cast, is compact and encapsulated within a bigger diameter tube preferably of aluminium, CrNi steel or polyamide, like an IPB, making the enclosure somewhat a Faraday Cage (Section 23.18). Now it serves a dual purpose – role of a shield for the space field and also as a ground conductor similar to XLPE cables. Since magnetic forces are low and buses flexible, they too are capable to withstand large fault currents. The outer insulation is protected against sudden shocks and humidity through a protection tube that also makes it resistant to moisture ingress. The touch voltage, surface to ground is maintained within safe limit of 65–130 V (Section 22.9.6). All this makes it an IP65 enclosure and since the busbars are sealed they can be safely operated up to much higher temperature as noted in Section 28.5.1. It is however preferred to operate them at lower temperatures as noted already, to save on heat loss and energy.

Insulating system between the conductor and its metallic shielding, and between the metallic shield and the outer sheath is the most important feature of such busbars. This insulation is usually epoxy resin that makes the whole conductor and its shield as a solid mass to enable an effective and efficient heat transfer through conduction rather than convection. Each individual busbar is capacitive graded*.

***Capacitive grading**

It is a measure of controlling electric field distribution along the surface of the conductor insulation during a transient condition, smoothing the distribution of surge voltages and saving the bus insulation system (major insulation area, Section 17.10.1) from the arriving surges. Now also the same theory of travelling waves apply as discussed in Section 17.8. Capacitive grading shrouds the bus insulation and is achieved by providing dielectric barriers usually at the ends (terminals) of the bus system that are more vulnerable to the arriving surges.

Dielectric barriers can be provided through a non-linear resistor (SiC or ZnO) (Sections 18.1.1 and 18.1.2) or through capacitive grading foils (Figure 25.1). In case of capacitive grading, metallic foils are inserted during the busbar insulating process. The foils form a series of capacitors between the current carrying conductor and the ground and are designed to grade the electric field at the terminals to optimize the insulating system during a transient condition.

Table 28.0(3) Technical data and dimensions with conductor in aluminium for partially isolated phase bus systems (PIPBs)

Rated voltage	*Power frequency withstand voltage, 50 Hz, 1 minute, dry*	*Dry lightning impulse voltage, 1.2/50 µs*	*Rated current*	*Diameter of the conductor*	*Diameter of the protection tube*	*Weight per single phase*	*Standard bend radius*	*Capacitance*
kV	*kV*	*kV*	*A*	*mm*	*mm*	*kg/m*	*mm*	*pf/m*
12/17.5	28/38	75/95	1250	36	55	4.1	180	1290
			1600	45	67	6.2	250	1400
			2000	55	80	9	250	1515
			2500	80/50	106	12	400	2410
			3150	110/80	146	18.6	550	2410
24	50	125	1000	30	55	3.7	180	640
			1250	40	67	5.7	180	820
			1600	50	80	8.5	250	930
			2000	70/40	106	15.7	400	1005
			2500	70/40	106	13.1	400	1440
			3150	100/70	146	19.5	550	1205
36	70	170	800	25	55	3.4	180	425
			1250	36	67	5.4	250	595
			1600	45	80	8	250	655
			2500	70/40	106	15.7	400	1005
			3150	100/70	146	19.5	550	1300
52	105	250	1100	36	80	7.2	250	370
			2000	60	106	14.3	400	–
72.5	140	325	900	30	80	6.8	250	300
			1250	40	106	12.2	400	290
			1600	50	106	13.1	400	410
			2500	80/50	146	20.8	550	555
123	230	550	800	30	106	–	550	–
			1250	55	146	24	550	–
			2000	55	146	–	550	–
			2500	70	146	–	–	–

Table 28.0(4) Technical data and dimensions with conductor in copper for partially isolated phase bus systems (PIPBs)

Rated voltage	*Power frequency withstand voltage, 50 Hz, 1 minute, dry*	*Dry lightning impulse voltage, 1.2/50 µs*	*Rated current*	*Diameter of the conductor*	*Diameter of the protection tube*	*Weight per single phase*	*Standard bend radius*	*Capacitance*
kV	*kV*	*kV*	*A*	*mm*	*mm*	*kg/m*	*mm*	*pf/m*
12/17.5	28/38	75/95	1250	32	55	8.8	180	845
			1600	40	67	16.1	250	1405
			2000	50	80	20.5	250	876
			2500	70/50	106	21.8	400	1005
			3150	80/50	106	30.7	400	2410
			4000	110/80	146	46.4	550	2410
24	50	125	1250	32	55	8.8	180	845
			1600	40	67	13.6	250	820
			2000	50	80	20.5	250	930
			2500	70/50	106	21.8	400	1005
			3150	80/50	146	30.7	550	–
			4000	110/80	146	46.4	550	2410
36	70	170	1000	25	55	6.5	180	425
			1250	32	67	10.1	250	590
			1600	40	80	15.1	250	525
			2000	50	106	25	400	845
			2500	70/50	106	21.8	400	1005
			3150	80/50	146	39.8	550	1133
52	105	250	1250	32	80	11.7	250	332
			2000	50	106	25	400	406
			2500	70/50	146	31	550	536
			3150	80/50	146	39.8	550	555
72.5	140	325	1250	32	80	11.7	250	332
			1600	50	106	25	400	406
			2500	70/50	146	31	550	536
			3150	80/50	146	39.8	550	555
123	230	550	1250	45	146	34	550	–
			2000	50	146	25	550	–
			2500	70/50	146	31	550	–

Courtesy: MGC Technologie

The outer sheath may be of PVC or synthetic material to protect the metallic shield and the conductor and the insulation system from mechanical damage. And if paper is used as insulating medium, prevent it from the ingress of atmospheric moisture. The conductor and its metallic shield are made of tubular section for ease of construction and to also extend flexibility in manoeuvring the busbars at bends, joints and terminations. It is easy to carry and clamp the bus lengths on structures or hang them through the ceiling. Figure 28.4(i) shows PIPB on racks.

Up to 3000 A there will be little field in the space, most of it being absorbed by the metallic shield itself (encapsulated ground conductor). Nevertheless for larger ratings it is desirable to take extra precaution at the joints and terminations to provide adequate bonding to avoid localized hot spots or even small field in the space. Jointing and termination kits are supplied by the manufacturer to bridge this requirement and provide an almost continuous single conductor bus system. Due to low 'X_a' on adjacent phases this system also, like the sandwich bus system, provides an almost balanced voltage system and calls for no-phase transposition. However, where necessary (like for long routes and very large current systems) the buses being flexible can be easily transposed at suitable intervals.

These busbars are usually produced in HV and MV systems being costly in LV. Where XLPE cables have a limitation PIPBs provide the solution. They conform to the same test requirements as other bus systems and also withstand fire retardant, humidity and ageing tests.

(3) Gas insulted busbars (GIB)

For SF_6 insulated busbars see Section 19.10.

28.3 Design parameters and service conditions for a metal-enclosed bus system

28.3.1 Design parameters

A bus system would be designed to fulfil the following parameters.

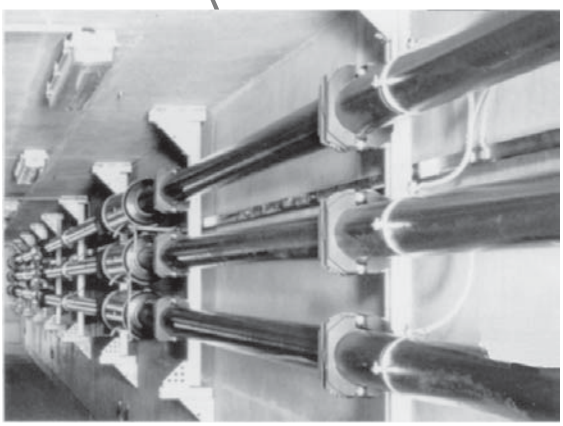


Figure 28.4(i) PIPB on horizontal racks (Courtesy: MGC Technologie AG)

Rating

A bus system, like a switchgear assembly, would be assigned the following ratings:

- Rated voltage: the same as that assigned to the associated switchgear (Section 13.4.1(1))
- Rated frequency: the same as that assigned to the associated switchgear (Section 13.4.1(2))
- Rated insulation level

  (i) Power frequency voltage withstand – see Section 32.3.2
  (ii) Impulse voltage withstand test – for all LV and HV bus systems see Section 32.3.3

- Continuous maximum rating (CMR) and permissible temperature rise: this is the maximum r.m.s. current that the bus system can carry continuously without exceeding temperature rise limits, as shown in Table 32.3. The preferred current ratings of the bus system would follow series R-10 of IEC 60059, as shown in Section 13.4.1(4).

  Energy conservation

  Like for cables Section A 16.9, it is suggestive to choose for slightly higher cross-section for bus sections for main bus as well as links (where convenient) to conserve on energy losses. It is also suggestive that manufacturers and equipment suppliers, who deal with energy efficient products or technologies, provide repayment schedule as customary, to their users to encourage them use energy efficient products and technologies and enable them take a more pragmatic decision while making the purchases.

- Rated short-time current rating: this is the same as for the system to which it is connected, and as assigned to the associated switchgear (Section 13.4.1(5)). The effects of a short-circuit on an electrical system are discussed below.
- Rated momentary peak value of the fault current: the same as assigned to the associated switchgear as in Tables 13.11 or 28.1. See also Section 13.4.1(7).
- Duration of fault: the same as assigned to the associated switchgear (Section 13.4.1(6)).

28.4 Short-circuit effects

(To determine the minimum size of current-carrying conductors and decide on the mounting arrangement)

A short-circuit results in an excessive current due to low impedance of the faulty circuit between the source of supply and the fault. This excessive current causes excessive heat ($\propto I_{sc}^2 \cdot R$) in the current-carrying conductors and generates electromagnetic effects (electric field) and electrodynamic forces of attraction and repulsion due to d.c. component (asymmetry) between the conductors and their mounting structure. These forces may be assumed as distributed uniformly over the length of conductors and cause shearing forces due to the cantilever effect as well as compressive and tensile stresses on the mounting structure. The effect of a short-circuit

Table 28.1 Momentary peak current ratings (asymmetrical) for switchgear and metal-enclosed bus systems, based on ANSI-C-37/20C

*Nominal voltage (V_r) kV(r.m.s.)	Rated current (I_r) A[a]	Non-segregated phase system kA[b]	Segregated phase system kA[b]	Isolated phase system kA[b]
0.6	1600	75	–	–
0.6	3000	100	–	–
0.6	4000 to 6000	150	–	–
4.16–13.8	1200 to 3000	19 to 78	–	–
14.4	1200 to 20 000	–	60 to 190	To match with the rating of the connected interrupting device
23–34.5	1200 to 20 000	58	60 to 190	,,

*For new voltage systems as per IEC 60038, see Introduction.
[a] (i)These values are based for a system, pertaining to series II and a frequency of 60 Hz.
(ii) For systems pertaining to Series I and a frequency of 50 Hz, values furnished in Section 13.4.1(4), would apply.
[b] The peak value is a function of fault level Section 13.4.1(7), Table 13.11. Which in turn, is a function of size and impedance of the feeding source, such as a transformer or a generator, Section 13.4.1(5), Table 13.7. The values prescribed in the above table are thus based on these parameters.

therefore requires these two very vital factors (thermal effects and electrodynamic forces) to be taken into account while designing the size of the current-carrying conductors and their mounting structure. The latter will include mechanical supports, type of insulators and type of hardware, besides the longitudinal distance between the supports and the gap between phase-to-phase conductors.

The electrodynamic forces may exist for only three or four cycles (Section 13.4.1(7)), but the mechanical system must be designed for these forces. On the other hand, the main current-carrying system is designed for the symmetrical fault current, I_{sc} (Table 13.7) for one or three* seconds according to the system design. For more details refer to Section 13.5.

The fault level, which is a function of the size of the feeding transformer, is generally considered to last for only one second, as discussed in Section 13.4.1(5), unless the system requirements are more stringent. This duration of one second on fault may cause such a temperature rise (not the electrodynamic forces), that unless adequate care is taken in selecting the size of the current-carrying conductors, they may melt or soften to a vulnerable level before the fault is interrupted by the protective devices. This philosophy, however, is not applicable for circuits protected through current-limiting devices. See note below.

Note
When the circuit is protected through HRC fuses or built-in short-circuit releases of a current limiting interrupting device the cut-off time may be extremely low, of the order of less than one quarter of a cycle, i.e. < 0.005 second (for a 50 Hz system) (Section 13.5.1) depending upon the size and the characteristics of the fuses or the interrupting device and the intensity of the fault current. Any level of fault for such a system would be of little consequence, as the interrupting device would isolate the circuit long before the fault current reaches its first peak. This is when the fault is downstream of the protective device. Refer to Example 28.1 below.

Example 28.1

Since the heating effect $\propto I_{sc}^2 \cdot t$
therefore heating effect of a 50 kA fault current for 0.005 second $\propto 50^2 \times 0.005$, compared to the heating effect of an equivalent fault current I_{sc} for 1 second, i.e. $\propto I_{sc}^2 \cdot 1$

or $I_{sc}^2 = 50^2 \times 0.005$

i.e $I_{sc} = 50 \times \sqrt{0.005}$

or 3.5 kA only

Thus to design a system protected through HRC fuses or a current limiting device for a higher fault level than necessary will only lead to overprotection and the extra cost of the current-carrying system, switching equipment and power cables. An individual device or component and its connecting links in such cases may therefore be designed for a size commensurate to its current rating. See also Section 13.5.1 (Figure 13.29).

Below we discuss the thermal effects and the electrodynamic forces which may develop during a fault to decide on the correct size of the conductor and its supporting system.

28.4.1 Thermal effects

With normal interrupting devices the fault current would last for only a few cycles (maximum up to one or three* seconds, depending upon the system design). This time is too short to allow heat dissipation from the conductor through radiation or convection. The total heat generated on a fault will thus be absorbed by the conductor itself. The size of the conductor therefore should be such that its temperature rise during a fault will maintain its end temperature below the level where the metal of the conductor will start to soften. Aluminium, the most widely used metal for power cables, overhead transmission and distribution lines or the LV and HV switchgear assemblies and bus duct applications, starts softening at a temperature of around 180–200°C. As a rule of thumb, on a fault a safe temperature rise of 100°C above the allowable end temperature of 85°C or 90°C of the conductor during normal service, i.e. up to 185–190°C during a fault condition, is considered safe and taken as the basis to determine the size of the conductor aluminium or copper.

*See Section 13.5(2)

The welded portion, such as at the flexible joints*, should also be safe up to this temperature. Welding of edges is essential to seal off flexible ends to prevent them from moisture condensation, oxidation and erosion of metal. Tin or lead solder starts softening at around this temperature and should not be used for this purpose. For joints other than flexibles it is advisable to use oxy-acetylene gas welding or brazing for copper and tungsten inert gas (TIG) or metal inert gas (MIG) welding for aluminium joints.

Note
In case of copper also, the end temperature is considered as 185°C only. Although this metal can sustain much higher temperature than this, without any adverse change in its mechanical properties, merely as a consideration to Table 32.3, and to safeguard other components, insulations and welded parts etc., used in the same circuit.

To determine the minimum size of conductor for a required fault level, I_{sc}, to account for the thermal effects one can use the following formula to determine the minimum size of conductor for any fault level:

$$\theta_t = \frac{k}{100} \cdot \left(\frac{I_{sc}}{A}\right)^2 \cdot (1 + \propto_{20} \theta) \cdot t \qquad (28.1)$$

where
θ_t = temperature rise (in °C)
I_{sc} = symmetrical fault current r.m.s. (in Amps)
A = cross-sectional area of the conductor (in mm²)
$\propto_{20}$ = temperature coefficient of resistance at 20°C/°C, which as in Table 30.1 is 0.00403 for pure aluminium and 0.00363 for aluminium alloys and 0.00393 for pure copper
θ = operating temperature of the conductor at which the fault occurs (in °C)
k = 1.166 for aluminium and 0.52 for copper
t = duration of fault (in seconds)

Example 28.2
Determine the minimum conductor size for a fault level of 50 kA for one second for an aluminium conductor.

Assuming the temperature rise to be 100°C and the initial temperature of the conductor at the instant of the fault 85°C then

$$100 = \frac{1.166}{100} \times \left(\frac{50\,000}{A}\right)^2 \times (1 + 0.00403 \times 85) \times 1$$

or $$100 = \frac{1.166}{100} \times \left(\frac{50\,000}{A}\right)^2 \times 1.34255$$

or $$A = \frac{50\,000}{100} \times \sqrt{1.166 \times 1.34255}$$

$$\simeq 625.6 \text{ mm}^2 \text{ for pure aluminium}$$

or $$\simeq 617.6 \text{ mm}^2 \text{ for alloys of aluminium}$$

(assuming α_{20} = 0.00363)

The standard size of aluminium flat nearest to this is 50.8 mm × 12.7 mm or (2″ × ½″) or any other equivalent flat size (Tables 30.4 or 30.5).

This formula is also drawn in the form of curves as shown in Figure 28.5, $\frac{I_{sc}}{A} \times \sqrt{t}$ (I_{sc} in kA) versus final temperature. From these curves the minimum conductor size can be easily found for any fault level, for both aluminium and copper conductors and for any desired end temperature. As in the above case

$$100 = \frac{1.166}{100} \times \left(\frac{I_{sc}}{A}\right)^2 \times 1.34255 \cdot t$$

or $$\frac{I_{sc}}{A}\sqrt{t} = \sqrt{\frac{10^4}{1.166 \times 1.34255 \times 10^6}}$$

$$= 0.0799 \ (I_{sc} \text{ is in kA})$$

Generalizing,

$$\frac{I_{sc}}{A} \times \sqrt{t} = 0.0799 \text{ for an operating temperature at 85°C and end temperature on fault at 185°C} \qquad (28.2)$$

Therefore, for the same parameters as in Example 28.2

$$A = \frac{50}{0.0799} \times \sqrt{1} \simeq 625.8 \text{ mm}^2$$

A small difference, if any, between this and that calculated above may be due to approximation and interpolation only.

This minimum conductor size will take account of the heating effects during the fault, irrespective of the current rating of the conductor. This much conductor size is essential for this fault level even for very low current ratings. However, the required conductor size may be more than this also, depending upon the continuous current it has to carry, as discussed later.

Example 28.3
If the conductor is of copper then, assuming the same parameters,

$$100 = \frac{0.52}{100} \times \left(\frac{50\,000}{A}\right)^2 \times (1 + 0.00393 \times 85) \times 1$$

or $$A = 50\,000 \times \sqrt{\left(\frac{0.52}{100} \times \frac{1.33405}{100}\right)}$$

$$= 416 \text{ mm}^2$$

Copper is two thirds the size of aluminium for the same parameters. The melting point of copper at almost 1083°C (Table 30.1) is approximately 1.5 times that of aluminium at 660°C. These melting points are also located on the nomograms in Figure 28.6. Refer to nomograms (a) and (b) for aluminium and (c) for copper conductors. The same area can also be obtained from the copper curves of Figure 28.5. Assuming the same end temperature at 185°C, then corresponding to the operating curve of 85°C,

$$\frac{I_{sc}}{A}\sqrt{t} = 0.12 \qquad (28.3)$$

and for the same parameters as in Example 28.3,

$$\frac{50}{A}\sqrt{1} = 0.12$$

or $A \simeq 416.7 \text{ mm}^2$

*Welding of flexible joints should preferably be carried out with high-injection pressing (welding by press heating), eliminating the use of welding rods.

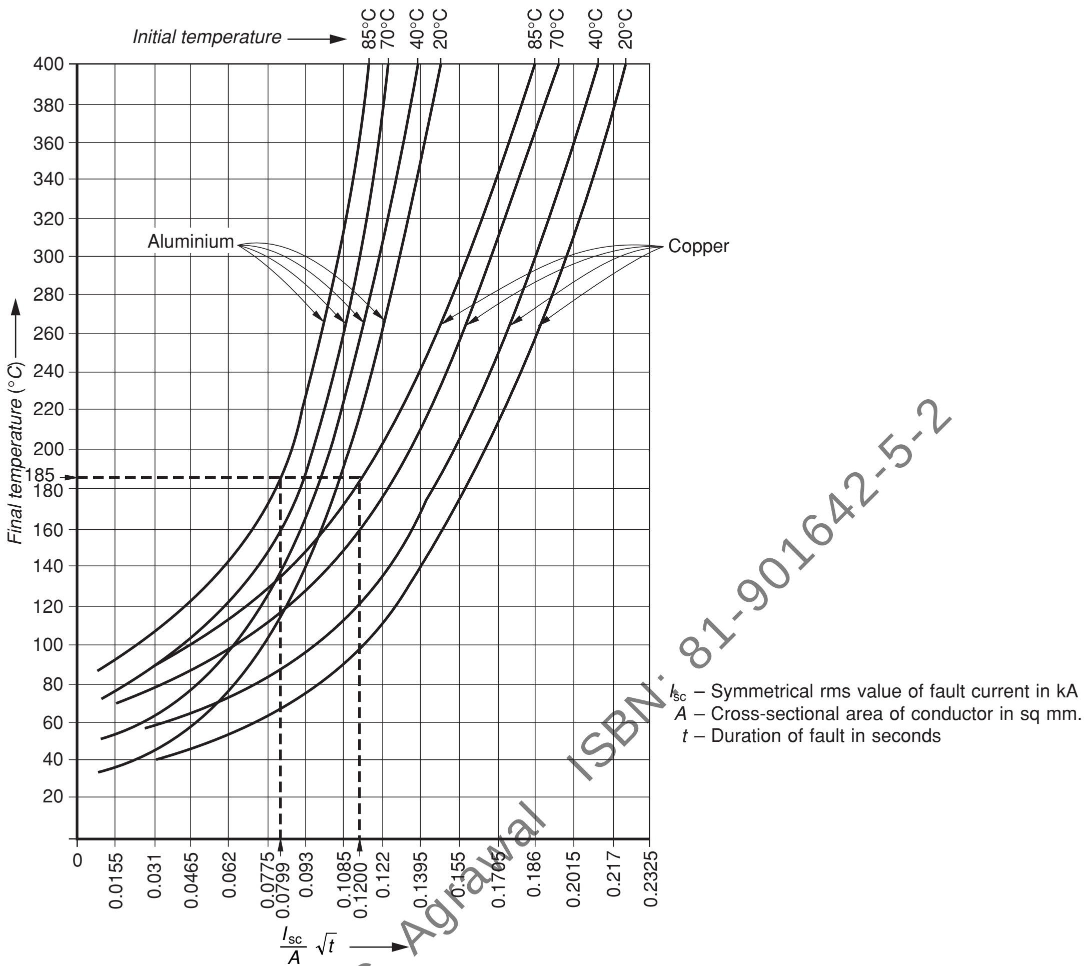


Figure 28.5 Determining the minimum size of conductor for a required fault level

Almost the same size is also determined through the use of nomograms drawn on subsidiary nomogram (c) and the main nomogram (d).

Nomograms Figure 28.6(a)–(d) have also been drawn based on Equation (28.1). From these nomograms the minimum conductor size can be extrapolated that would be necessary to sustain a given fault level for a particular duration.

The results of these nomograms are also the same as those from the earlier two methods except for the approximation and the interpolation.

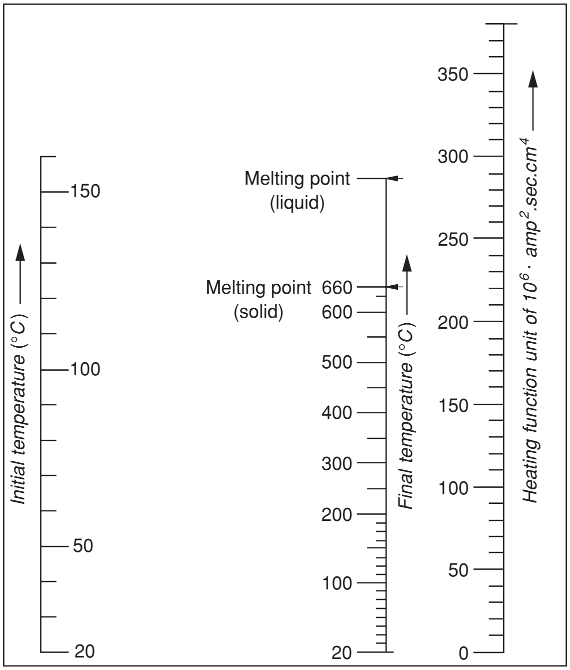
Example 28.4
Assume the same parameters as in Example 28.2.

Procedure

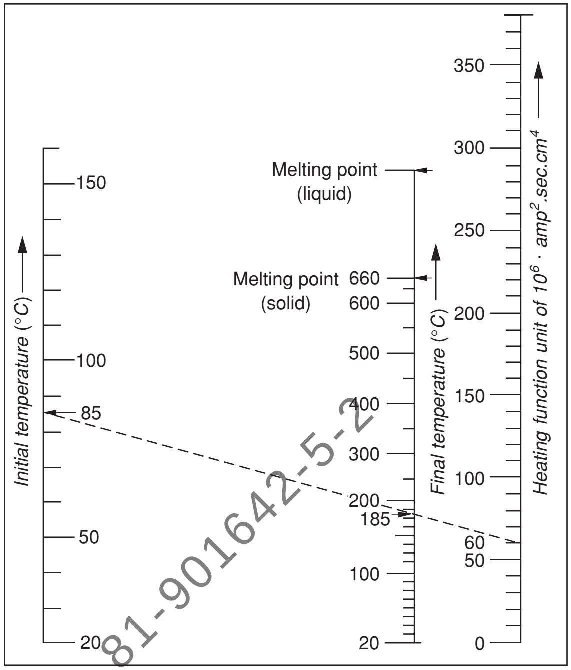
- Locate the initial temperature (85°C) and the final temperature (185°C) on the subsidiary nomogram (b).
- Draw a straight line between these points to obtain the heating function *H*.
- Transfer the value of the heating function *H* to the *H* scale on the main nomogram (d).
- Locate time *t* as one second on the *T* scale.
- Locate the current to be carried, I_{sc}, as 50 000 A on the I_{sc} scale.
- Draw a straight line through the points on the *T* and I_{sc} scales to intersect the turning axis *X*.
- Draw a straight line through the points on the *H* scale and on the turning axis *X*. The point where the line intersects on the *A* scale will determine the conductor area required. In our case it is 1 square inch or 645 mm^2.

28.4.2 Electrodynamic effects (applicable in case of conventional busbar systems)

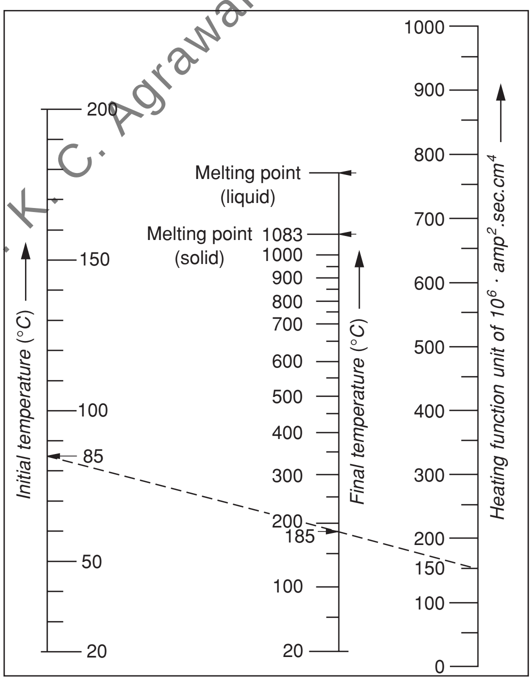
The short-circuit current is generally asymmetrical and contains a d.c. component, I_{dc}, as discussed in Section 13.4.1(7). The d.c. component, although lasts for only three or four cycles, creates a sub-transient condition and causes excessive electrodynamic forces between the current-carrying conductors. The mounting structure, busbar supports and the fasteners are subjected to these forces. This force is greatest at the instant of fault initiation and is represented by the first major loop of the fault current, as noted in Table 13.11. Although this force is only momentary, it may cause permanent damage to these components and must be considered when designing the current-carrying system and its mounting structure. The maximum force in flat busbars may be expressed by



(a) Subsidiary nomogram for electrolytic grade aluminium 'INDAL'–CISM.



(b) Subsidiary nomogram for electrolytic grade aluminium 'INDAL'–D 50S WP.



(c) Subsidiary nomogram for 100% IACS copper.

Figure 28.6 Use of nomograms

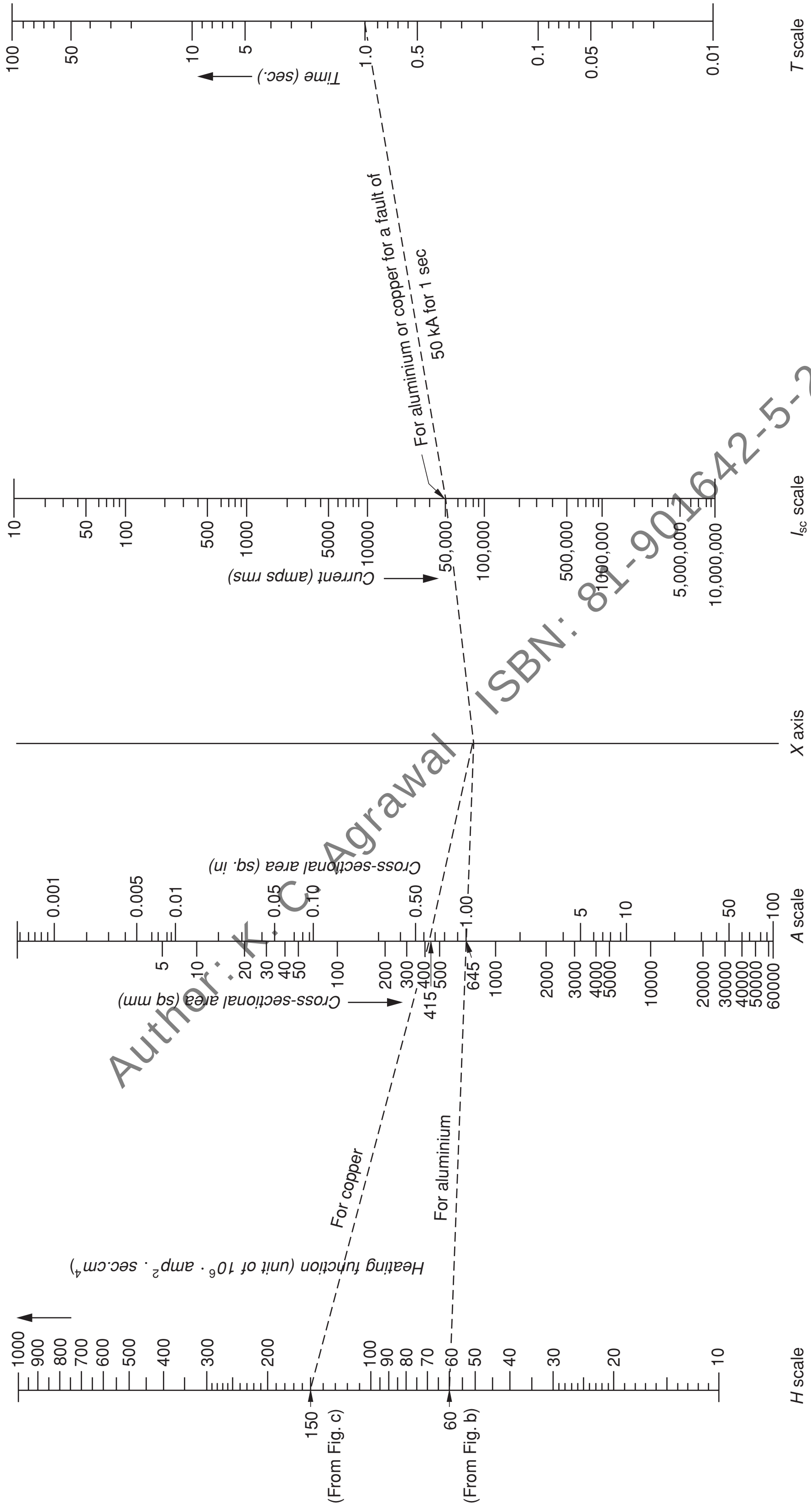


Figure 28.6(d) Main nomogram

$$F_m = k \cdot \frac{16 \cdot I_{sc}^2}{S} \times 10^{-4} \text{ N/m} \qquad (28.4)$$

where

F_m = estimated maximum dynamic force that may develop in a single- or a three-phase system on a fault. This will vary with the number of current-carrying conductors and their configuration but for ease of application and for brevity only the maximum force that will develop in any configuration is considered in the above equation. It will make only a marginal difference to the calculations, but it will be on the safe side. For more details refer to the Further Reading at the end of the chapter.

I_{sc} = r.m.s. value of the symmetrical fault current in amperes

Factor of asymmetry
= as in Table 13.11, representing the momentary peak value of the fault current. This factor is considered in the numerical factor 16 used in the above equation.

k = space factor, which is 1 for circular conductors. For rectangular conductors it can be found from the space factor graph (Figure 28.7) corresponding to

$$\frac{S - a}{a + b}$$

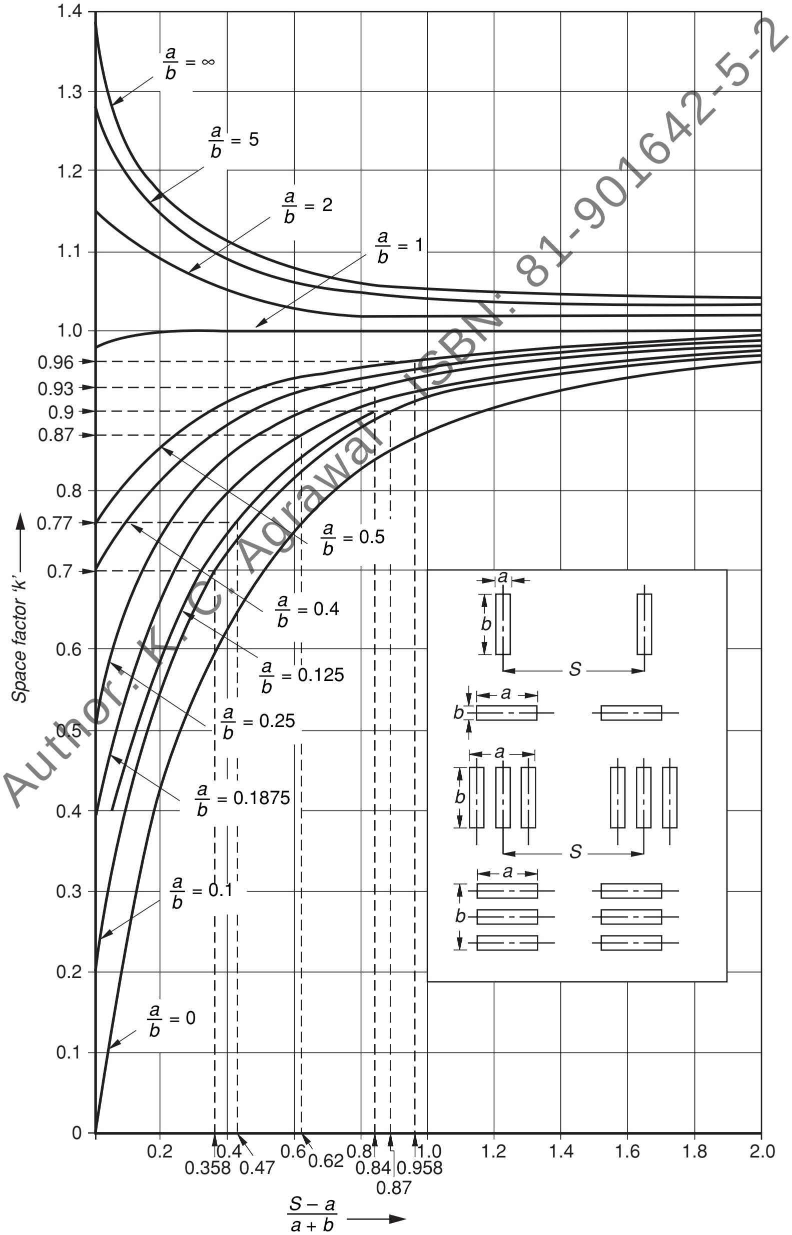


Figure 28.7 Space factor for rectangular conductors (Source: The Copper Development Association)

where

S = centre spacing between two phases in mm (Figure 28.8)
a = space occupied by the conductors of one phase in mm, and
b = width of the conductors in mm.

The factor k decreases with the increase in spacing 'S'. For application of the above equation, refer to Example 28.12.

28.5 Service conditions

The performance of a bus system can be affected by the following service conditions:

1 Ambient temperature
2 Altitude
3 Atmospheric conditions and
4 Excessive vibrations and seismic effects

28.5.1 Ambient temperature

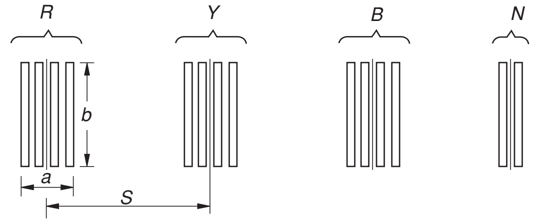
The ratings as provided in Tables 30.2 (a, b and c), 30.4 and 30.5 and others refer to an ambient temperature, with a peak of 40°C and an average of 35°C over a period of 24 hours. The end temperature for aluminium is considered safe at 85–90°C, at which the metal does not degenerate (oxidise) or change its properties (mechanical strength) over a long period of operation. Figure 28.9 shows the effect of higher operating temperatures on the mechanical strength of aluminium metal. The oxidation and mechanical strength are two vital factors that need be borne in mind when selecting busbar size to ensure its adequacy during long hours of continuous operation. Table 28.2 lists the permissible operating temperatures of the various parts of a bus system.

For higher ambient temperatures, current capacity should be suitably reduced to maintain the same end temperature during continuous operation. Refer to Tables 28.3(a) and (b), recommending the derating factors for a higher ambient temperature or a lower temperature rise for the same end temperature of 85°C or 90°C respectively. For intermediate ambient temperatures, see Figure 28.10.

Operating temperatures of bus conductors

Aluminium and copper conductors are susceptible to oxidation and corrosion as noted in Section 29.2. But at elevated temperatures above 85–90ºC this phenomenon becomes rapid and may endanger the joint. The oxides of aluminium (Al_2O) and copper (CuO) are poor conductors of electricity and adversely affect bus conductors, particularly at joints reducing their current-transfer capacity over time. This may lead to their over-heating, even an eventual failure. Universal practice therefore, is to restrict the operating temperature of the bus conductors aluminium or copper to 85–90ºC for all ratings, at least in the medium range say, up to 3200 A.

– The joints as such, however good they are made, make only micro contacts surface to surface and contain air



$S > 2a$ or $2b$ whichever is more.

Figure 28.8 Placement of busbars to minimize the effect of proximity

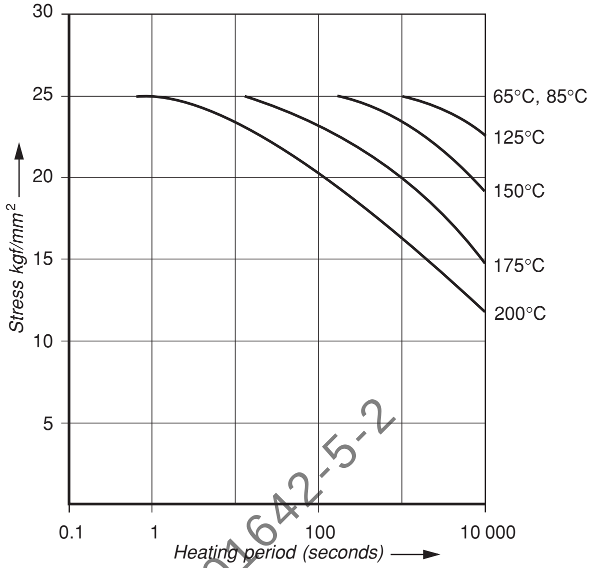


Figure 28.9 Curves showing the tensile strength of Indal D50SWP at higher temperatures

Table 28.2 Operating temperature of a bus system

Type of bus connection	*Maximum temperature limit as in IEEE-C-37-20.1*[a]
• Bus conductor with plain connection joints	70°C
• Bus conductor with silver plated or welded contact surfaces	105°C
Enclosure	
• Accessible part	80°C
• Non-accessible part	110°C
• Termination at cables with plain connections	70°C
• Termination at cables with silver-surfaced or equivalent connections	85°C

[a]Or as specified by the user.

Note
For temperatures above 100°C it is recommended to use epoxy insulators/supports, which can continuously operate up to 125°C. FRP (fibreglass reinforced plastic) insulators/supports may not withstand 125°C.

Table 28.3 Derating factors on account of higher ambient temperature or restricted temperature rise

(a) *Operating temperature 85°C*			(b) *Operating temperature 90°C*		
Ambient temperature °C	*Permissible bar temperature rise °C*	*Derating factor*	*Ambient temperature °C*	*Permissible bar temperature rise °C*	*Derating factor*
30	55	1.05	35	55	1.05
35	50	1.0	40	50	1.0
40	45	0.945	45	45	0.945
45	40	0.88	50	40	0.88
50	35	0.815	55	35	0.815
55	30	0.75	60	30	0.75

Notes
1 These data are drawn in the shape of a graph in Figure 28.10.
2 Intermediate values can be obtained by interpolation.

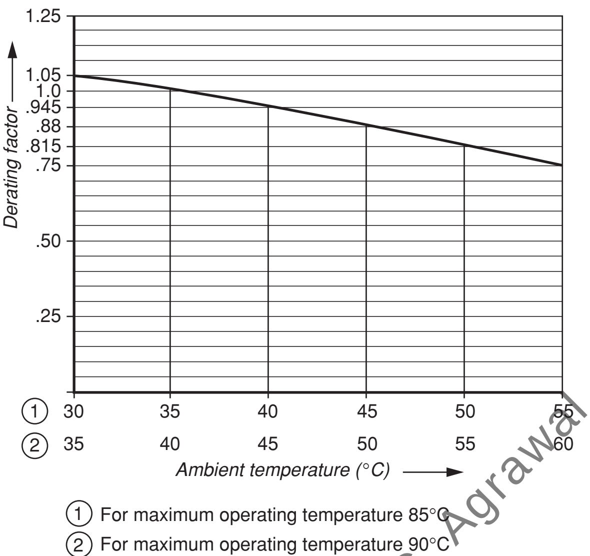


Figure 28.10 Derating factors for different ambient and maximum operating temperatures

pockets (as established by experiments). Outer contact surfaces of the joints are noticed to be more prone to this feature which may lead to quicker erosion of metal and failure of joints.

- In chemically aggravated, humid or saline locations this phenomenon accelerates yet more rapidly and renders the joints more vulnerable to failures.
- At higher temperatures the erosion further accelerates because of breathing action as a result of expansions and contractions of busbars with the variations in load.
- There is a differential movement within the joint also because of different thermal expansions of busbars and MS bolts.

A good joint capable of maintaining adequate contact pressure over long periods and proper greasing may prevent the erosion. But this is too theoretical because the regular heating and cooling of busbars may also cause gradual loosening of grip (contact pressure). To overcome all this, sealing of joints as noted below is considered a good technique to make a perfect joint. With proper sealing the operating temperature of the bus conductors can also be raised up to 105–125°C.

Using better techniques of making joints, the trend is changing towards accepting higher operating temperatures. But it is not in keeping with the spirit of energy saving that one is obliged to exercise (Section 1.19). It is therefore suggestive that the manufacturers use higher cross-sections of busbars to contain the heat losses (I^2R) as low as possible and furnish a repayment schedule to the user, showing recovery of the initial higher cost of equipment in a short period by saving on losses and ensuring recurring savings thereafter, saving environment in the process.

Sealing of joints

Silver or silver oxide (Ag_2O) is a good conductor of electricity and so also the welded joints. Silver plating* and welding** are two different methods and both can seal the inside surfaces from the atmosphere and can also prevent the contact surfaces from oxidation. If the joints are silver plated or welded, the bus system can also be made suitable to operate at higher temperatures. In aluminium conductors, for instance, they can be operated up to an optimum temperature of 125°C, until aluminium begins to lose its mechanical strength (Figure 28.9). Similarly, copper conductors can operate at still higher temperatures. The entire bus system can now be operated at much higher temperatures than given in Table 28.2.

However, operation at such high temperatures may impose many other constraints, such as high temperature in the vicinity which may endanger the operating personnel. It may even become a source of fire hazard. Such a high temperature may also damage components mounted inside the enclosure, which may not be able to sustain such high temperatures. It may also cause limitations on gaskets and other hardware of the bus system to operate at such high temperatures continuously. Accordingly, the maximum operating temperature of a bus system aluminium or copper with silver-plated or welded joints is also permitted up to 105°C only. The enclosure temperature is still restricted to 80°C, or up to 110°C at locations that are safe and inaccessible to a human body (Table 28.2).

* The procedure of silver plating the joints is mentioned in Section 29.2.6.
** The welding is usually carried out by tungsten inert gas (TIG) or metal inert gas (MIG).

28.5.2 Altitude

The standard altitude for a metal enclosed bus system will remain the same as for a switchgear assembly (Section 13.4.2). Higher altitudes would require similar deratings in dielectric strength and the current ratings as for a switchgear assembly (Table 13.12). To achieve the same level of dielectric strength, the insulation of the bus system may be improved by increasing the clearances and creepage distances to ground and between phases, as noted in Tables 28.4 and 28.5. To achieve the same value of continuous current, the size of the current-carrying conductors may be increased sufficient to take care of the derating.

Note
It is also possible to derive almost the same value of derating by reducing the allowable temperature increase by 1% for every 300 m rise in altitude above the prescribed level.

Clearances and creepage distances

Clearance : It is the shortest distance in air between two conductive parts
Creepage : It is the shortest distance along the surface of an insulating material between two conductive parts.

The clearances and creepage distances for enclosed indoor-type air-insulated busbars, as suggested by BS 159, are given in Tables 28.4 and 28.5 respectively.

These values are considered for an altitude of up to 2000 m for LV and 1000 m for HV systems. For higher altitudes to achieve the same level of dielectric strength, the values of clearances and creepage distances, may be increased by at least 1% for every 100 m rise in altitude.

28.5.3 Atmospheric conditions

The same conditions would apply as for a switchgear assembly (Section 13.4.2). Unlike a controlgear or a switchgear assembly, a bus system may be required to be partly located outdoors. This is true for most installations, as the switchyard is normally located outdoors as is the feeding transformer, while, the switchgears are located indoors, to which the bus system is connected.

In such conditions, it is important that adequate care is taken to construct the bus enclosure to weather the outdoor conditions such as by providing a canopy on the top and special paint treatment on the outdoor part. It is also recommended to seal off the indoor from the outdoor part to prevent the effect of rainwater, dust and temperature and other weather conditions on the indoor part. This can be achieved by providing seal-off bushings, one on each phase and neutral, wherever the bus enclosure passes through a wall. The bushings may be of SMC/DMC/FRP or porcelain for LV and epoxy compound for HV systems. They may be fitted at the crossovers so that the indoor bus is sealed off from the outdoor one. The bus conductors will pass through the bushings. The HV bus conductors may be moulded with the epoxy bushings, as illustrated in Figure 28.11(b), similar to bar primary CTs (Figure 15.14) to make the joint airtight. In LV a simpler method is found by providing glass wool in the part that passes through the wall as illustrated in Figure 28.11(a).

28.5.4 Excessive vibrations and seismic effects

These will require a more robust enclosure, similar to a switchgear assembly. For details refer to Section 13.4.2.

Table 28.4 Clearances for enclosed, indoor air-insulated busbars

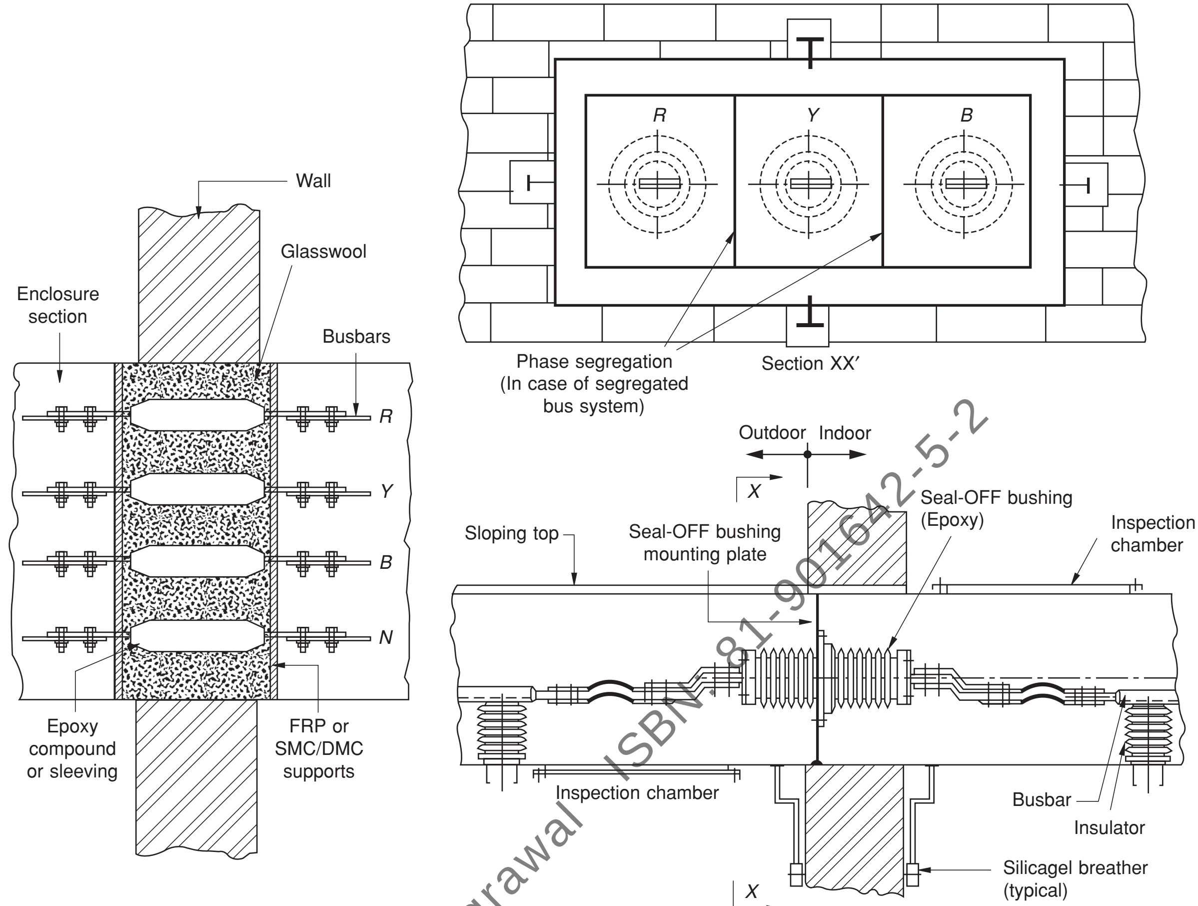
Rated voltage kV (r.m.s.)	*Minimum clearance to ground in air mm*	*Minimum clearance between phases in air mm*
Up to 0.415	16	19
0.6	19	19
3.3	51	51
6.6	64	89
11	76	127
15	102	165
22	140	241
33	222	356

Table 28.5 Creepage distances for enclosed indoor air insulated busbars as in BS 159

Rated voltage kV (r.m.s.)	*Minimum creepage distance to ground in air mm*	*Minimum creepage distance between phases in air*
Up to 0.415	19	Minimum 50% more (all ratings)
0.6	25	
3.3	51	
6.6	89	
11	127	
15	152	
22	203	
33	305	

Notes
1 The above figures are only indicative, and may be considered as a minimum for a bus system that is dry and free from dust or any contamination, which may influence and reduce the effective creepage over time. These creepages may be increased for damp, dirty or contaminated locations.
2 For clarification and more details refer to BS 159.

Common to both tables
1 The above clearances and creepage distances are for altitudes of up to 2000 m for LV and 1000 m for HV systems.
2 For higher altitudes than this, these distances should be increased by at least 1%, for every 100 m rise in altitude.
3 Voltages higher than above, are usually not applicable in case of conventional bus systems. Seemingly in this form above 33 kV it may not be practical to use them because of their rigidity. With the availability of gas insulation (Section 19.10), however, there is no limitation in manufacturing them for any voltage system. They can be fabricated to any shape and size to suit the site requirements particularly where GIS are installed.
4 For higher voltage requirements such as for large substations and switchyards or large industries, particularly at locations not using gas insulated switchgear (GIS) XLPE cables or partially isolated phase bus system (PIPB) (Section 28.2.6) will be a better option as they can facilitate easy bending and manoeuvring.



(a) For LV systems (b) For HV systems

Figure 28.11 Wall frame assembly with seal-OFF bushing

28.6 Other design considerations

- Size of enclosure (not relevant for non-conventional bus systems)
- Voltage drop
- Skin and proximity effects

28.6.1 Size of enclosure

The enclosure of the bus system provides the cooling surface for heat dissipation. Its size has an important bearing on the temperature rise of conductors and consequently their current-carrying capacity. The enclosure effect and the ventilating conditions of the surroundings in which the enclosure is to be installed should thus be considered when designing a bus system. The ratio of the area of the current-carrying conductors to the area of the enclosure will provide the basis to determine the heat dissipation effect. Table 28.6 suggests the approximate dissipation factors that can be considered as likely deratings for a bus system under different conditions. See also Example 28.12.

Note
For busbar mounting configurations see Section 13.6.

28.6.2 Voltage drop

The voltage drop across a bus system should be as low as possible and generally within 1–2% of the rated voltage. This criterion will generally be applicable to a high current LV system. On HV and low LV current-carrying systems, this drop may be quite low. The length of a bus system, in most of applications, may not be long enough to cause a high voltage drop, *IZ*, to be taken into consideration. It may be the connection from the incoming transformer to the main receiving switchgear or the length of busbars of the main switchgear assembly itself. Applications requiring extra-long current-carrying conductors, however, may have large impedance and cause high voltage drops, of the order of 3–5% and even more. When so, they may affect the stability of the system as well as the performance of the connected load. This is illustrated in Example 28.9. To ascertain the voltage drop in such cases it is essential to determine the actual values of the conductor's own resistance, reactance and the impedance under actual operating conditions. It may be noted that reactance is the main cause of a high voltage drop. Skin and proximity effects play a vital role in affecting the resistance and reactance of such systems. We discuss these aspects briefly below.

28.6.3 Skin and proximity effects on a current-carrying conductor

In a d.c. system the current distribution through the cross-section of a current-carrying conductor is uniform as it consists of only the resistance. In an a.c. system the inductive effect caused by the induced-electric field causes skin and proximity effects. These effects play a complex role in determining the current distribution through the cross-section of a conductor. In an a.c. system, the inductance of a conductor varies with the depth of the conductor due to the skin effect. This inductance is further affected by the presence of another current-carrying conductor in the vicinity (the proximity effect). Thus, the impedance and the current distribution (density) through the cross-section of the conductor vary. Both these factors on an a.c. system tend to increase the effective resistance and the impedance of the conductor, and cause a higher $I_{ac}^2 \cdot R_{ac}$ loss, and a higher voltage drop $I_{ac} \cdot Z$, and reduce its current-carrying capacity. An a.c. system is thus more complex than a d.c. system and requires far more care when designing it for a particular requirement. While these phenomena may be of little relevance for a low-current system, they assume significance at higher currents and form an essential parameter to design a high current-carrying system say, 2000 A and above. These phenomena are discussed briefly below.

Table 28.6 Heat dissipation factor

	Enclosure	*Cross-sectional area of busbars ÷ cross-sectional area of enclosure*	*Derating factor*
1	Outdoors	< 1%	0.95
		5%	0.90
		10%	0.85
2	Indoors, where the enclosure is in a well-ventilated room	< 1%	0.85
		5%	0.75
		10%	0.65
3	Indoors, where the enclosure is poorly ventilated and the room temperature is high	< 1%	0.65
		5%	0.60
		10%	0.50

Notes

1 Intermediate values can be obtained by interpolation.

2 These deratings are meant only for non-magnetic enclosures, where the heat generated is only through induced electric currents (I^2R) and hence low. There are no hysteresis or eddy current losses.

3 For MS enclosures, which will have both hysteresis loss ($\propto B^{1.6}$) and eddy current loss ($\propto B^2$), a higher derating factor must be considered. The subsequent text will clarify this aspect.

28.7 Skin effect

A current-carrying conductor produces an electric field around it which induces a back e.m.f. and causes an inductive effect. This e.m.f. is produced in the conductor by its own electric field cutting the conductor. It is more dense at the centre and becomes less at the surface. The conductor thus has a higher inductance at the centre than at the surface, and causes an uneven distribution of current through its own cross-section. The current tends to concentrate at the outer surface of the conductor, i.e. its 'skin', shares more current than the other parts of the conductor and reduces with depth. It is lowest at the nucleus. For more than one conductor per phase all the conductors together may be considered as forming a large conductor for the purpose of analysing the skin effect. Now the bulk of the current will be shared by the end conductors and only partly by the middle conductors. Figure 28.12 demonstrates an approximate sharing of current and the heat generated in one, two, three and four flat sections per phase, placed in vertical disposition, in an almost isolated plane, where they have no or only a negligible effect of proximity.

Note

These current sharings are only indicative. The actual current sharing will depend upon the thickness, the width and the configuration of the conductors. Refer to Tables 30.2(a, b and c), 30.4 and 30.5.

The phenomenon of uneven distribution of current within the same conductor due to the inductive effect is known as the 'skin effect' and results in an increased effective resistance of the conductor. The ratio of a.c. to d.c. resistance, R_{ac}/R_{dc}, is the measure of the 'skin effect' and is known as the 'skin effect ratio'. Figure 28.13(a) illustrates the skin effect for various types and sizes of aluminium and copper in flat sections. For easy reference, the skin effects in isolated hollow round and channel conductors (in box form) are also shown in Figures 28.13(b) and (c) respectively.

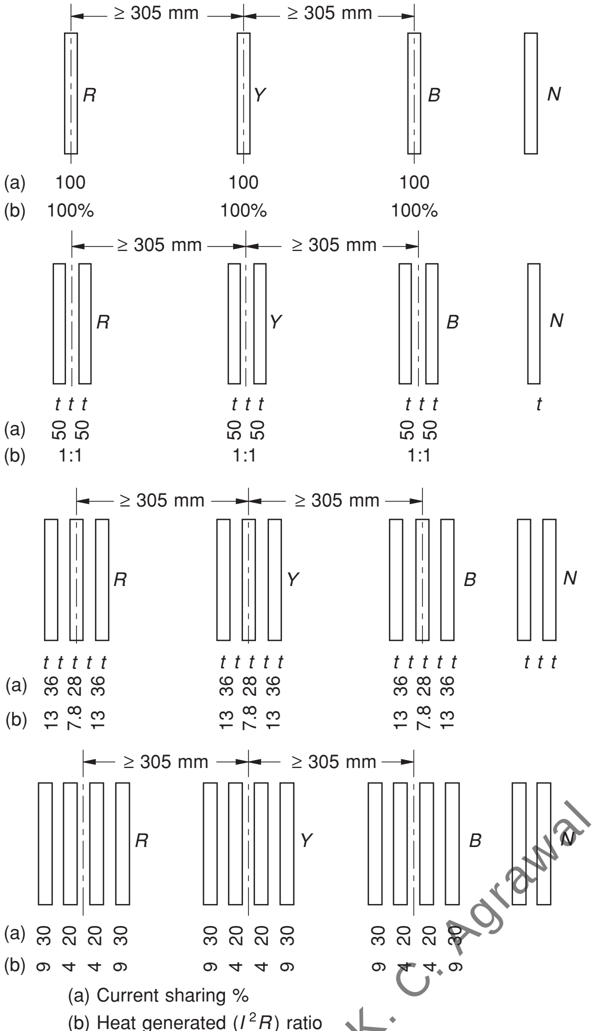
Tables 30.7, 30.8 and 30.9 for rectangular, tubular and channel sections respectively, give the d.c. resistance and the reactance values between two aluminium conductors of small and medium current ratings of any two adjacent phases, with a centre-to-centre spacing of 305 mm or more, when the proximity effect is considered almost negligible in these ratings.

Since the skin effect results in an increase in the effective resistance of the busbar system it directly influences the heating and the voltage drop of the conductor and indirectly reduces its current-carrying capacity. If R_{ac} is the resistance as a result of this effect then the heat generated

$$= I_{ac}^2 \cdot R_{ac}$$

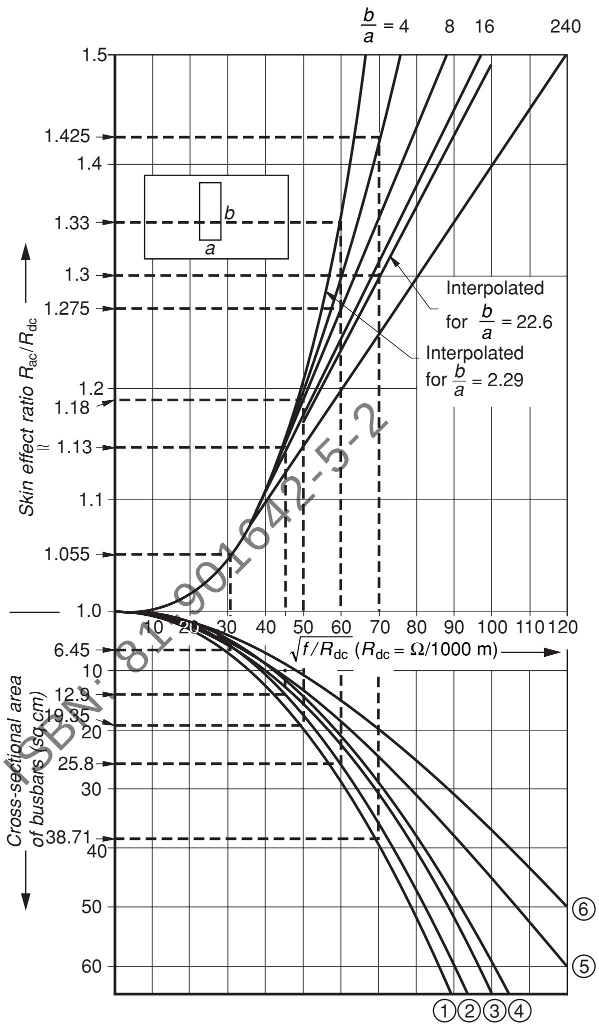
where I_{ac} is the permissible current-carrying capacity of the conductor on an a.c. system to keep the same heating effect as on a d.c. system then the reduction in the current rating due to the skin effect can be deduced by equating the two heats, i.e.

$$I_{ac}^2 \cdot R_{ac} = I_{dc}^2 \cdot R_{dc}$$



Note Each phase is considered in isolation not influenced by proximity effect

Figure 28.12 Skin effect in different bus sections of the same phase



① Indal D 50 SWP at 85°C
② Indal CISM at 85°C
③ Indal D 50 SWP at 20°C
④ Indal CISM at 20°C
⑤ Copper at 85°C
⑥ Copper at 20°C

Note

1. The lower cross-sectional area curves relate to f = 50 Hz. For other frequencies $\sqrt{f/R_{dc}}$ must be calculated by multiplying these values by $\sqrt{f/50}$
2. Small variation is possible while drawing these curves

(a) Flat busbars

Figure 28.13(a) Skin effect in isolated busbars standing on edges. (neglecting the proximity effect) (Source: Indian Aluminium Co. based on Alcan of Canada)

or $$I_{ac} = I_{dc} \cdot \sqrt{\frac{R_{dc}}{R_{ac}}} \qquad (28.5)$$

The skin effect can be minimized by employing different configurations and arrangement of busbars, as discussed later and illustrated in Figure 28.14. It can also be minimized by selecting hollow round or hollow rectangular (channels in box form) conductors, and thus concentrating the maximum current in the annulus and optimizing metal utilization. For current ratings of aluminium in round and channel sections, refer to Tables 30.8 and 30.9, respectively and for copper Tables 30.2 (a, b and c) for flat, tube and channel sections, respectively.

Example 28.5
If there is a rise of 5% in the effective resistance of the busbars due to the skin effect, then the a.c. rating will be

$$= \sqrt{\frac{R_{dc}}{1.05 \cdot R_{dc}}}$$

= 0.976 or 97.6% that of the d.c. rating.

28.7.1 Skin effect analysis

When a number of flat bars are used in parallel their

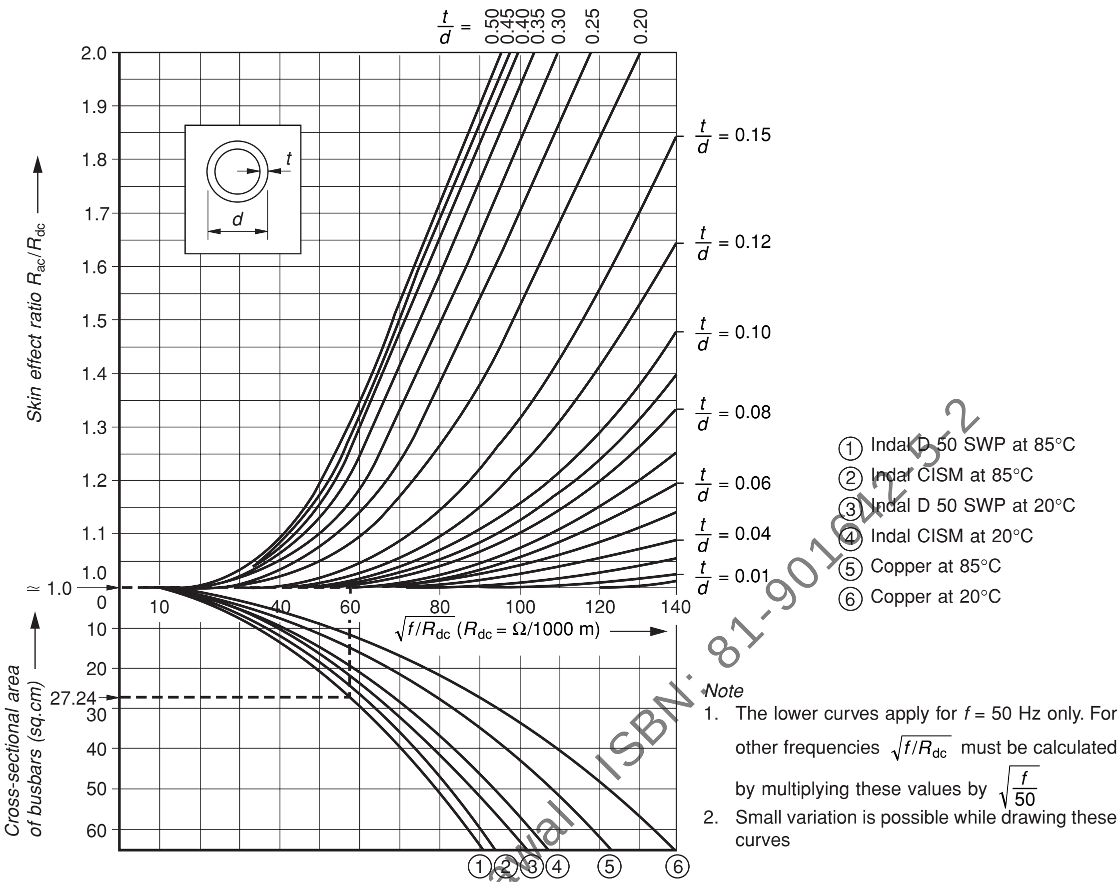


Figure 28.13(b) Skin effect in isolated tubular conductors

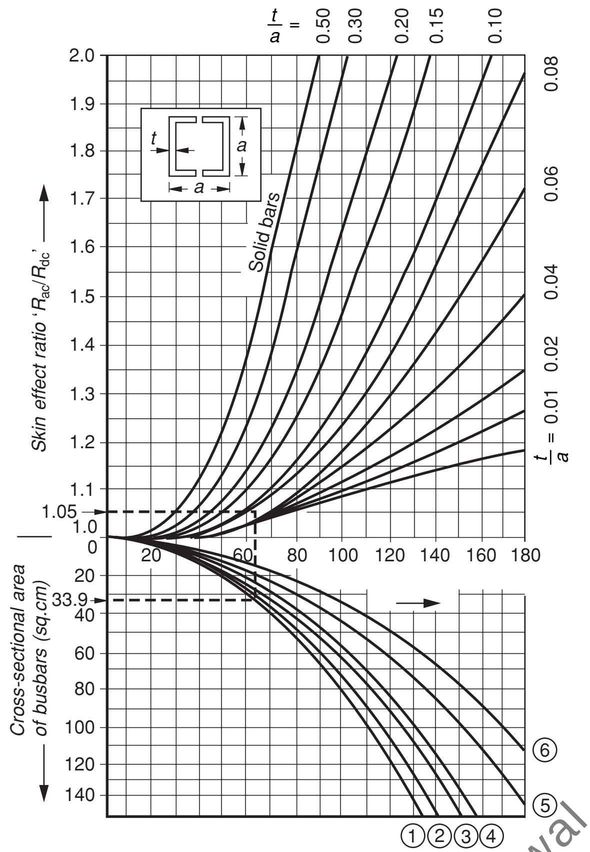
effective current-carrying capacity is the result of the cumulative effect of the restricted heat dissipation and the increased content of the skin effect. A stage may arise when further addition of any more bars may not appreciably increase the overall current-carrying capacity of such a system. Referring to Tables 30.4 and 30.5, we can observe a wide variation in the current-carrying capacity of a conductor when it is added to an existing system of one, two or three conductors per phase, depending upon the thickness and width of the conductors. Thinner sections of shorter widths provide better metal utilization, compared to a thicker section and larger widths. Use of bars up to four sections per phase is quite common for higher current systems (2500 A–3200 A). For still higher current ratings, use of more than four bars in parallel is not advisable due to an extremely low utilization of metal, particularly in larger sections. While larger sections would be imperative for such large ratings, their own rating would fall to a low of 14–18% of their normal current capacity. (See Table 30.5 for larger sections, providing current ratings up to six bars in parallel.) In such cases it is advisable to arrange the bars in any other convenient configuration than in parallel, as illustrated in Figure 28.14 or to use tubular or channel sections which form into hollow conductors and the current flows through their annulus (skin) optimizing the metal utilization.

28.7.2 Determining the skin effect

As a result of the electric field around the conductors the frequency of the system has a very significant bearing on the skin effect. The various curves as established through experiments and, as reproduced in Figures 28.13 (a), (b) and (c) respectively for rectangular, tubular and channel conductors, are thus drawn on the $\sqrt{f/R_{dc}}$ basis. At 50 Hz, the value of the skin effect, R_{ac}/R_{dc}, can be read directly from these curves, as the curves for different cross-sectional areas and conductivity, at 50 Hz, have also been drawn in the lower part of the figure.

At 60 Hz the skin effect ratio can be read corresponding to $\sqrt{\frac{60}{50 R_{dc}}}$ or $1.095\sqrt{\frac{1}{R_{dc}}}$

One will notice that lower the rating or conductor cross-section, lower is the effect of frequency on skin effect ratio (R_{ac}/R_{dc}). Accordingly, in smaller sections nearly the same ratings of conductors can be assumed at 60 Hz as for 50 Hz system without much error. But as the rating or the cross-section of the conductor increases so increases



① Indal D 50 SWP at 85°C

② Indal CISM at 85°C

③ Indal D 50 SWP at 20°C

④ Indal CISM at 20°C

⑤ Copper at 85°C

⑥ Copper at 20°C

Note

1. The lower curves apply for f = 50 Hz only. For other frequencies, $\sqrt{f/R_{dc}}$ must be calculated by multiplying these values by $\sqrt{f/50}$
2. Small variation is possible while drawing these curves

(c) Channels in box form

Figure 28.13(c)

the skin effect ratio. For large ratings say 2000 A and above compared to ratings at 50 Hz, the ratings at 60 Hz may be reduced by roughly 2.5–5% as a rough estimate. For accurate calculation one may interpolate the curves and determine the skin effect ratio more accurately.

CDA has mentioned the same ratings for 50 and 60 Hz systems, Tables 30.2(a),(b), and (c). However, if the ratings are established for 60 Hz, for larger cross-sections the ratings at 50 Hz may be enhanced by 2.5–5% without much error. Similarly, tables that mention ratings at 50 Hz, Tables 30.7, 30.8, 30.9, the ratings at 60 Hz may be reduced roughly by 2.5–5% (depending upon cross-section) to be on the safe side.

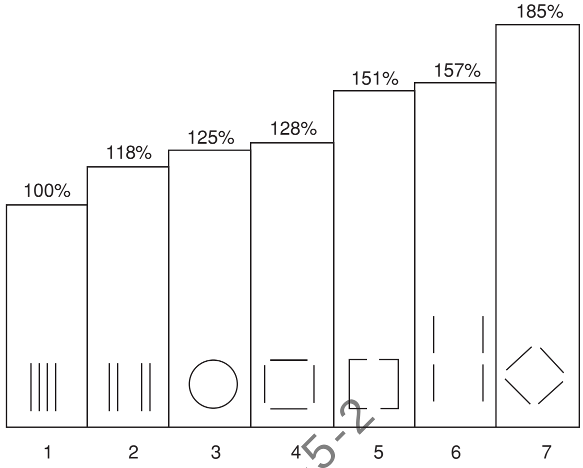


Figure 28.14 Ratio of a.c. current ratings for different configurations of busbars of the same cross-sectional area (Source: The Copper Development Association, U.K.)

Ratings up to 3200 A are normally required for distribution purposes such as for inter-connecting a distribution transformer to a PCC, or a large PCC to another large PCC in a substation. Common practice for making such connections is to use rectangular cross-sections, which are easy to handle, manoeuvre and make joints, compared to a channel or a tubular section. Channel and tubular sections require special tools and skilled workers, particularly when bending or making joints and end terminations. However, suitable fittings and fixtures, some of which are shown in Figure 28.15 (a) and (b), are also provided by leading manufacturers as standard practice to facilitate such connections. The welding of such joints will require special welding equipment and adequate in-house testing facilities to check the quality of weld. It is, however, recommended to use such sections, for ratings 3200 A and above, for better utilization of active metal compared to flat sections. We briefly deal with all such sections as follows.

(i) Rectangular sections

Example 28.6

Consider a section of 101.6 mm × 6.35 mm of grade EIE-M as in Figure 28.16. From Table 30.7 for its equivalent grade CIS-M

(i) R_{dc} = 44.55 $\mu\Omega$/m at 20°C

or 44.55 × 1000 × 10^{-6} Ω/1000 m

i.e. 0.0445 Ω/1000 m

Area of cross-section = 101.6 × 6.35 × 10^{-2} cm^2

= 6.4516 cm^2

Since the operating temperature should be considered to be 85°C,

$$R_{dc} \text{ at } 85°C = R_{dc20}\,[1 + \alpha_{20}(\theta_2 - \theta_1)] \quad (28.6)$$

where

α_{20} = temperature coefficient of resistance for CIS-M grade of aluminium from Table 30.1,

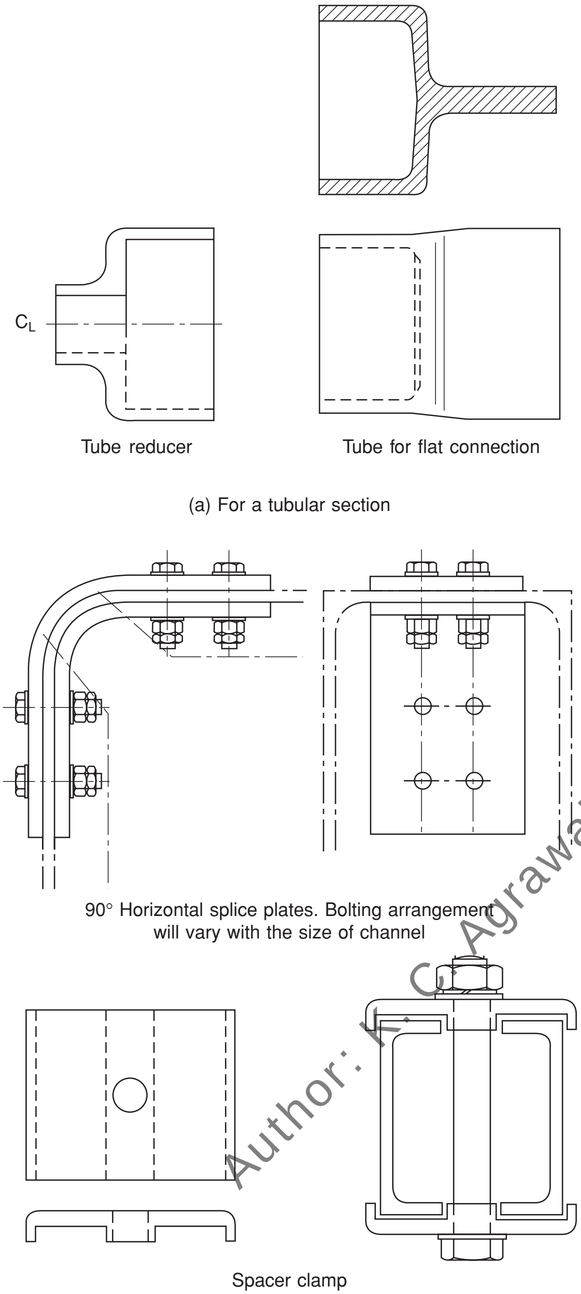


Figure 28.15 Typical fittings for different busbar sections

= 0.00403 per °C at 20°C

R_{dc20} = d.c. resistance at 20°C

θ_2 = Operating temperature = 85°C

θ_1 = Since the value of R_{dc} is available at 20°C therefore, θ_1 = 20°C.

R_{dc} at 85°C = 0.0445 [1 + 0.00403 (85 – 20)]

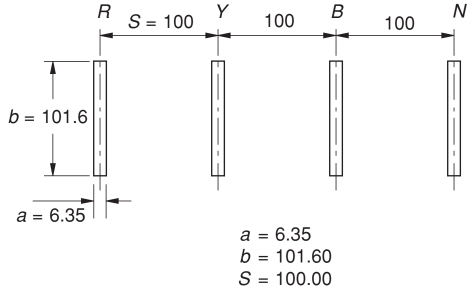


Figure 28.16 Illustration of Example 28.6

= 0.0445 (1 + 0.26195)

= 0.056 Ω/1000 m

Now refer to Figure 28.13(a) to obtain the skin effect ratio R_{ac}/R_{dc}. Consider the cross-sectional curves for EIE-M grade of flat busbars at an operating temperature of 85°C for a cross-sectional area of 6.45 cm^2 and determine the R_{ac}/R_{dc} ratio on the skin effect curve having

b/a = 101.6/6.35 = 16.

$$\therefore \quad \frac{R_{ac}}{R_{dc}} = 1.055$$

i.e. an increase of almost 5.5%, due to the skin effect alone and

R_{ac} = 1.055 × 0.056

= 0.059 Ω/1000 m

(ii) Skin effect for more than one conductor per phase

In such cases, the group of busbars in each phase may be considered to be one large conductor and outside dimensions *a* and *b* as illustrated in Figure 28.8 measured for all calculations.

Example 28.7

Consider a four-conductor system of section 101.6 mm × 6.35 mm in each phase (Figure 28.17(a)) of grade EIE-M for carrying a current of 2000 A.

R_{dc} : As calculated above for one section of bus

= 0.056 ohm/1000 m per conductor of four bus-sections in parallel

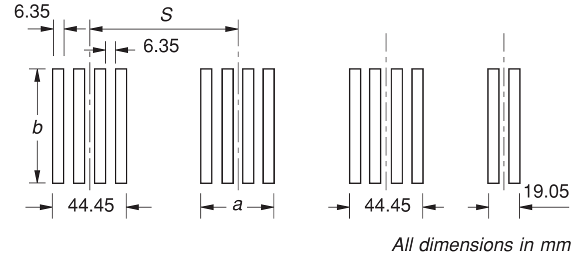
Skin effect ratio R_{ac}/R_{dc} from the graph of Figure 28.13(a), at an operating temperature of 85°C for a cross-sectional area of 25.8 cm^2 (4 × 101.6 × 0.635) for an EIE-M grade of aluminium having

$$\frac{b}{a} = \frac{101.60}{44.45} \simeq 2.29$$

$R_{ac}/R_{dc} \simeq 1.33$

$$\therefore \quad R_{ac} \text{ for the phase } = \frac{1}{4} \times 1.33 \times 0.056$$

$$= 18.62 \times 10^{-3}\ \Omega/1000 \text{ m}$$



a = 44.45
b = 101.60
S = 184.45 (It is recommended to be min. 300)

Figure 28.17(a) Illustration of Example 28.7

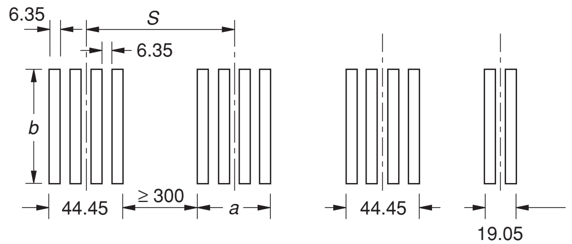


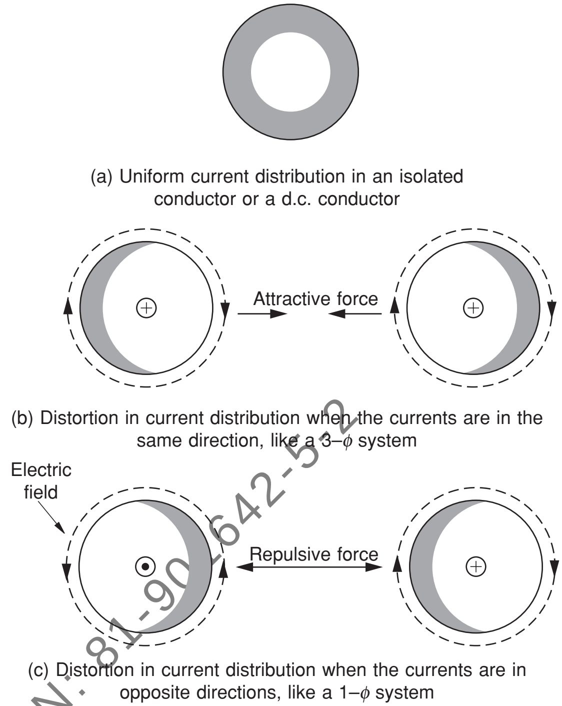
Figure 28.17(b) Minimizing the effect of proximity in thicker sections (Section 28.8.4)

(iii) Busbar configurations (To improve heat dissipation and minimize skin effect)

The busbars may be arranged in different configurations as shown in Figure 28.14 to improve heat dissipation and reduce the skin effect as well as the proximity effect. The improvement in the ratings is indicative of the cooling and skin effects with different configurations. When a number of bars are used in parallel, each bar shields the adjacent bar and reduces its heat dissipation. Moreover, together they form a large conductor and due to the skin effect the current will tend to concentrate at the outer surfaces only. It will cause inner surfaces to share smaller and the outer surfaces the larger currents. In configurations other than parallel bars, an attempt is made to improve heat dissipation and reduce the skin effect. It is obvious that most of the conductors are now sufficiently independent of the others and can carry higher currents.

28.8 Proximity effect

If there is more than one current-carrying conductor other than of the same phase, placed adjacent to each other, so that the electric field produced by one can link the other, mutual induction will take place. The magnitude of this will depend upon the amount of current and the spacing between the two. This tends to further distort the self-resistance of the conductor over and above the distortion already caused by the skin effect and so also the current distribution through its cross-section. Figure 28.18(a), (b) and (c) illustrate diagrammatically distortion of current



Note
1. ⊕ or ⊙ – Direction of current in a conductor looking from top.
⊙ – Current coming out
⊕ – Current going in.
2. Direction of electric field by Cork-Screw rule.

Figure 28.18 Current distribution in round conductors, illustrating the effect of proximity

flow in a round conductor and also the mechanical forces exerted on the conductors, due to this distorted current distribution. There is always a force between two current-carrying conductors placed adjacent to each other, whether it is a d.c. or an a.c. system. The proximity effect, however, will exist only in an a.c. system due to mutual induction between the two current-carrying conductors. It may be less pronounced in low current systems, say, 1600 A or less, and all HV systems, where the spacings between the phases are considerably more, except their effect on the enclosure, which is discussed in Chapter 31 on isolated phase bus systems. If the second conductor carries current in the same direction, such as in a three-phase system (Figure 28.18(b)) the current will flow in the remote parts of the two conductors. If the current flows in the opposite direction, as in a single-phase system (Figure 28.18(c)) the current will flow in the adjacent parts of the two conductors.

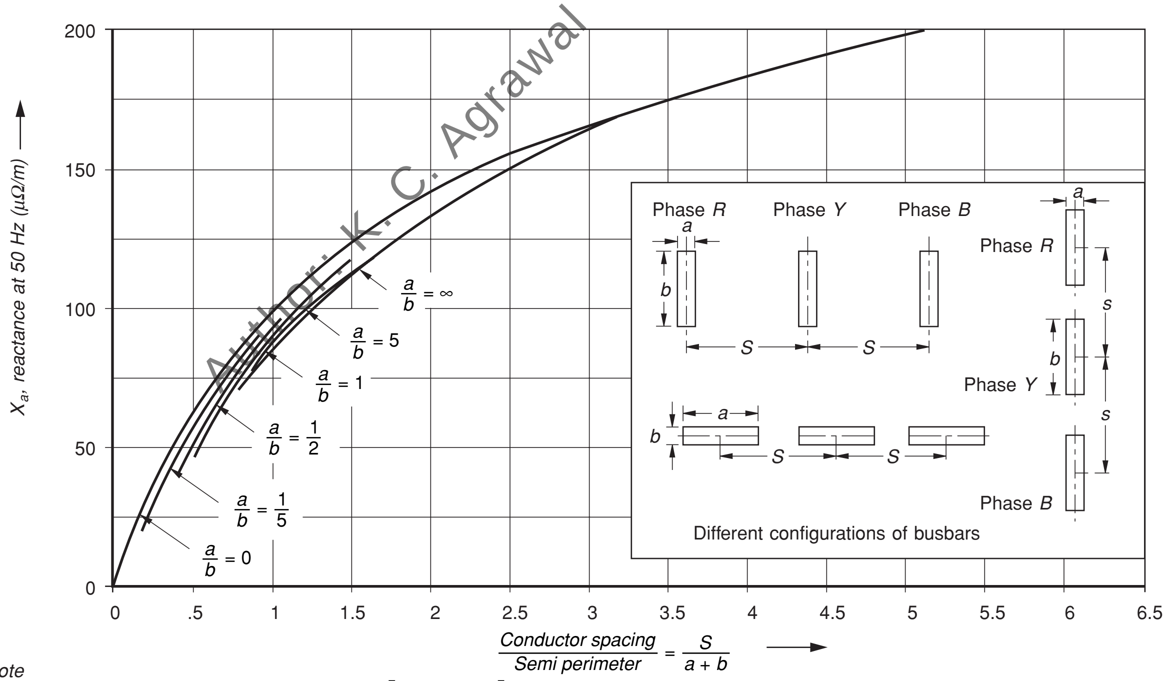
The displacement of current and the forces (Equation (28.4)) on the conductors are two different effects. The effect of current displacement is to increase the effective resistance and the impedance of the conductor on one side, as illustrated in Figure 28.18(b) and (c) and cause a distortion in its heating pattern. This will lead the various conductors of a particular phase to operate at different temperatures and add to $I_{ac}^2 \cdot R_{ac}$ losses. The rating of all the conductors of one phase must therefore be determined by the hottest conductor. The distortion of current will also distort the heat produced. The area having high current density will produce higher heat. The proximity effect thus also causes a derating in the current-carrying capacity of a conductor.

In general, the proximity effect is directly proportional to the magnitude of the current and inversely to the spacing between the two conductors. The smaller the phase spacing, the greater will be the effect of proximity as well as the derating and the greater will be the forces developed between the adjacent conductors (Equation (28.4)). But the reactance of the two phases is directly proportional to the spacing. Reactance is the main cause of an excessive voltage drop (IZ). The smaller the spacing, the lower will be the reactance, due to the proximity effect and vice versa. While the requirement of a lower reactance will require less spacing and will mean higher forces, demanding stronger busbar supports and mounting structure, requiring a lower effect on current-carrying capacity would require a larger spacing between the phases, which would result in a higher reactance and consequently a higher voltage drop. But a high reactance would help to reduce the level of fault current, I_{sc} and also forces, F_m, between the conductors.

A compromise is therefore struck to meet both needs and obtain a more balanced system or other methods adopted, as discussed in Section 28.8.4, to reduce the skin and proximity effects.

28.8.1 Proximity effect in terms of busbar reactance

Self-reactance, X_a, of the conductors plays a significant role in transmitting the power through a bus system from one end to the other. For long bus systems, it must be ascertained at the design stage whether the voltage drop in the total bus length on account of this will fall within the permissible limits, particularly for higher ratings (2000 A and above), besides the current-carrying capacity. A higher reactance will mean a higher drop. For smaller ratings and shorter lengths, as well as HV systems, this drop would be too low as a percentage of the rated voltage, to be taken into account. For higher ratings, however, it may assume a greater significance and precautionary measures may become necessary to restrict it within permissible limits. To determine X_a, proximity effect curves have been established for different bus systems by conducting actual tests on the metal and are available for all sections, configurations and spacings of busbars. We have reproduced a few of them for aluminium busbars for a 50 Hz system (for a 60 Hz system, $X_{a60} = X_{a50} \cdot 60/50$ or $1.2\ X_{a50}$), for rectangular sections as in Figure 28.19(a), tubular sections as in Figure 28.19(b) and channel sections in box form as in Figure 28.19(c). A brief procedure to determine the reactances with the help of these curves is given below.



Note

1. For 3–ϕ systems read reactance against $\rightarrow \left[1.26 \cdot \frac{S}{a+b}\right]$
2. The reactance varies with the ratio $\frac{'a'}{b}$ and therefore there may be a number of possible busbar combinations and the corresponding curves for different $\frac{'a'}{b}$. However, only a few curves have been drawn for the likely minimum and the maximum values of $\frac{'a'}{b}$. Since the variation is not large therefore by interpolation the more pertinent value of reactance can be determined from these curves.
3. Small variation is possible while drawing these curves.

Figure 28.19(a) Reactance of rectangular busbars at 50 Hz on account of proximity effect

Note
Similar procedure would apply for copper busbars also. CDA has provided simplified formulae to determine the same (for more details one may see references 6, 7, 8 and 15 of Further Reading in Chapter 31). Readymade curves as for aluminium are not readily available, but the proximity curves of aluminium can be used to evaluate approximate values of X_a for copper busbars also, for the purpose of design work without much error. Where accurate values are imminent one may use the formulae provided by CDA. Leading manufacturers who have standardized some of these products such as overhead busways, rising mains, compact bus systems and partially isolated phase bus (PIPB) system usually determine or work out these details by actual laboratory experiments and provide the same as standard in their catalogues such as shown in Tables 28.01 and 28.02 or furnish them on demand.

For smaller ratings up to 2000 A or so, proximity effect is not of much concern as noted above, unless the bus length is too large and it may be essential at the design stage to determine the voltage drop. Single section X_a for different sections of aluminium and copper busbars are provided as standard by the manufacturers of extruded sections. Some such data for different sections in flats, tubes and channels are provided in Tables 30.2(a, b and c) for copper and Tables, 30.7, 30.8 and 30.9 for aluminium.

In absence of proximity curves the reactance can still be determined for different configurations from the available data by approximation rather than attempting to work out the same the onerous way using the formulae provided by CDA. For clarity see calculation of Example 28.12 and explanation (b) under Table 28.8. The variation in 'X_a' suggests that it varies with the configuration of busbars and assumes a very high value for more number of busbars in parallel. It becomes low with efficient use of metal. Like adapting to interleaving or compact system it can be achieved nearly up to the reactance of one section divided by the number of parallel paths. The X_a in compact bus systems (Table 32.0(1) and 30.0(2)) corroborates this.

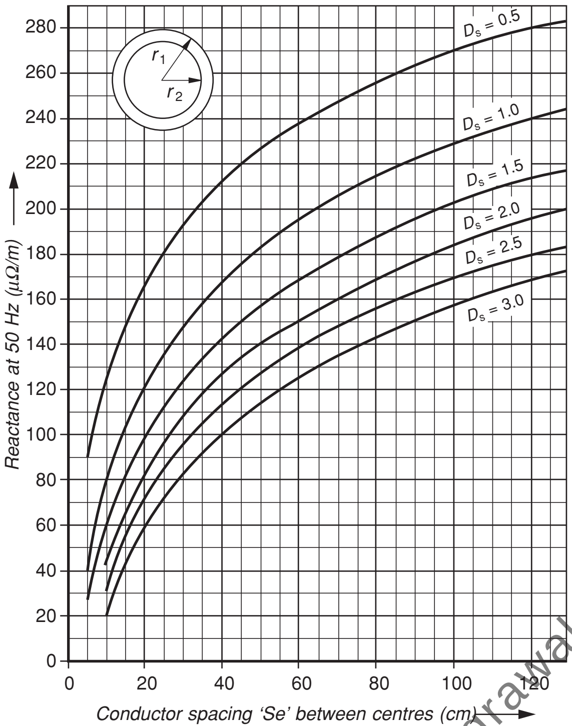


Figure 28.19(b) Reactance of tubular busbars for single-phase or three-phase systems at 50 Hz

Rectangular sections (Figure 28.19(a))

The reactance is drawn as a function of

$$\frac{\text{Centre spacing ('}S\text{')}}{\text{Semi-perimeter } (a + b)}$$

At lower spacings this value will be influenced by the width (b) and the thickness (a) of the conductor. At lower spacings, therefore, proximity curves are different for different ratios of a/b whereas for larger spacings they approach the same curve.

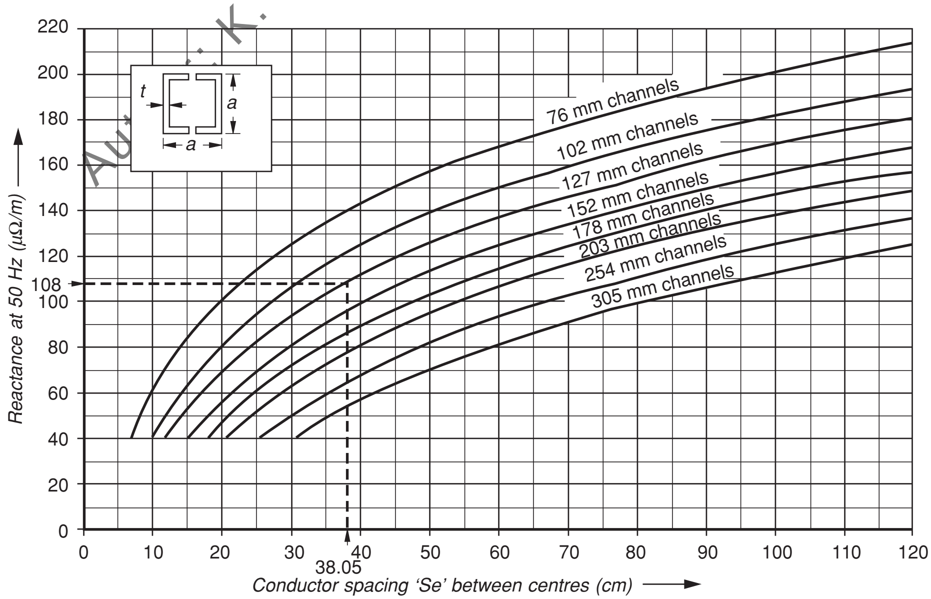


Figure 28.19(c) Reactance of channel busbars, two channels per phase in box form, single-phase or three-phase, at 50 Hz

When more than one section is used together, to make larger ratings, all the sections of one phase may be considered to be one large section. The dimensions *a* and *b* of the whole section are now considered as one conductor, as illustrated in Figure 28.8.

The basic graphs represent a singe phase system. The single phase reactance is twice the reactance so obtained. For a three-phase system the configuration of the three phases with respect to each other will play a significant role and the linear centre spacing *S* has to be modified to an effective or geometric mean spacing S_e, where

$$S_e = (S_a \cdot S_b \cdot S_c)^{1/3} \qquad (28.7)$$

For configuration (a) of Figure 28.20

$$S_a = S_b = S$$

$$S_c = 2S$$

$$\therefore \quad S_e = S \cdot (2)^{1/3}$$

$$= 1.26\ S$$

and for configuration (b) of Figure 28.20

$$S_a = S_b = S_c = S$$

$$\therefore \quad S_e = S$$

For any configuration, the effective spacing, S_e, may thus be calculated.

Tubular sections (Figure 28.19(b))

For determining S_e in solid or hollow round sections it is essential to first determine the self geometric mean distance, D_s, of the conductors which varies with the thickness *t* (annulus) of the conductor. D_s approaches its outer radius, r_1, in an infinitely thin conductor and to $0.778 r_1$ in a solid bar. This variation, in the form of D_s/r_1 is drawn in Figure 28.21, as a function of r_2/r_1.

For very thin conductors, when $r_2 \simeq r_1$, $r_2/r_1 = 1$, D_s/r_1 will also approach to unity and $D_s \simeq r_1$. For solid conductors, when $r_2 = 0$, $r_2/r_1 = 0$, D_s/r_1 becomes 0.778 and $D_s = 0.778\ r_1$ etc.

After having obtained the value of D_s, value of S_e is determined as discussed above. The reactance of the conductors can then be obtained from the graphs of Figure 28.19(b) drawn for S_e versus X_a, for varying thicknesses of round conductors. Here also the basic graph will represent a single-phase system and the single-phase reactance will be twice the reactance so obtained. Refer to Example 28.8.

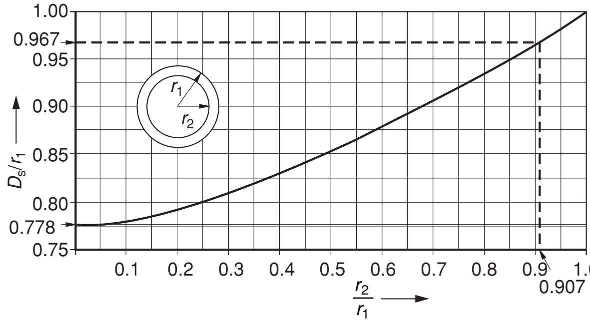


Figure 28.21 Graph to determine D_s of a tubular bus section

Channel sections (Figure 28.19(c))

These should normally be used in a box form for better metal utilization, easy mounting and uniformity of conductors. The method of determining the reactance for single- and three-phase systems is the same as for rectangular sections (Figure 28.20(a)).

From the proximity curves it may be noted that X_a rises with *S*. While a higher centre spacing would reduce the effect of proximity on the current-carrying conductors and which is so much desired, it will increase X_a, which would mean a lower p.f. for the power being transferred (through the busbars) and a higher voltage drop. In LV systems the spacings can be adjusted only marginally to reduce X_a, as a lower spacing would mean a higher electrodynamic force, F_m (Equation (28.4)) and greater proximity effects, requiring higher busbar deratings. A compromise may therefore be drawn to economize on both. In HV systems, however, which require a larger spacing, no such compromise would generally be possible and they will normally have a high content of X_a. But in HV systems, voltage drop plays an insignificant role in view of a lower voltage drop as a percentage of the system voltage.

28.8.2 Voltage unbalance as a consequence of the proximity effect

The proximity effect does not end here. It still has some far-reaching consequences in terms of unequal voltage

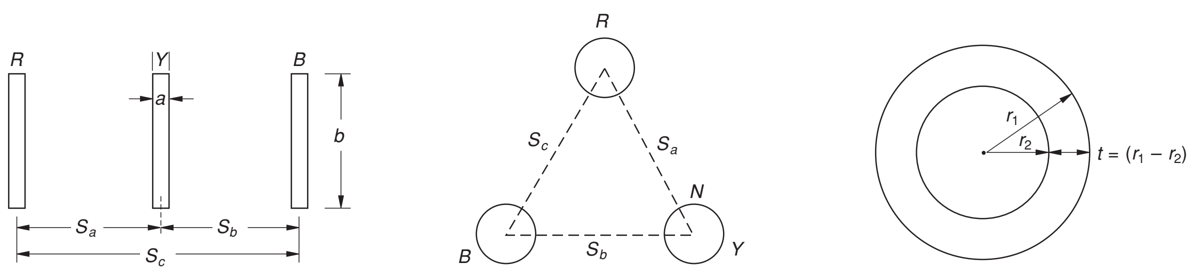


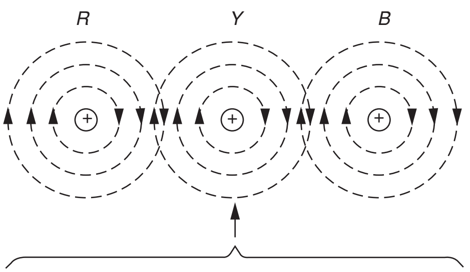
Figure 28.20 Influence of conductor configuration on linear spacing *S*

drops in different phases at the same time. This is more so on large LV current-carrying, non-isolated bus systems of 2000 A and above, resulting in an unbalance in the supply voltage, as discussed below.

A three-phase system has three current-carrying conductors in close proximity. While the conductors of phases *R* and *B* will have an almost identical impedance, with the same skin and the proximity effects, the conductor of phase *Y* is under the cumulative effect of electric fields of the other two phases, which would offset their proximity effects (see Figure 28.22). The conductor of phase *Y* therefore would carry no distortion beyond the distortion already caused by the skin effect (R_{ac}/R_{dc}). The result of this would be that in a balanced three-phase system the three phases will assume different impedances and cause an unbalance in the current distribution. The *Y* phase having a smaller impedance, would share more current compared to the *R* and *B* phases and cause a smaller voltage drop. Such an effect may not be as pronounced in lower ratings and shorter lengths of current-carrying conductors, as much on higher currents, depending upon the spacing between the phases and the length of the system.

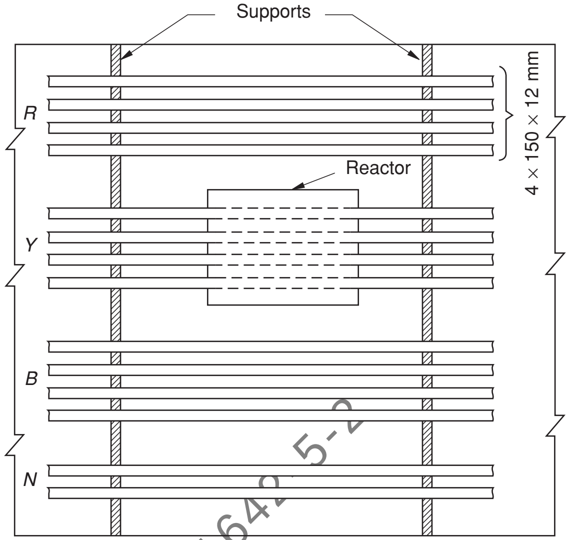
Consider a feeding line from a transformer to a power switchgear through a bus duct. The voltage available at the distribution end of this feeding line may be unequal and tend to cause a voltage unbalance. Depending upon the rated current and length of the feeding line, it may even cause a voltage unbalance beyond permissible limits (Section 12.2(v)) and render the system unstable and in some cases even unsuitable for an industrial application.

For larger current systems, 2000 A and above and lengths of over 50 m, a correct analysis for such an effect must be made and corrective measures taken to equalize the voltage and current distribution in all the three phases. Where adequate precautions are not taken at the design stage through phase interleaving or transposition techniques, as discussed later, the problem can still be solved by making up for the lost inductance in the *Y* phase by introducing an external inductance of an appropriate value in this phase. It is possible to do this by introducing an air core saturable type reactor (Section 27.3) into this phase, as illustrated in Figure 28.23. This inductor will compensate for the deficient inductance and equalize the impedances in all three phases, thus making the system balanced and stable. We illustrate



Influence of electric fields of conductors *R* and *B* is offset in a 3-ϕ system. The proximity effect in phase *Y* therefore gets nullified

Figure 28.22 Influence of proximity



Plan of a 3ϕ and *N* bus system

Figure 28.23 Balancing of phase currents in a large three-phase system by introducing a reactor in the middle phase

briefly later a procedure to determine the size of a saturable reactor core, when required, to meet such a need.

Example 28.8

Consider Example 28.6 to determine the content of proximity;
(i) For reactance X_a on account of the proximity effect, use Figure 28.16 and the graph of Figure 28.24:

$$1.26 \frac{S}{a+b} = 1.26 \times \frac{100}{(101.6 + 6.35)}$$

$$= 1.26 \times \frac{100}{107.95} \simeq 1.167$$

and $$\frac{a}{b} = \frac{6.35}{101.6} = 0.0625$$

then from the graph

$X_a = 106\ \mu\Omega$/m or $106 \times 10^{-6} \times 1000\ \Omega$/1000 m

i.e. 0.106 Ω/1000 m and

(ii) Impedance $Z = \sqrt{R_{ac}^2 + X_a^2}$

$$= \sqrt{(0.059^2 + 0.106^2)}\ \Omega/1000\text{ m}$$

$$= 0.12\ \Omega/1000\text{ m}$$

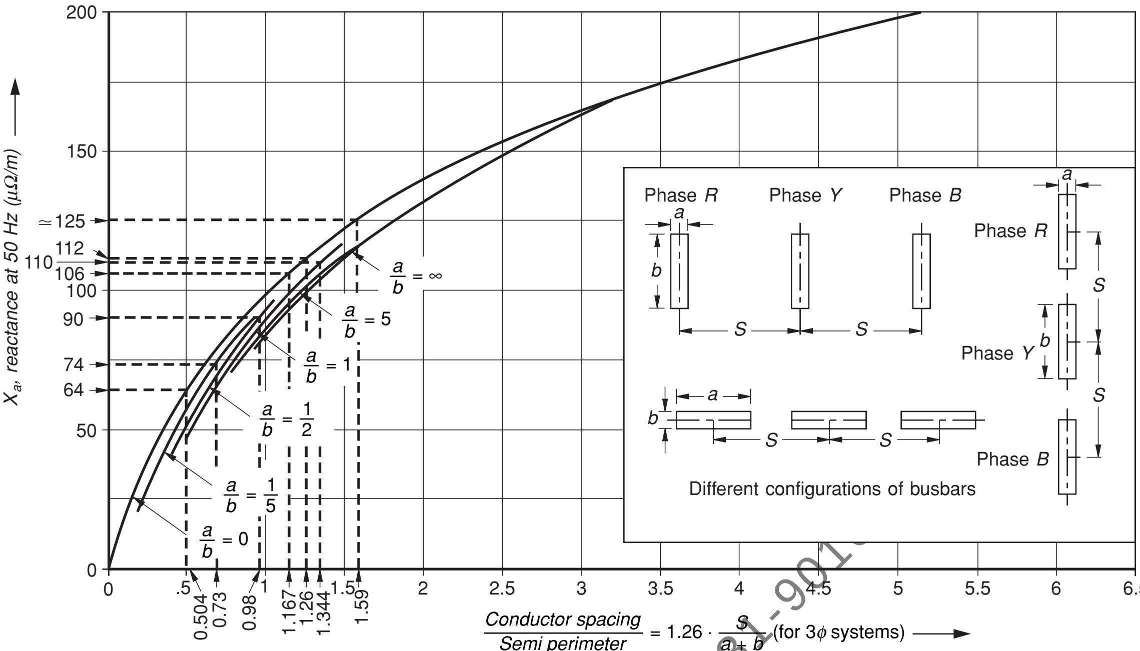
(iii) Voltage drop

If we consider the average current-carrying capacity of this section as 1000 A, after normal deratings (without a derating 1235 A from Table 30.4), then the voltage drop during normal running, say, for a 150 m length of this section of busbar

$$= 1000\text{ A} \times 0.12 \times \frac{150}{1000}\text{ volts}$$

$$= 18.0\text{ V}$$

which is around 4.3% of a 415 V system. Such a high voltage drop, although less than 5% and normally permissible, may not be advisable in this case, since in addition to this drop there



Note
Lesser the spacing 'S' between the phase conductors lesser is the reactance 'X_a' of the conductors.

Figure 28.24 Reactance of rectangular busbars at 50 Hz on account of proximity effect

may be further voltage drops in the connecting cables, resulting in a higher drop than 5% up to the connected load. It is also possible that the voltage at the receiving end itself is already a little less than rated, due to drops in the upper network.

This example is considered only to emphasize the significance of voltage drops in current-carrying conductors, particularly when the system load is high and the end distribution is distant from the receiving end. In normal practice, however, consideration of a voltage drop in a bus system may not be of much significance, due to the generally short lengths of the bus ducts, which may not be more than 30–40 m in most of installations, irrespective of the size of the feeding transformer. However, if such a situation arises, as in this particular instance, one may reduce the content of X_a by reducing S if permissible, or consider the next higher cross-section of busbars. This size of bus section, in this particular instance, may be considered for a current rating up to 800 A.

Example 28.9
Consider Example 28.7 to determine the effect of proximity:
(i) For the configuration of Figure 28.17(a)

$$\frac{a}{b} = \frac{44.45}{101.60} = 0.4375$$

$$1.26\,\frac{S}{a+b} = 1.26 \times \frac{184.45}{44.45 + 101.60} \simeq 1.59$$

then X_a, due to the proximity effect from the graph of Figure 28.24,

$\simeq 125\ \mu\Omega/\text{m}$

or $0.125\ \Omega/1000$ m per phase and

$R_{ac} = 18.62 \times 10^{-3}\ \Omega/1000$ m

(ii) impedance, $Z = \sqrt{0.0186^2 + 0.125^2}$

$= 0.126\ \Omega/1000$ m per phase and

(iii) voltage drop, considering a length of busbars as 40 m and current rating as 2000 A,

$$= 2000 \times 0.126 \times \frac{40}{1000}$$

$= 10.08$ V which is 2.43% for a 415 V system

The bus system is therefore suitable to carry 2000 A up to a length of 40 m. Beyond this the voltage drop may become higher than permissible and the bus rating may call for a derating.

Note
The rating for this section considered here as 2000 A, is hypothetical and must be checked for the various design parameters as discussed already, in Sections 28.5 and 28.6, and analysed in Example 28.12.

Use of a saturable reactor (choke) to balance a large unbalanced power distribution system

Determining the size of reactor

Consider a three-phase bus system as shown in Figure 28.27. If X_s and X_p are the inductive reactances of each phase on account of skin and proximity effects respectively, then the impedances of each of the three phases can be expressed as

$$\overline{Z_R} = \overline{R} + \overline{X_s} + \overline{X_p} = \overline{Z}$$

$$\overline{Z_Y} = \overline{R} + \overline{X_s} = \overline{Z} - \overline{X_p}$$

(since the Y phase will have no proximity effect) and $Z_B = \bar{R} + \bar{X}_s + \bar{X}_p = \bar{Z}$

Therefore inductive reactance equal to X_p must be introduced into the Y phase to equalize the reactance distribution and make the system balanced (Figure 28.25).

If I_r, I_y and I_b are the currents in the three phases and V_{ph} the phase voltage then

$$I_r = I_b = I_r \text{ (say)}$$

and $$I_r = \frac{V_{ph}}{Z} \quad \text{or} \quad Z = \frac{V_{ph}}{I_r}$$

and $$I_y = \frac{V_{ph}}{(\bar{Z} - \bar{X}_p)}$$

$$= \frac{V_{ph}}{\left(\dfrac{V_{ph}}{I_r} - X_p\right)}$$

(Basically these are all phasor quantities but for ease of illustration absolute values are considered)

or $$I_y = \frac{I_r \cdot V_{ph}}{(V_{ph} - I_r \cdot X_p)}$$

$$V_{ph} - I_r X_p = \frac{I_r \cdot V_{ph}}{I_y}$$

$$I_r \cdot X_p = V_{ph} - \frac{I_r \cdot V_{ph}}{I_y}$$

or $$X_p = V_{ph}\left(\frac{1}{I_r} - \frac{1}{I_y}\right) = 2\pi \cdot f \cdot L \qquad (28.8)$$

The values of I_r and I_y must be known to determine the value of the reactor, X_p. Otherwise the reactance, X_a, as determined earlier, to account for the proximity effect may be considered as the lost reactance in the Y phase and for which the reactor may be designed for this phase.

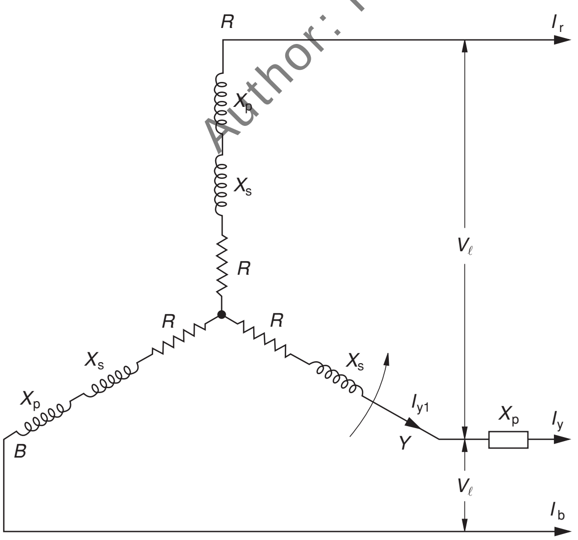


Figure 28.25 Distribution of inductive reactance and impedance of each phase in a three-phase system

Designing a reactor

The self-inductance

$$L = \frac{\phi \cdot Z_c}{I_r} \text{ henry}$$

where
L = self-inductance of the choke in henry (H)
ϕ = flux produced in Weber (wb)
I_r = rated current in Amps
Z_c = number of turns in the choke = 1
(since it will be used like a bar primary, as shown in Figure 28.27)

Total reluctance R_1 of the magnetic circuit of the choke

$$= \frac{\text{MMF}}{\phi} = \frac{Z_c \cdot I_r}{\phi}$$

since $$\phi = \frac{L \cdot I_r}{Z_c}$$

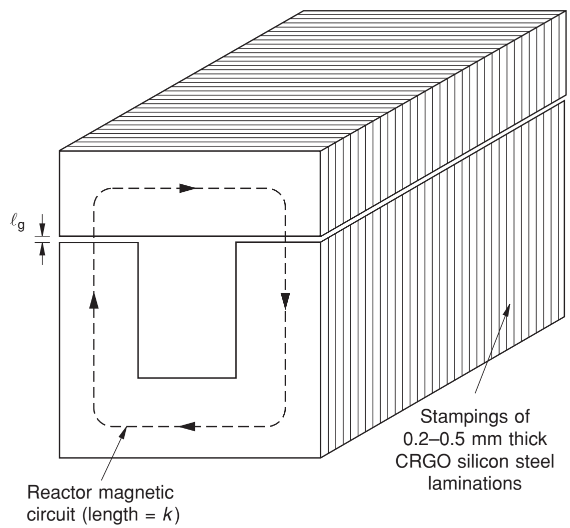
$$\therefore \quad R_1 = \frac{Z_c \cdot I_r}{L \cdot I_r} \cdot Z_c \quad \text{or} \quad \frac{Z_c^2}{L}$$

The total reluctance of an iron choke (Figure 28.26) can also be expressed by $R_1 = R_{air} + R_{core}$
where R_{air} = reluctance of the air gap

$$= \frac{2\ell_g}{\mu_0 A}$$

and R_{core} = reluctance of the iron path

$$= \frac{k - 2\ell_g}{\mu_o \cdot \mu_r \cdot A}$$



ℓ_g – Variable air gap, say, 1.5 mm to 5.0 mm

Figure 28.26 A typical reactor core

$$\therefore \qquad R_1 = \frac{2\,\ell_g}{\mu_o \cdot A} + \frac{k - 2\,\ell_g}{\mu_o \cdot \mu_r \cdot A} \qquad (28.9)$$

where
ℓ_g = length of the air gap in metres (Figure 28.26)
μ_o = permeability* of air (free space) = $4\,\pi \cdot 10^{-7}$ H/m
μ_r = relative permeability of the silicon steel used for the laminations in H/m
A = area of cross-section of core in square metres
k = total length of the magnetic circuit in metres

$$\text{or} \qquad R_1 - \frac{k}{\mu_o \cdot \mu_r \cdot A} = \frac{2\,\ell_g}{\mu_o \cdot A}\,[1 - 1/\mu_r]$$

$$\text{or} \qquad \frac{(R_1 \cdot \mu_o \cdot \mu_r \cdot A - k)}{\mu_o \cdot \mu_r \cdot A} = \frac{2\,\ell_g(\mu_r - 1)}{\mu_o \cdot \mu_r \cdot A}$$

$$\text{or} \qquad \ell_g = \frac{(R_1 \cdot \mu_o \cdot \mu_r \cdot A - k)}{2 \cdot (\mu_r - 1)}$$

where

$$\mu_r = \frac{\mu}{\mu_o}$$

and μ is a design parameter for the silicon steel and $= B/H$.

where
B = flux density in wb/m^2
and H = magnetic field strength in A/m

It may be observed that the value of permeability is a function of the flux density being attained to energize the magnetic circuit. It is therefore not a constant parameter and is measured at a particular flux density.

Example 28.10
Consider a bus duct having a rated current of 4000 A and an unbalanced current in the middle phase of 4400 A. Determine the size of the reactor to achieve a balanced voltage system.

Solution
If the line voltage = 440 V

then $V_{ph} = 440/\sqrt{3} = 254$ V

$$\therefore\ X_p = 254 \times \left(\frac{1}{4000} - \frac{1}{4400}\right)$$

$$= \frac{254 \times 400}{4000 \times 4400}\ \Omega$$

$= 0.00577 = 2 \times \pi \times 50 \times L$ (for a 50 Hz system)

$$\text{or} \quad L = \frac{0.00577}{2 \times 3.14 \times 50}\ \text{H}$$

$$= 18.38 \times 10^{-6}\ \text{H}$$

$$\therefore \text{ Total flux } \phi = \frac{L \times I_r}{Z_c}$$

i.e.
$$\phi = \frac{18.38 \times 10^{-6} \times 4000}{1}\ \text{wb}$$

$$= 73.52 \times 10^{-3}\ \text{wb}$$

Therefore area of cross-section of the core

$$A = \frac{\phi}{B}$$

$$= \frac{73.52 \times 10^{-3}}{1.1}\ (\text{assuming } B = 1.1\ \text{wb/m}^2)$$

$= 66.84 \times 10^{-3}$ square metres.

If we assume the stacking factor of the core laminates to be 0.9, the gross cross-sectional area of the core

$$A = \frac{66.84 \times 10^{-3}}{0.9}$$

or 74.27×10^{-3} square metres

or 74270 mm^2

Assuming the width of the laminates to be 150 mm and the depth of the core as d (Figure 28.27),

$\therefore$ Area of cross-section of the choke = $150 \cdot d = 74270$

$$\text{or} \quad d = \frac{74\,270}{150}$$

$= 495$ (say, 500 mm)

$\therefore\ A = 150 \times 500 = 75\,000$ mm^2 or 0.075 m^2

The size of the opening will depend upon the width and height required by the current-carrying conductors. Say, for six numbers 152.4 mm × 6.35 mm busbars, as shown in Figure 28.27, an opening of 170 mm × 250 mm will be adequate.

To determine the value of μ, the saturation or the B–H curve of the silicon steel being used must be available.

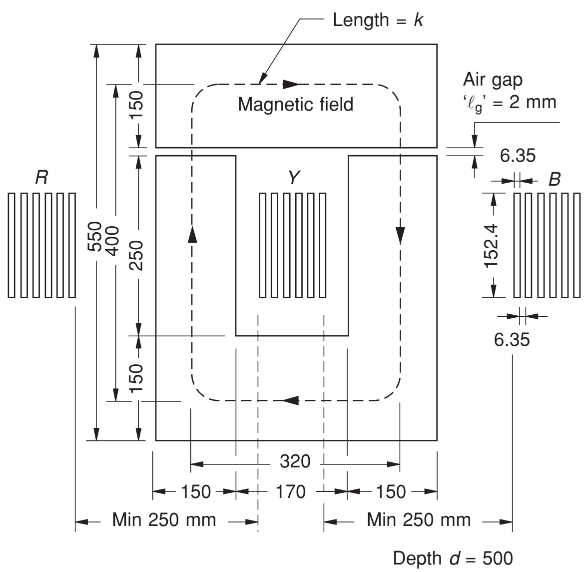


Figure 28.27 Design of a reactor for a power distribution bus system. Illustrating Example 28.10

*Permeability defines the magnetic property of a material, and is a measure of how easily it can be magnetized. The greater the permeability of a material, the easier it is to magnetize.

Assuming a normal flux density for such a core to be 1.1 wb/ m^2 (see also Section 1.9) and making use of a normal B–H curve as shown in Figure 28.28, the corresponding value of H for a value of B as 1.1 wb/m^2 can be read as 200 A/m,

$$\therefore \quad \mu = \frac{B}{H} = \frac{1.1}{200} = 0.0055 \text{ H/m}$$

and $\mu_r = \dfrac{\mu}{\mu_o}$

$$\therefore \quad \mu_r = \frac{0.0055}{4\pi \times 10^{-7}}$$

$$= 4378 \text{ H/m}$$

length of magnetic circuit

$$k = 2(320 + 400) + 2 \cdot \ell_g$$

$$\simeq 2 \times 720 \text{ mm or } 1.44 \text{ m}$$

and $R_1 = \dfrac{Z_c^2}{L}$

$$= \frac{1^2}{18.38 \times 10^{-6}} \text{ H}$$

$$= 5.44 \times 10^4 \text{ H}$$

$\therefore$ Air gap

$$\ell_g = \frac{R_1 \cdot \mu_o \cdot \mu_r \cdot A - k}{2(\mu_r - 1)}$$

$$= \frac{5.44 \times 10^4 \times 4\pi \times 10^{-7} \times 4378 \times 0.075 - 1.44}{2(4378 - 1)}$$

$$= \frac{22.44 - 1.44}{2 \times 4377} \text{ m}$$

$$\simeq 2.4 \text{ mm}$$

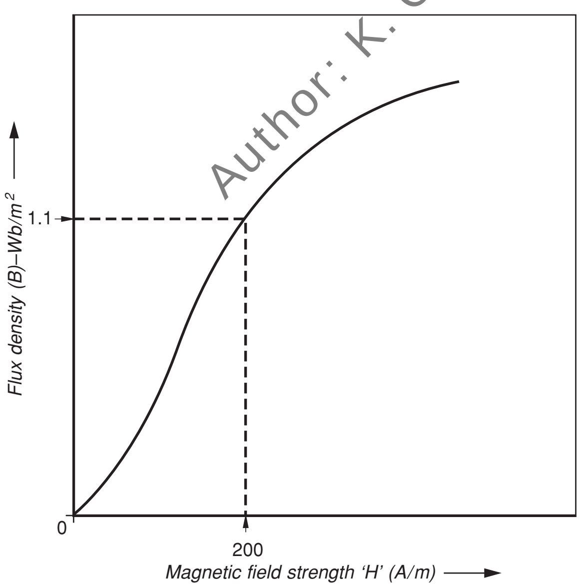


Figure 28.28 A typical magnetic saturation (B–H) curve for CRGO sheets

and weight of the choke

$$W = \text{Volume} \times \text{specific gravity}$$

where

$$\text{Volume} = 1440 \times 150 \times 500 \text{ mm}^3$$

Assuming the specific gravity of the laminates to be $\simeq$ 8.5 g/cm^3

$$\therefore \; W = \frac{1440 \times 150 \times 500}{1000} \times \frac{8.5}{1000} \text{ kg}$$

$$= 918 \text{ kg}$$

28.8.3 Derating due to the proximity effect

We will discuss this aspect in two parts, one for the non-isolated bus systems and the other for the phase-isolated bus systems as in Chapter 31.

Proximity effect on non-isolated bus systems

Drawing inferences from the literature available on the subject (see the Further Reading at the end of the chapter), based on laboratory tests, practical experience and the field data available, deratings for different configurations are shown in Table 28.7 which should be sufficient to account for the likely proximity effects.

Proximity effect on the enclosure

The electric field produced by the current-carrying conductors of each phase also links the metallic bus enclosure, its mounting supports, and structures existing in the vicinity, parallel and around the axis of the current-carrying conductors. It causes induced (parasitic) currents in such structures and leads to the following:

- Resistance losses (I^2R) and
- Magnetic losses.

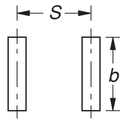
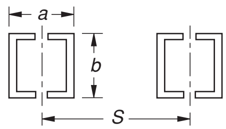
Magnetic losses will constitute the following:

- Eddy current losses ($\propto B^2$, Section 1.6.2.A-iv) and
- Hysteresis losses ($\propto B^{1.6}$, Section 1.6.2.A-iv)

The electrodynamic forces between the enclosure and the conductors will be small because the enclosure, which is non-continuous, will carry much less current than the main conductors. They therefore need not be considered separately, as the metallic structure will have sufficient strength to bear them.

In a non-magnetic enclosure, such as aluminium or stainless steel, there will be only resistance losses. In a magnetic enclosure, such as mild steel (MS), there will also be hysteresis and eddy current losses in addition to resistance losses. All these losses appear as heat in the enclosure and the metallic structures in the vicinity. At higher currents say, 2000 A and above, this phenomenon, particularly with MS enclosures, may assume such large proportions that the enclosure, instead of providing a heat-dissipating surface to the heat generated by the current-carrying conductors inside, may add to their heat. Depending upon the current rating and the configuration of the busbars, the material of the enclosure should be

Table 28.7 Approximate deratings due to proximity effect for different configurations of bus systems

Current rating	*Centre spacing S*	*Approx. derating*
(1) ***Flat busbar*** 		
(I) LV systems		
1 Smaller ratings up to 1600 A	Normal spacings	5%
2 2000–3000 A	(i) $S \geq 4b$ (ii) $S \geq 2b$	5% 15%
3 Larger ratings up to around 6500 A*	$S \geq 4b$	15%
(II) For HV systems 2000–3000 A	Generally $S \geq 4b$	5%
(2) ***For channel sections*** For 2 channels in box form	$S \geq 3a^a$	18%
	$S \geq 4a^a$	11%
	$S \geq 5a^a$	5%
	$S \geq 6a^a$	1%

*Applications:
(i) Required for medium sized turbo-alternators, up to 5 MVA used for captive power generation in a process plant, such as a sugar mill, mostly utilizing its own surplus or waste gases/fuel and steam.
(ii) Small gas and hydroelectric power-generating stations
[a]Channels in box form in smaller sections $a > b$ as shown in Table 30.9.

chosen to minimize these effects as far as possible. It is possible to do this by adopting one or more of the following methods. Since the spacing in an HV system is already large, an HV system is generally not affected by the proximity effects. The following discussion therefore relates primarily to an LV system.

28.8.4 Minimizing the proximity effect

Following are some conspicuous methods to achieve this:

1 *Maintaining greater spacing (S) between the phases*

This can be done by providing adequate clearances (say, ≥ 300 mm) between the conductors and the inside of the enclosure. Table 30.5 and all the other tables in Chapter 30 are based on the fact that the proximity effect is almost negligible at 300 mm from the centre of the current-carrying conductors and the conductor is subject to its self-inductance only. But in thicker sections, or where a number of smaller sections are used together to form a phase, the current will concentrate at the outer surfaces only (skin) rather than the nucleus. Therefore, to achieve an almost zero-proximity effect condition it is desirable to provide a space of 300 mm and more between the extreme outer surfaces, rather than between the centres, as shown in Figure 28.17(b). The condition of $S \geq 4b$ (Table 28.7) will also be almost satisfied by doing so. For still higher currents, this distance must be increased further or a segregated construction adopted (Section 28.2.2). But to keep the phase conductors completely out of the inductive effect of the other phases may require very large enclosures, particularly at higher ratings (above 3200 A or so), which may not be practical.

Below we describe improvised bus systems to limit the reactance and hence the voltage drop and obtain an inductively balanced system to achieve a balanced voltage and equal load sharing by the three phases at the far end.

2 *Phase interleaving*

This is a highly efficient and more practical method for large ratings and offers a very high metal utilization of the conductors. It provides an almost balanced and a low reactance system. Each phase, consisting of a number of conductors, is split into two or more groups and each group of conductors is then rearranged into three or three and a half phases, according to the system requirement, as illustrated in Figures 28.29(a) and (b). It is, however, suggested, to limit the number of groups to only two for considerations of size and the cost of enclosure (for open bus systems, however, such as for large smelters, electroplating and rectifier plants, there may not arise such a limitation).

The two groups would meet the design requirements in most cases. Therefore if four or more flats are used per phase it is not always necessary that as many groups be arranged, unless the current rating of the system is too large to effectively reduce the reactance of the entire system. In four conductors, for instance, two groups, each with two conductors per phase, can be arranged as

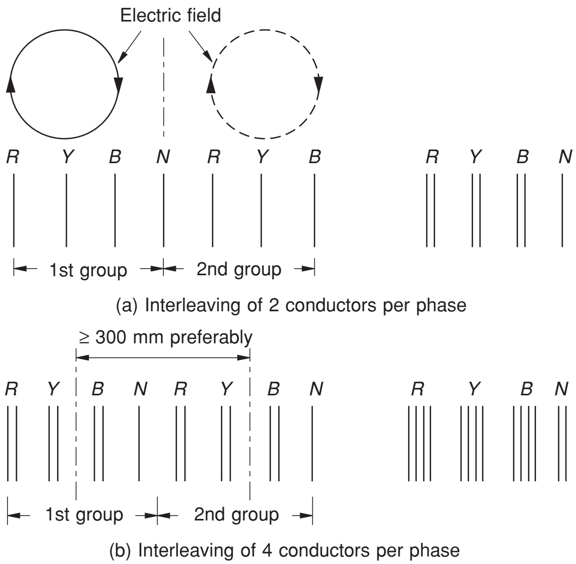


Figure 28.29 Minimizing the effects of skin and proximity through phase interleaving

shown in Figure 28.29(b) to achieve a low reactance system as a result of the smaller spacings between the split phases, on the one hand, and two parallel paths, on the other. The two parallel paths will further reduce the total reactance to one half. The field produced by each split phase would now become half ($\phi \propto I$) and fall out of the inductive region of the other. The arrangement would thus provide a system with a low proximity effect.

Since the conductors in each phase are now arranged as close as di-electrically possible, the electrodynamic forces on each group in the event of a fault on account of the spacing would be high as a result of the smaller spacing between the phase conductors ($F_m \propto 1/S$ Equation (28.4)). But the overall forces would become much less compared to the conventional arrangement because of two or more parallel current paths, each carrying a reduced amount of current, depending upon the number of parallel paths so formed. For two parallel paths, for instance, $F_m \propto 2 \cdot (I_{sc}^2/2)$ or $\propto I_{sc}^2/2$. Generalizing, $F_m \propto$, $1/n$ if n is the number of parallel paths. Moreover, the mounting supports will also become stronger than before, because there are as many mounting supports as the number of parallel paths, each sharing the total force equally. The method of interleaving will therefore require no extra reinforcement of the busbar supports or the mounting structures. (See also Example 28.11.) As a result of the low reactance obtained the arrangement will provide a somewhat inductively balanced system. The reactance of the conductors can be calculated on an individual group basis and then halved when the conductors are split into two halves, or reduced by the number of parallel paths arranged.

The arrangement will also minimize the skin effect to a very great extent, as the current of each phase is now shared by two or more independent circuits, each of a thinner section than a composite phase. It can be considered an improvised version of arrangement 2 in Figure 28.14. The thinner sections (smaller nucleus) will provide a better and more uniform sharing of current by all the conductors. The current rating may now be determined by multiplying the individual current rating of each split phase by the number of parallel circuits. As the space between the two groups of the same phase will now be large, 300 mm or more, they will have nil or only negligible influence of skin effect among themselves.

For instance, a bus system with $4 \times 152.4 \times 6.35$ mm conductors may be arranged into two groups of two conductors each, according to Figure 28.29(b). Then the improved rating of this system as in Table 30.4 will be

$$= 2 \times 2860$$

$$= 5720 \text{ A}$$

as against

- 4240 A for all conductors put together as in Figure 28.33(a) or
- 1.18×4240, i.e. 5003 A when arranged as in arrangement 2 of Figure 28.14.

Thus, in phase interleaving, there will be better utilization of conductor capacity by 5720/5003 or >14% over arrangement 2 in Figure 28.14.

Example 28.11
Consider Example 28.7 again, using four sections of 101.6×6.35 mm Al conductors, now interleaved as shown in Figure 28.30. To determine the improved reactance and resistance of this arrangement we can proceed as follows.

Proximity effect:

$a = 19.05$ mm

$S = 94.05$ mm

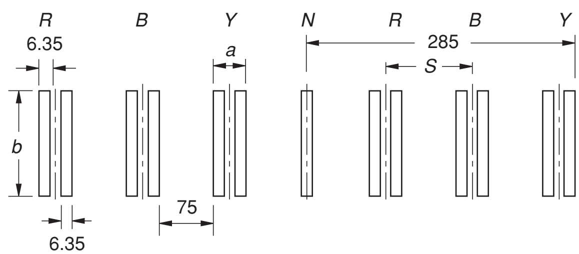
$$\frac{a}{b} = \frac{19.05}{101.6} = 0.1875$$

and space factor, $1.26 \times \dfrac{S}{a+b} = \dfrac{1.26 \times 94.05}{19.05 + 101.6} = 0.98$

X_a from graph of Figure 28.24 = 90 $\mu\Omega$/m

and for two parallel circuits = 90/2

= 45 $\mu\Omega$/m or 0.045 Ω/1000 m



a = 19.05 mm
b = 101.60 mm
S = 94.05 mm
(Depending upon the current rating, it would be advisable to keep it minimum 300 mm, by increasing the gap between the split phases.)

Figure 28.30 Illustrating Example 28.11

as against 125 $\mu\Omega$/m with the conventional arrangement calculated in Example 28.9.

Skin effect
Area of cross-section per split phase = 2 × 101.6 × 6.35

$$= 12.9 \text{ cm}^2$$

$$\frac{b}{a} = \frac{101.6}{19.05} = 5.33.$$

$\therefore \dfrac{R_{ac}}{R_{dc}}$ from the graph in Figure 28.13(a) by interpolation for an EIE-M grade of aluminium $\simeq$ 1.13

$$R_{dc} = 0.056\ \Omega/1000 \text{ m per conductor}$$

$$= 0.056/4\ \Omega/1000 \text{ m for 4 conductors}$$

$$\therefore R_{ac} = 1.13 \times \frac{0.056}{4}$$

$$= 0.0158\ \Omega/1000 \text{ m}$$

$$\therefore \text{Impedance } Z = \sqrt{0.0158^2 + 0.045^2}$$

$$= 0.0477\ \Omega/1000 \text{ m}$$

Voltage drop
Accordingly the revised voltage drop for 40 m of bus length

$$= 2000 \times 0.0477 \times \frac{40}{1000}$$

$$= 3.82 \text{ V}$$

which is even less than 1% for a 415 V bus system.

Electrodynamic forces
For a system fault level of 50 kA maximum forces on each group,

$$F_m = k \cdot \frac{16 \cdot I_{sc}^2}{S} \times 10^{-4} \text{ N/m}$$

(i) For a conventional arrangement (Figure 28.17(a))

k for a space factor of $\dfrac{S-a}{a+b} = \dfrac{184.45 - 44.45}{44.45 + 101.6}$, i.e. 0.958

corresponding to $\dfrac{a}{b}$ of $\dfrac{44.45}{101.6}$, i.e. 0.4375

from the graph in Figure 28.7 by interpolation $k \simeq 0.96$

$$\therefore \quad F_m = \frac{0.96 \times 16 \times 50\,000^2}{184.45} \times 10^{-4}$$

$$= 20\,819 \text{ N/m}$$

(ii) For the improvised interleaving arrangement in Figure 28.30:

k for a space factor of $\dfrac{94.05 - 19.05}{19.05 + 101.6}$, i.e. 0.62 from the graph in Figure 28.7 corresponding to

$\dfrac{a}{b}$ of $\dfrac{19.05}{101.6}$, i.e. 0.1875 $\simeq$ 0.87

$\therefore F_m$ on each set of supports

$$= \frac{0.87 \times 16 \times \left(\dfrac{50\,000}{2}\right)^2}{94.05} \times 10^{-4}$$

$$= 9250.4 \text{ N/m}$$

$$\therefore \quad F_m \text{ on both supports} = 2 \times 9250.4$$

$$= 18\,500.8 \text{ N/m.}$$

This is less than the force developed with the conventional arrangement in Figure 28.17(a).

3 *Phase transposition*

In this arrangement the three-phase conductors are evenly transposed in a length of busbars by interchanging their physical location so that each phase is under an equal inductive effect (proximity effect) produced by the other two phases. The arrangement is illustrated in Figure 28.31. This can be performed by arranging a straight length of a bus into three equal sections (or in multiples of three), as shown. If x is the reactance of phases R and B, and y that of phase Y in the first section, then phases B and Y will have reactance x and R a reactance y in the second section. In the third section, phases Y and R will have a reactance of x each and phase B will have a reactance y. Hence, the reactance of each phase, at the end of the three lengths, will be balanced at $(2x + y)$, causing equal load sharing and an equal voltage drop in all three phases. This arrangement would thus make the system almost balanced inductively by each phase having equal exposure to the inductive fields produced by the other two phases. Due to inductive balancing, the transposition equalizes the reactances in each phase and improves the current sharing by all the three phases, besides an equal voltage drop through the length of the bus.

However, there may not be an appreciable improvement in the proximity effect between each section (it is not required also), unless the transpositions are increased infinitely, as in the case of a stranded three-phase cable which has continuously twisted conductors and represents an ideal transposition. In addition, there is no change in the skin effect. This arrangement therefore has the purpose primarily of achieving an inductively balanced system and hence a balanced sharing of load and equal phase voltages at the far end.

Phase transposition boxes are made separately and installed at reasonable distances to provide an inductively balanced system. This technique is found very useful in dealing with inductive interferences in communication lines (Section 23.5.2(D)). Similar arrangement is practised in EHV high rating XLPE cables also. See Figure A16.6.

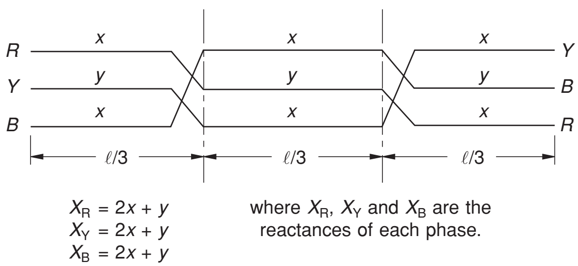


Figure 28.31 Balancing of reactances through phase transposition

4 *Changing the configuration of busbars*

By arranging the busbars into a few more configurations along the lines discussed above it is possible to reduce the proximity effect to a great extent. Some of these configurations are illustrated in Figure 28.14. See also Example 28.12, illustrating the marked improvement in the capacity utilization of the busbars by using different configurations.

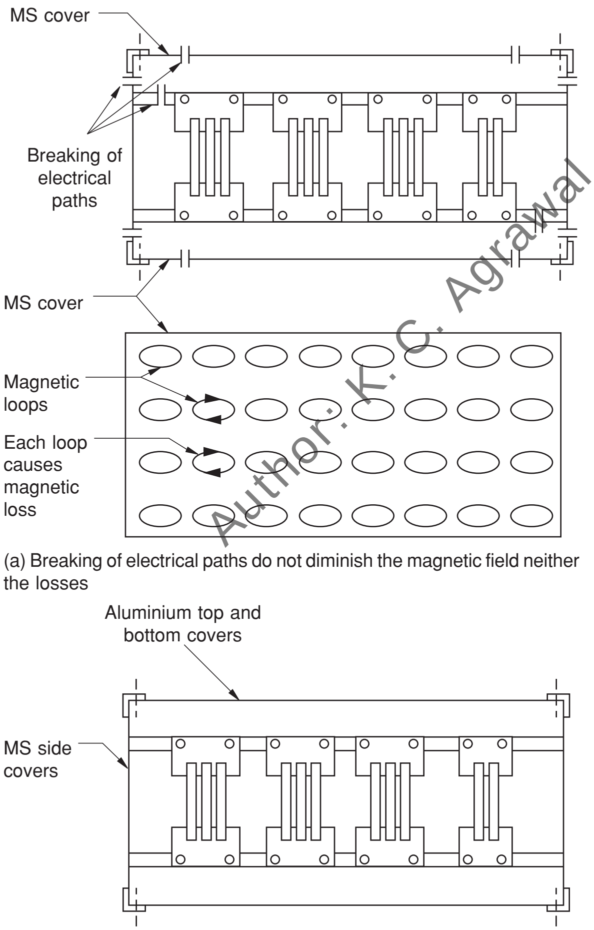
5 *Busbar enclosure*

- Non-magnetic enclosure. The proximity effect can also be minimized by using a non-magnetic enclosure of aluminium or stainless steel. In magnetic materials the field in the enclosure is produced in the form of small magnetic loops. Its effect cannot be mitigated by breaking the electrical path alone, as illustrated in Figure 28.32. Its effect can be diminished only by replacing a few parts of the magnetic enclosure itself, such as its top or bottom covers or both, with a nonmagnetic material. It is possible to achieve an economical and low-loss enclosure by replacing only its top and bottom covers with a non-magnetic material. The covers constitute the larger part of the surface area of the enclosure.
- By providing adequate louvres in the enclosure as shown in Figure 28.33(b) or by using a forced-air draught through the length of the enclosure.

6 *Using non-conventional bus systems (Section 28.2.6)*

28.8.5 Energy saving

In today's energy scenario and global warming energy saving by all heat generating equipment and devices is desirable even mandatory as discussed in Section 1.19. In busbar systems also, like for cables, it is recommended to choose at least the next higher busbar size to reduce resistance losses (I^2R) (higher the cross-section lower the conductor resistance and the heat generated). So also by using thinner cross-sections and large surface busbars.



(a) Breaking of electrical paths do not diminish the magnetic field neither the losses

(b) An economical and low loss enclosure

Figure 28.32 Magnetic field in a magnetic material

28.9 Sample calculations for designing a 2500 A non-isolated phase aluminium busbar system

Example 28.12
Design parameters

Supply system three-phase four-wire 415 V ± 10%, 50 Hz ± 3%	
Fault level	45 kA
Duration of fault	1 second
Continuous current rating	2500 A
Ambient temperature	50°C
Maximum permissible operating temperature	85°C
Permissible final temperature at the end of the fault	185°C

(A) Rectangular sections

(i) ***Minimum size of busbars for short-circuit conditions***
The minimum size of busbars for an operating temperature of 85°C and a final temperature of 185°C can be ascertained from the curves of Figure 28.5, suggesting

$$\frac{I}{A} \cdot \sqrt{t} = 0.0799$$

or $$A = \frac{45}{0.0799} \cdot \sqrt{1}$$

$$= 563.2 \text{ sq. mm.}$$

Maximum temperature rise of the busbars at the rated current

$= 85 - 50$

$= 35°C$

Assume the temperature of the busbars at the time of fault = 85°C and rectangular flats of electrolytic grade E-91E or its equivalent. Busbars chosen for each phase – four (152.4 mm × 6.35 mm) – which are more than the minimum size required to account for the thermal effects during a short-circuit condition,

for neutral – two (152.4 mm × 6.35 mm)

Size of busbar enclosure – 870 mm × 380 mm (Figure 28.33(b)).
Material of enclosure – aluminium
Busbar configuration – as in Figure 28.33(a)
Busbar support made of SMC or DMC (Section 13.6.1(iii)).
Distance between two busbar supports: 400 mm (Figure 28.33(b))

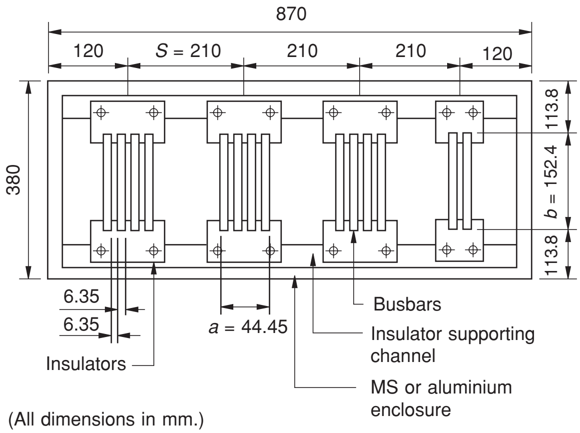


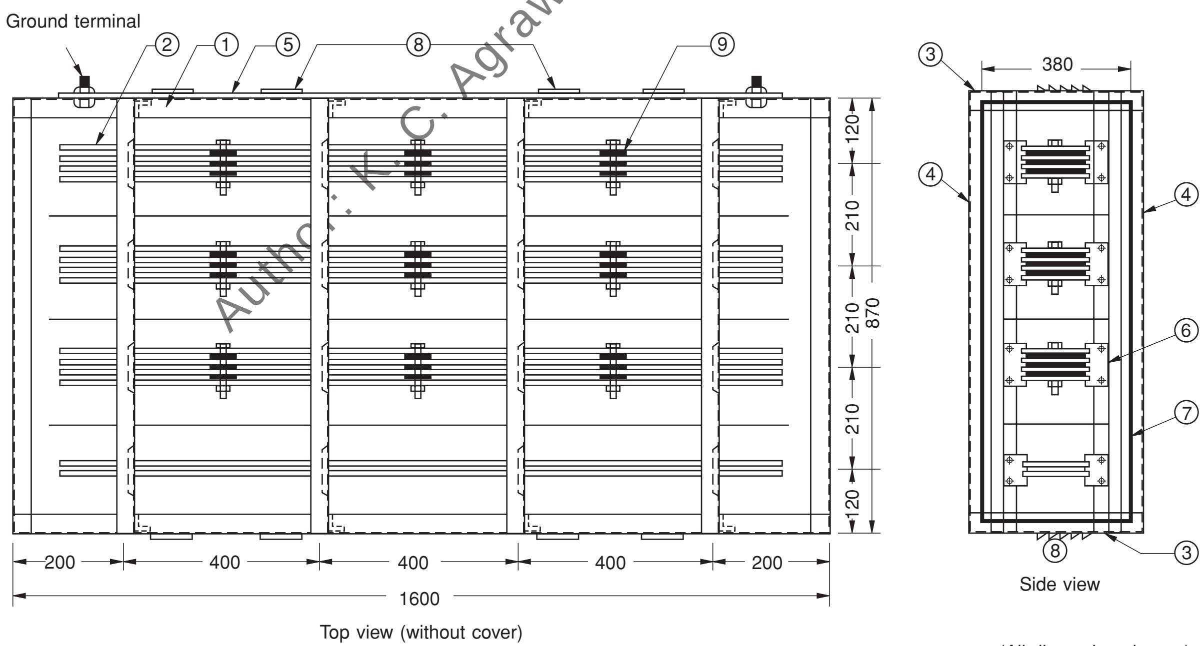
Figure 28.33(a) Busbar arrangement and enclosure size for bus duct of Example 28.12

(ii) ***Data available***
Aluminium busbars, from Tables 30.4 and 30.6
Current rating = 4240 A
Electrical conductivity = 1
Minimum tensile strength = 2050 kgf/cm^2 (Table 30.1)
Minimum cross-breaking or yield strength = 1650 kgf/cm^2 (Table 30.1)
Busbar supports: from Table 13.14

Mechanical properties	*DMC in kgf/cm^2*	*SMC in kgf/cm^2*
Minimum tensile or shearing strength	250–500	500–900
Minimum compressive strength	1200–1800	1600–2000
Minimum cross-breaking or flexural strength (bending strength)	700–1200	1400–1800

Hardware

Mechanical properties	*High tensile (HT) fasteners as in ISO 4014 and ISO 898, grade 8.8*	*Ordinary MS (mild steel) fasteners as in ISO 4016, grade 4.6*
Minimum tensile strength	8000 kgf/cm^2	4000 kgf/cm^2
Minimum cross-breaking or yield strength	4400 kgf/cm^2	2200 kgf/cm^2



Legend
1. M.S. angle
2. Al. bus 4 × 152.4 × 6.35 mm
3. Side frames 2 mm M.S. or 3 mm Al.
4. Bottom and top covers 2 mm M.S. or 3 mm Al.
5. Ground bus 50 × 6 mm Al
6. Insulators
7. Gasket
8. Louvres
9. Metallic spacers

Figure 28.33(b) General arrangement of a typical running section of the bus duct of Figure 28.33(a) *(iii)* ***Deriving the actual current rating***

Applicable deratings:

- Due to higher ambient temperature
  For 50°C as in Table 28.3 and Figure 28.10 = 0.815
- Due to altitude
  Nil, since the installation of the equipment is assumed to be within 2000 m above the mean sea level
- Due to grade of busbars
  For E-91E or its equivalent, as in Table 30.6 = 1.0
- Due to size of enclosure and environmental conditions of location
  The Enclosure is of non-magnetic material, therefore it will be devoid of hysteresis and eddy current losses.
  Heat dissipation factor

$$= \frac{\text{Cross-sectional area of active aluminium}}{\text{Area of enclosure}}$$

$$\text{i.e. } \frac{(3 \times 4 \times 152.4 \times 6.35) + (2 \times 152.4 \times 6.35)}{380 \times 870}$$

$$= \frac{14 \times 152.4 \times 6.35}{380 \times 870}$$

$$= 0.041$$

or 4%

  As in Table 28.6, by simple interpolation, for condition of location against serial number 2, derating = 0.77
- Due to skin effect
  Nil, as it is already considered in Tables 30.2, 30.4 and 30.5, while establishing the basic ratings of the busbars.
- Due to proximity effect
  Approximately 20%, since $S < 2b$. It is recommended to have the centre spacing S at least 2×152.4, i.e. 305 mm.

  If the width of the enclosure poses a limitation, a more appropriate configuration such as in Figure 28.34 or the technique of interleaving as in Figure 28.35 may be adopted to achieve better utilization of the active metal. In our calculations we have considered all these alternatives for better clarity.
- Due to voltage variation
  We have already discussed the impact of voltage variation on an industrial drive in Section 1.6.2(A-iii). The impact of this on a bus system may not be the same. A bus may have to supply lighting, heating and other resistive or inductive loads. All such loads except electric motors will perform low at lower voltages and hence draw a lower current. Generally, we can assume that the loading on a bus, as enhanced by the industrial drives, will be almost offset by the decrease of loading by the other loads if we assume industrial drives to be up to 50% of the total connected load. Usually therefore no derating will be necessary for a lower voltage, except for large installations where the drives may constitute the bulk of the load. Consideration of voltage variation will therefore depend

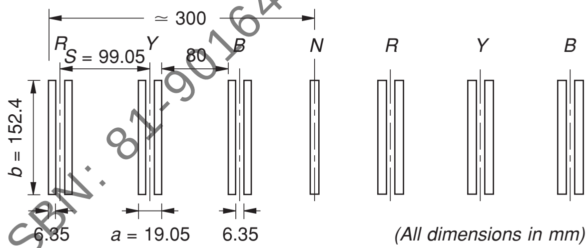
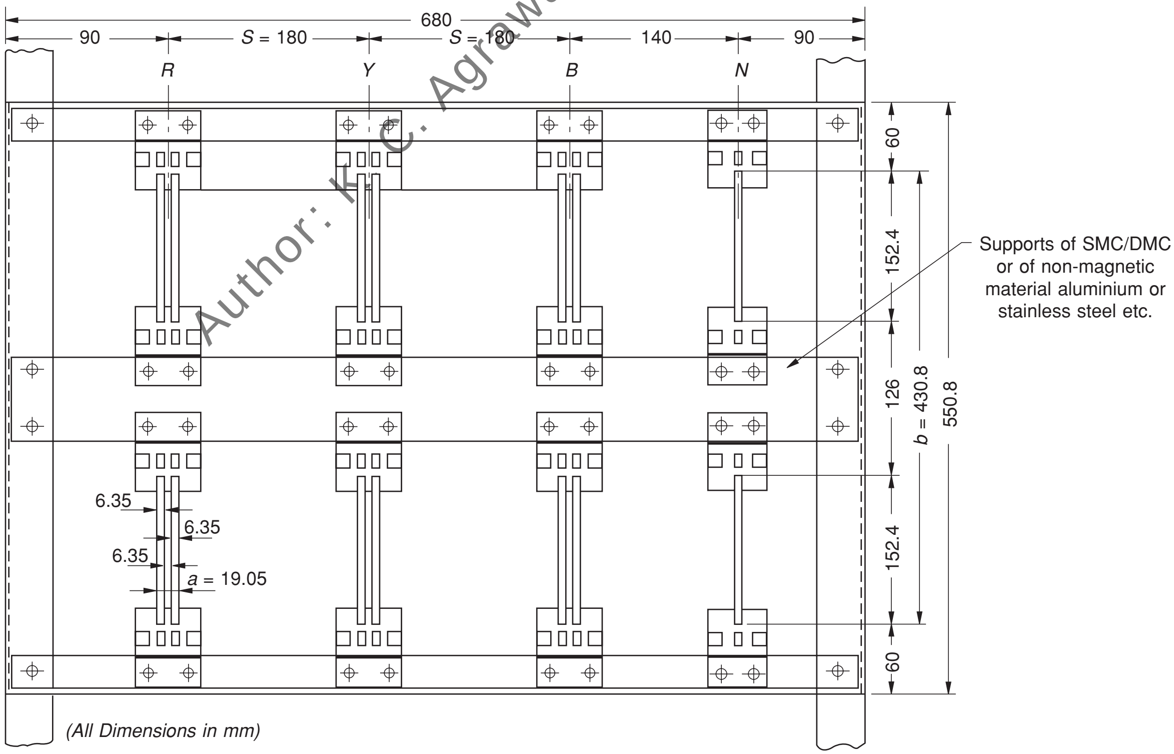


Figure 28.35 For Example 28.12



Note: Horizontal distance between busbar supports = 400 mm (same as in Figure 28.33(b))

Figure 28.34 Illustration of Example 28.12

upon the type of installation. In our calculations, however, we are ignoring the impact of this.

- Frequency variation
  At higher frequencies up to 3% skin and proximity effects would be slightly higher, but can be ignored as their impact will be only marginal.

Considering all these deratings the total derating for the configuration of Figure 28.33(a) or (b) will be

$$= 0.815 \times 1 \times 1 \times 0.77 \times 0.8$$

$$= 0.50$$

Basic current rating of 4 × 152.4 mm × 6.35 mm aluminium busbars per phase as in Table 30.4

$$= 4240 \text{ A}$$

∴ Effective rating after considering all possible deratings

$$= 4240 \times 0.5$$

$$= 2120 \text{ A}$$

These sections of busbars are not adequate for the required current rating of 2500 A. The rating of the bus system can, however, be improved by almost 20% and make it suitable for the required rating by providing the busbars and the inside of the enclosure with a non-metallic, matt finish black paint. If voltage variation is also to be considered, then this bus may not be suitable for the required duty even after painting.

(iv) ***Voltage drop***

- R_{dc} for E-91E grade of conductor, from Table 30.7

$$= 32.38 \ \mu\Omega/\text{m per conductor at } 20°\text{C}$$

∴ R_{dc} at an operating temperature of 85°C

$$= R_{dc20}\,[1 + \alpha_{20}\,(\theta_2 - \theta_1)]$$

$$= 32.38\,[1 + 0.00363\,(85 - 20)]$$

$$= 32.38\,(1 + 0.236)$$

or $R_{dc} = 40.02 \ \mu\Omega$/m per conductor and

for the phase $= \dfrac{40.02}{4}$ or $10.005 \times 10^{-3} \ \Omega/1000$ m

- Area of cross-section per phase $= 4 \times 152.4 \times 6.35 \text{ mm}^2$

$$= 38.71 \text{ cm}^2$$

For this area of cross-section, the skin effect ratio R_{ac}/R_{dc} from Figure 28.13(a) for aluminium grade E-91E at 85°C, having $b/a = 152.4/44.45 \simeq 3.43$ measures almost 1.425 by approximating the interpolation,

$$\therefore \quad R_{ac}/R_{dc} = 1.425$$

i.e. an increase of almost 42.5%, due to the skin effect alone.

$$R_{ac} = 10.005 \times 10^{-3} \times 1.425$$

$$= 14.257 \times 10^{-3} \ \Omega/1000 \text{ m per phase}$$

- Proximity effect

Measure reactance X_a from Figure 28.24 for

$$1.26 \times \frac{S}{a+b} = 1.26 \times \frac{210}{44.45 + 152.4}$$

i.e. 1.344, as in the curve, corresponding to a/b, as

$\dfrac{44.45}{152.4}$ i.e. 0.29,

$X_a = 110 \ \mu\Omega$/m per phase or $110 \times 10^{-3} \ \Omega/1000$ m per phase.

- Impedance,

$$Z = \sqrt{(14.257^2 + 110^2)} \times 10^{-3}$$

$$= 0.111 \ \Omega/1000 \text{ m per phase}$$

- For a 50 m length of bus duct this impedance will cause a voltage drop of

$$2500 \times 0.111 \times \frac{50}{1000} = 13.9 \text{ V}$$

which is 3.3% of the rated voltage and is therefore acceptable. For higher bus lengths, however, which may be rare, while the current rating of the system selected will be suitable the voltage drop may exceed the recommended limits. In this case it will be advisable to adopt the alternative configuration of Figure 28.34 or the technique of interleaving (Figure 28.35). A comparison is drawn for these configurations as in Table 28.8, which reveals that both alternatives significantly improve the performance of the same bus section.

(v) ***Effect of proximity on the centre phase Y***

For a length of 50 m the voltage drop in phase Y, due to R_{ac}, and assuming the content of $X_a \simeq 0$

$$= 2500 \times 14.257 \times 10^{-3} \times \frac{50}{1000}$$

$$= 1.78 \text{ V}$$

∴ Receiving side voltage of phases R and B

$$= \frac{415}{\sqrt{3}} - 13.9$$

$$= 225.7 \text{ V}$$

and of phase $Y = \dfrac{415}{\sqrt{3}} - 1.78$

$$= 237.8 \text{ V}$$

The imbalance for this length and rating of bus system is not substantial, yet if we assume that a balanced supply source is desirable, then we must make up the lost inductance in phase Y by inserting a reactor into this phase, as discussed in Section 28.8.2 of an equal value of X_a, i.e.

$$X_a = 110 \times 10^{-3} \times \frac{50}{1000} = 0.0055 \ \Omega$$

(vi) ***Calculation for short-circuit effects***

Electrodynamic forces

These can be determined from Equation (28.4),

$$F_m = \frac{16 \cdot I_{sc}^2 \cdot k \cdot 10^{-4}}{S} \text{ N/m}$$

where

I_{sc} = r.m.s. value of fault current in Amperes = 45 000 A

k = space factor for rectangular conductors, determined from the curves of Figure 28.7, corresponding to

$$\frac{S-a}{a+b}, \quad \text{i.e.} \quad \frac{210 - 44.45}{44.45 + 152.4}$$

or 0.84

corresponding to the curve for $a/b = 44.45/152.4$ or 0.29

Table 28.8 Calculation of electrodynamic forces

Description	*Arrangement as in Figure 28.33(a)*	*Arrangement as in Figure 28.34*	*Interleaving as in Figure 28.35*
Basic current rating without derating	4240 A	4240×1.57 = 6657 A (Fig. 28.14)	2×2860 (2860 A is the rating of one split phase Table 30.4) = 5720 A
Effective current rating considering approximately the same deratings	0.5×4240 = 2120 A	0.5×6657 = 3328 A[a]	0.5×5720 = 2860 A[a]
Proximity effect			**On per split phase basis**
$\frac{a}{b}$	$\frac{44.45}{152.4} = 0.29$	$\frac{19.05}{430.8} = 0.044$	$\frac{19.05}{152.4} = 0.125$
$1.26 \frac{S}{a+b}$	$\frac{1.26 \times 210}{44.45 + 152.4} = 1.344$	$\frac{1.26 \times 180}{19.05 + 430.8} = 0.504$	$\frac{1.26 \times 99.05}{19.05 + 152.4} = 0.73$
[b]Approx. X_a from Figure 28.24	110 $\mu\Omega$/m	64 $\mu\Omega$/m	74 $\mu\Omega$/m per circuit. Since there are two parallel circuits, $\therefore$ Combined $X_a = 37\ \mu\Omega$/m
Skin effect			
Area of cross-section	$4 \times 152.4 \times 6.35$ = 38.71 cm^2	$4 \times 152.4 \times 6.35$ = 38.71 cm^2	$2 \times 152.4 \times 6.35$ = 19.35 cm^2 (per circuit)
$\frac{b}{a}$	$\frac{152.4}{44.45} \simeq 3.43$	$\frac{430.8}{19.05} = 22.6$	$\frac{152.4}{19.05} = 8$
Approx. $\frac{R_{ac}}{R_{dc}}$ from Figure 28.13(a)	1.425	1.3	1.18
R_{dc} at 85°C as calculated in step iv	40.02 $\mu\Omega$/m per conductor	40.02 $\mu\Omega$/m per conductor	40.02 $\mu\Omega$/m per conductor
$\therefore R_{ac}$	$= \frac{1.425 \times 40.02}{4}$ = 14.257 $\mu\Omega$/m	$= \frac{1.3 \times 40.02}{4}$ = 13.01 $\mu\Omega$/m	$= \frac{1.18 \times 40.02}{4}$ (for both circuits) = 11.81 $\mu\Omega$/m
Impedance Z	$\sqrt{110^2 + 14.257^2}$ = 111 $\mu\Omega$/m	$\sqrt{64^2 + 13.01^2}$ = 65.31 $\mu\Omega$/m	$\sqrt{37^2 + 11.81^2}$ = 38.84 $\mu\Omega$/m
Voltage drop	$2500 \times 50 \times 111 \times 10^{-6}$ = 13.9 V	$2500 \times 50 \times 65.31 \times 10^{-6}$ = 8.16 V	$2500 \times 50 \times 38.84 \times 10^{-6}$ = 4.85 V
as % of system voltage	$\frac{13.9}{415} \times 100 \simeq 3.3\%$	$\frac{8.16}{415} \times 100 = < 2\%$	$\frac{4.85}{415} \times 100 \simeq 1.1\%$
Electrodynamic forces			
$\frac{S-a}{a+b}$	$\frac{210 - 44.45}{44.45 + 152.4} = 0.84$	$\frac{180 - 19.05}{19.05 + 430.8} \simeq 0.358$	$\frac{99.05 - 19.05}{19.05 + 152.4} = 0.47$
$\frac{a}{b}$	$\frac{44.45}{152.4} = 0.29$	$\frac{19.05}{430.8} = 0.044$	$\frac{19.05}{152.4} = 0.125$
k from Figure 28.7	0.93	0.7 (considering curve for $a/b = 0.1$)	0.77
F_m in N/m	$\frac{16 \times (45\,000)^2 \times 0.93}{210} \times 10^{-4}$ = 14,348.6	$\frac{16 \times {}^{c}(45000)^2 \times 0.7}{180} \times 10^{-4}$ = 12 600	$\frac{16 \times 2 \times \left(\frac{45000}{2}\right)^2 \times 0.77}{99.05} \times 10^{-4}$ = 12593.64
In kgf/m	1463.1	1285	1284

(Contd.)

Table 28.8 *(Contd.)*

Description	*Arrangement as in Figure 28.33(a)*	*Arrangement as in Figure 28.34*	*Interleaving as in Figure 28.35*
Forces on each set of busbar insulators and mounting fasteners, when 400 mm apart	= 1463.1 × 0.4 = 585.24 kgf	= 1285 × 0.4 = 514 kgf	= 1284 × 0.4 = 513.6 kgf

[a]These arrangements of bus systems are suitable for higher load demands also at –10% voltage if it is an industrial installation where most of the loads are industrial drives.
[b]It is noticeable that as the configuration of busbars improves, the 'X_a' improves (decreases) and so improves the metal utilization. Interleaving has worked out the best with least 'X_a' nearly equal to the reactance of single section (at more than 300 mm spacing) divided by number of sections i.e., $\simeq \frac{134.51}{4}$ or 33.6 μΩ/m (Table 30.7).
[c]We have considered each phase composed of four bus sections to calculate F_m, to be on the safe side. In fact the current of each phase is split into two circuits in this arrangement similar to the arrangement of interleaving and hence the actual F_m will also be only half that considered above.

Assuming the curve for $a/b = 0.25$ with little error, $k = 0.93$

As in Figure 28.33(a) S = centre spacing between two phases = 210 mm
a = space occupied by the conductors of one phase = 44.45 mm
b = width of the busbars = 152.4 mm

$$\therefore \quad F_m = \frac{16 \times (45\,000)^2 \times 0.93}{210} \times 10^{-4} \text{ N/m}$$

$$\simeq 14\,348.6 \text{ N/m}$$

$$1 \text{ N/m} = \frac{1}{9.807} \text{ kgf/m}$$

$$\therefore \quad F_m \simeq 1463.1 \text{ kgf/m}$$

Since the busbar supports are assumed to be at a distance of 400 mm,

∴ force on each section of busbars, insulators and the mounting fasteners

= 1463.1 × 0.4

= 585.24 kg

We have drawn a comparison of these forces for the other busbar configurations in Table 28.8 for more clarity.

Since Figure 28.34 is found to be a better arrangement, we have considered forces as in this arrangement only in all our subsequent calculations.

(vii) ***Mechanical suitability of busbars and their supporting system***

Below we analyse the adequacy and the suitability of busbars, fasteners and the insulators supporting the busbars, to withstand the above forces acting differently at different locations.

Bending stresses on the busbars

$$\text{Bending stress at section } x - x = \frac{F_m \cdot l}{12 \cdot M \cdot N} = \text{kg/cm}^2 \qquad (28.10)$$

where

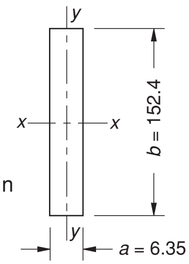
F_m = maximum electrodynamic forces acting on each support, in the event of a fault, as calculated in Table 28.8 for Figure 28.34 = 514 kgf
l = centre distance between two busbar supports = 40 cm
M = sectional modulus of each busbar at section $x - x$

$$= \frac{1}{6}\, a \cdot b^2 \text{ in cm}^3$$

where for a 152.4 mm × 6.35 mm busbar section

a = 6.35 mm

b = 152.4 mm



$$\therefore \quad M = \frac{1}{6} \times \frac{6.35 \times 152.4^2}{1000} \text{ cm}^3$$

$= 24.58 \text{ cm}^3$ (same as indicated in Table 30.7)

N = number of busbars per phase = 4

$$\therefore \text{ Bending stress } = \frac{514 \times 40}{12 \times 24.58 \times 4} \text{ kg/cm}^2$$

$$\simeq 17.43 \text{ kg/cm}^2$$

To calculate the sectional modulus (or moment of resistance) of the four bus sections in parallel we have multiplied the sectional modulus of one bus by 4. This is a simple method when the busbars of each phase are in the same plane and equally spaced as in Figure 28.33(a) with no additional spacers between them to hold them together.

But when other configurations are adopted as shown in Figure 28.34, this concept may not hold true. In other configurations, however, the sectional modulus will only rise and reduce the bending stress on the busbars.

The method adopted to calculate the sectional modulus is therefore simple and on the safe side. However, to calculate the sectional modulus more accurately or to derive it for any other section of the support than considered here reference may be made to a textbook on the strength of materials or a machine handbook.

Note
The sectional modulus, when required, can be increased by providing spacers between the straight lengths of bus sections, as shown in Figure 28.33(b). The spacers, when provided, can make the busbars more rigid and add to their bending strength due to higher sectional modulus. At joints these spacers occur automatically in the form of overlapping of busbars or fishplates (Figures 29.4 and 29.5). The spacers prevent the bus lengths from getting deflected towards each other.

Inference
The minimum shearing strength of aluminium is 1650 kg/cm^2 (Table 30.1) which is much larger than the actual force to which the busbars will be subject, in the event of a fault. They are thus more than adequate in cross-section and numbers. Other than bending stress, there is no significant tensile or shearing force acting on the busbars.

Suitability of fasteners

On fasteners also, other than cross-breaking or shearing stress, there is no significant compressive or bending force.

Fasteners for busbar supports

As in Figure 28.34, each phase of four aluminium sections is supported on four two-way insulators. Each insulator is mounted on 2 × M8 size of bolts (diameter of bolt shank, 8 mm).

$\therefore$ Total number of bolts = 4 × 2 = 8 of size M8

But it is possible that the first peak of the force, F_m, may act either downwards or upwards. In which case only four fasteners would be sharing the force at a time. Stress area of four bolts

$$= 4 \times \frac{\pi}{4} \times 8^2 \text{ sq.mm}$$

$$= 2.01 \text{ cm}^2$$

Cross-breaking strength of

(i) Ordinary MS fasteners as in ISO 4016 of grade 4.6,

$$= 2200 \text{ kg/cm}^2 \text{ (minimum)}$$

$\therefore$ Total force they can withstand considering a factor of safety as 100%

$$= \frac{2.01 \times 2200}{2} = 2211 \text{ kg}$$

(ii) High tensile fasteners as in ISO 4014 and ISO 898 of grade 8.8,

$$= 4400 \text{ kg/cm}^2 \text{ (minimum)}$$

$\therefore$ Total force they can withstand

$$\frac{2.01 \times 4400}{2} = 4422 \text{ kg}$$

In this particular instance, due to the large number of fasteners, even an ordinary type of MS fastener will be suitable.

Notes

1 The above situation may not always be true particularly when the current rating is low, say up to 600 A and the system fault level is still high. In this case much less cross-section of aluminium would be used, and the number of supports and fasteners would also be less. Then the fasteners will also be of smaller cross-sections. In such cases as the magnitude of electrodynamic forces remain the same, the suitability of fasteners becomes more relevant. See illustration of Example 28.6 below.

2 For busbar joints, however, use of high tensile fasteners alone is recommended with a view to ensuring adequate contact pressure per unit area over long periods of operation, as discussed in Section 29.2 and noted in Table 29.1, which an ordinary fastener may not be able to maintain over long periods.

Illustration of Example 28.6 for short-circuit forces

For more clarity on the subject, in the light of note 1 above we have also worked out the earlier Example 28.6, for short-circuit conditions and then analysed the above details for this arrangement (Table 28.9). Assuming

$$I_{sc} = 45 \text{ kA}$$

$$S = 100 \text{ mm (Figure 28.16)}$$

and $k = 0.9$ from graph of Figure 28.7 for

$$\frac{S-a}{a+b} = \frac{100-6.35}{6.35+101.6}$$

$$\simeq 0.87$$

and $a/b = 6.35/101.6$, i.e. 0.0625

Choosing the curve for $a/b = 0.1$. A slight interpolation in this curve will determine k as 0.9 for a/b as 0.0625

$$\therefore\ F_m = \frac{16 \times (45\,000)^2 \times 0.9}{100} \times 10^{-4} \text{ N/m}$$

$$= 29\,160 \text{ N/m}$$

or 2973.4 kg/m

Assuming the distance between each busbar support of the same phase to be 400 mm then the force on each section of busbars, insulators and the fasteners.

$$= 2973.4 \times 0.4 \text{ kg}$$

$$= 1189.36 \text{ kg}$$

Suitability of busbars; for the given parameters:

$$F_m = 1189.36 \text{ kg}$$

$$\ell = 40 \text{ cm}$$

$$M = \frac{1}{6} \times \frac{6.35 \times 101.6^2}{1000} \text{ cm}^3$$

$$\simeq 10.925 \text{ cm}^3 \text{ and}$$

$$N = 1$$

$$\therefore \text{ Bending stress} = \frac{1189.36 \times 40}{12 \times 10.925 \times 1} \quad \text{(from Equation 28.10)}$$

$$= 362.89 \text{ kg/cm}^2$$

which is much less than the cross-breaking strength of aluminium. Therefore size of busbars is ok.The analysis of forces and suitability of insulators is carried out in Table 28.9.

Fasteners for busbar joints

For busbar joints we have considered 8 numbers bolts of size M-10 (diameter of bolt shank, 10 mm), as in Figure 29.4. As the size of these fasteners is greater than that of the busbar supports, their suitability is not determined separately.

Suitability of insulators

The busbar support is the most vulnerable component in a current-carrying system. It has to withstand all kinds of stresses developed by the busbars on a fault. From Figure 28.36 we have identified the following likely vulnerable locations in a support that may yield on the occurrence of a fault;

- Finger between the two busbars, section *a–a*, which may shear off from its roots.
- At the bolt mounting holes section *y–y*.
- At the wedges marked with hatching.

But the insulator is more vulnerable at *a–a*, than at the wedges, since the shear area at *a–a* is only 0.6 × 1.5 cm^2 compared to 1.98 × 1.5 cm^2 at the wedges. Hence, for brevity, we analyse possibilities (i) and (ii) only.

In Table 28.9 we have evaluated the cross-breaking, shearing and bending (flexural) stresses, that may act at such locations, to establish the suitability of the supports used.

Suitability of fasteners

As in Figure 28.36, although each phase will be supported on two insulators and each insulator mounted on 2 × M8 size of fasteners, it is possible that at the instant of fault, the forces are acting either upwards or downwards. Therefore, assuming forces to be acting only on two fasteners, at the instant of fault and assuming a factor of safety as 100%.

Table 28.9 Checking suitability of insulators

	Example 28.12 *Figures 28.34 and 28.36*	*Example 28.6* *Figures 28.16 and 28.37*
1 Cross-breaking stress X_b at section $a - a$	F_m = 514 kgf/cm^2	F_m = 1189.36 kgf/cm^2
$X_b = \dfrac{1.5\, F_m \cdot \ell}{A \cdot B^2}$	ℓ = 1.3 cm	ℓ = 1.3 cm
	A = 1.5 cm	A = 1.5 cm
	B = 0.6 cm	B = 2.24 cm
	$\therefore\ X_b = \dfrac{1.5 \times 514 \times 1.3}{1.5 \times 0.6^2}$	$\therefore\ X_b = \dfrac{1.5 \times 1189.36 \times 1.3}{1.5 \times 2.24^2}$
	= 1856 kgf/cm^2	= 308 kgf/cm^2
Shared by	4 fingers	4 wedges
Factor of safety	100%	100%
$\therefore$ Minimum cross-breaking stress the supports should be able to withstand	$= \dfrac{1856}{4} \times 2$ = 928 kgf/cm^2	$= \dfrac{308}{4} \times 2$ = 154 kgf/cm^2
Inference	Only SMC supports must be used	DMC supports can be used
2 Shearing stress S_s at section $a - a$	$A = 0.6 \times 1.5$ cm^2	$A = 2.24 \times 1.5$ cm^2
$S_s = \dfrac{F_m}{A}$	$\therefore S_s = \dfrac{514}{0.6 \times 1.5}$	$\therefore S_s = \dfrac{1189.36}{2.24 \times 1.5}$
(A = cross-sectional area of section $a - a$)	= 571 kgf/cm^2	= 354 kgf/cm^2
Shared by	4 fingers	4 wedges
Factor of safety	100%	100%
$\therefore$ Min. shearing stress the supports should be able to withstand	$= \dfrac{571}{4} \times 2$ = 285.5 kgf/cm^2	$= \dfrac{354}{4} \times 2$ = 177 kgf/cm^2
Inference	DMC supports may be used but limiting factor is cross-breaking stress hence only SMC supports must be used	DMC supports can be used
3 Bending (cantilever)	L = 3.9 cm	L = 3.9 cm
or flexural stress, B_s at	a = 1.0 cm	a = 1.0 cm
Section y–$y = \dfrac{F_m \cdot L}{M}$	$b = 6 - 2 \times 0.85$ = 4.3 cm	$b = 5.2 - 2 \times 0.85$ = 3.5 cm
where		
$M = \dfrac{1}{6} \cdot a \cdot b^2$	$\therefore\ M = \dfrac{1}{6} \times 1.0 \times (4.3)^2$	$\therefore\ M = \dfrac{1}{6} \times 1.0 \times 3.5^2$
	= 3.08 cm^3	= 2.04 cm^3
	and $B_s = \dfrac{514 \times 3.9}{3.08}$	and $B_s = \dfrac{1189.36 \times 3.9}{2.04}$
	= 650.8 kgf/cm^2	= 2273.8 kgf/cm^2
Shared by	4 supports	2 supports
Factor of safety	100%	100%
$\therefore$ Min. bending stress the supports may have to withstand	$= \dfrac{650.8}{4} \times 2$ = 325.4 kgf/cm^2	$= \dfrac{2273.8}{2} \times 2$ = 2273.8 kgf/cm^2

Table 28.9 *(Contd.)*

	Example 28.12 *Figures 28.34 and 28.36*	*Example 28.6* *Figures 28.16 and 28.37*
Inference	DMC supports may be acceptable but limiting factor is cross-breaking stress at location *a* – *a*. Hence only SMC supports must be used	SMC supports alone must be used with a modified design, to withstand a higher bending stress or the design of the bus system itself be modified as mentioned below under note 3.
Conclusion	In this particular instance, section *a* – *a* at the fingers is more vulnerable. If the supports fail, they may fail from here.	In this case, section *y* – *y* at the bolt mounting holes is more vulnerable. If the supports fail, they may fail from here.

Notes

1 Factor of safety
It is possible that during the fault only one of the insulators is subject to the transitory first peak of the fault, as there may be slight misalignment between the insulators, asymmetry in the busbars, an imperfect bolt fixing and their fastening, or a combination of such factors. To be on the safe side it is advisable to consider each support and its fasteners to be suitable to withstand the forces by themselves. We have assumed a factor of safety of 100% in all the above calculations to account for this.

2 F_m for all particular fault levels remains the same, irrespective of the current rating of the system (Equation (28.4)). A low current system employs fewer and smaller busbars and is supported on less and smaller supports and hardware. Such a system therefore may have to withstand much higher stresses than a higher current-carrying system and is more likely to yield to such stresses unless adequate measures are taken while selecting the size of supporting hardware or spacing between the adjacent horizontal supports.

3 When a component supporting the current-carrying system is likely to be subject to severe stresses, and its own stress-bearing capacity may be marginal as in Example 28.6, it is advisable to take a higher size of such a component in its thickness or diameter or a better quality material. It is also possible to mitigate the stresses by reducing the distance between the two mounting supports of the same phase. In the above case we have assumed this as 400 mm. If the centre spacing *'S'* between the two phases can be raised conveniently, it can also reduce the severity of F_m.

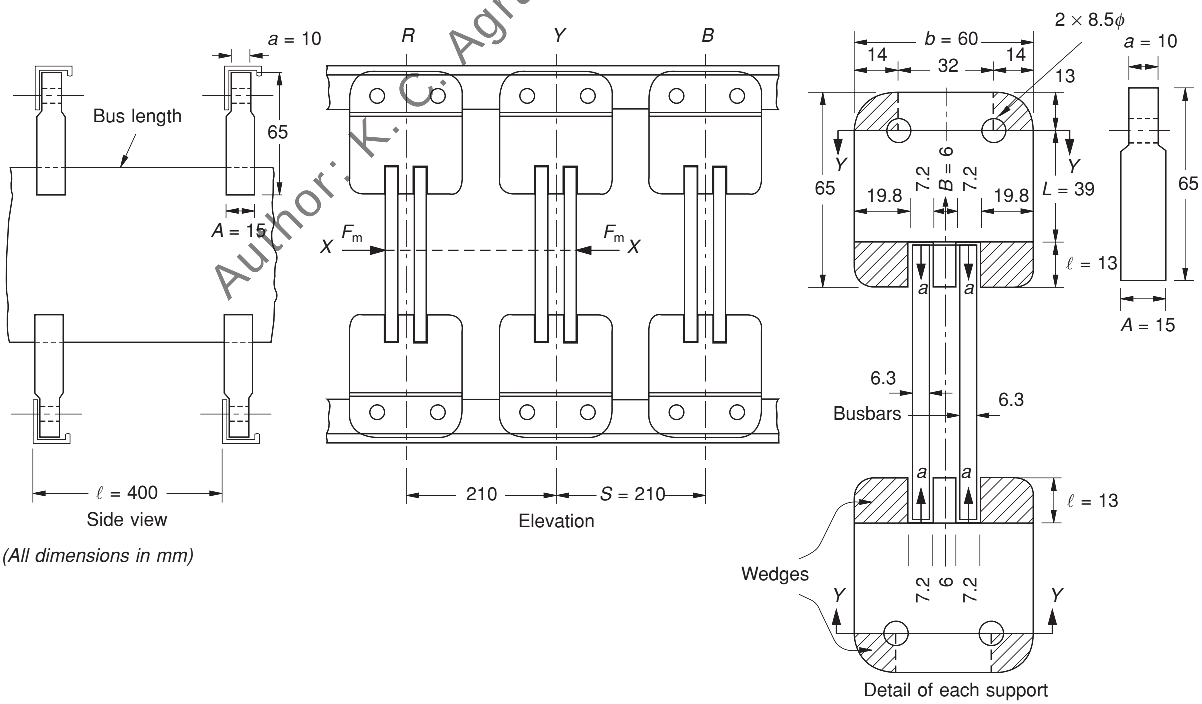


Figure 28.36 Mounting arrangement of busbars for Example 28.12

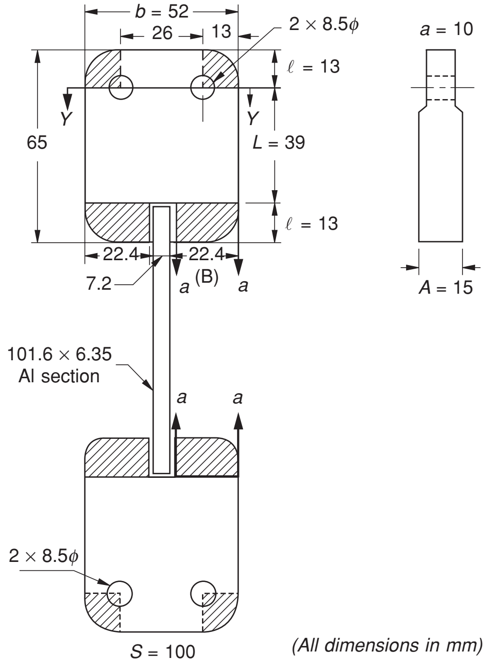


Figure 28.37 Mounting arrangement of busbars for Example 28.6

Cross-breaking strength of these fasteners

$$= \frac{1}{2} \times 2 \times \frac{\pi}{4} \times \frac{8^2}{100} \times 2200\,\text{kg (for ordinary MS fasteners)}$$

$= 1105.28$ kg

which is marginal compared to F_m of 1189.36 kg.
It is advisable to make use of high tensile fasteners only.

Suitability of insulators

We give in Table 28.9 a comparison of different types of forces that the insulators may have to encounter during a fault condition at different locations.

(B) Channel sections

Consider channels in a box form for the same requirements and operating conditions as for rectangular sections.

Choose two channels for the phases and one for the neutral of size 127 mm as in Table 30.9 and let them be arranged as shown in Figure 28.38.

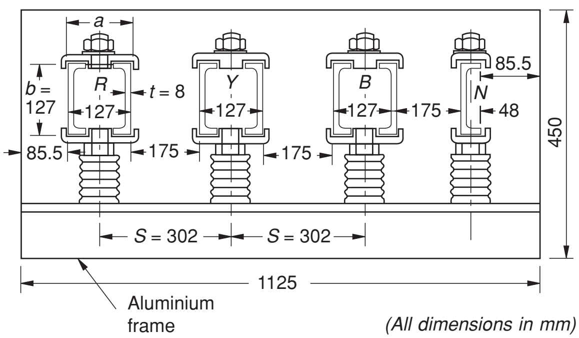


Figure 28.38 Configuration of channels in box form for Example 28.12(b)

- Electrical conductivity for grade E-91E = 1.0
- Derating for an ambient of 50°C = 0.815
- Derating for altitude = 1.0
- Derating for size of enclosure;

Area of each channel = 1695 mm^2 (Table 30.9)

$\therefore$ Total area of active material

$= 7 \times 1695$ mm^2

Area of enclosure = 1125×450 mm^2

$$\therefore \text{ enclosure factor } = \frac{7 \times 1695}{1125 \times 450}$$

$= 2.34\%$

Derating as in Table 28.6 for item 2 $\simeq 0.8$

- Derating due to skin effect – included in the basic rating of channels at 5440 A (Table 30.9)
- Derating due to proximity = minimum 0.80

$\therefore$ Total derating $= 1 \times 0.815 \times 1 \times 0.8 \times 1 \times 0.80$

$= 0.5216$

$\therefore$ Actual current rating of channels $= 0.5216 \times 5440$

$= 2837.5$ A

which is good for the required rating. The conductors have enough margin for higher load demands which may arise due to a voltage drop of up to –10% of the rated voltage if most of the loads are industrial drives.

Voltage drop

- Skin effect

d.c. resistance for one channel (Table 30.9)

$= 18.41\ \mu\Omega$/m at 20°C

R_{dc} at 85°C $= 18.41 \times 1.236$* per channel

*(refer to step (iv) above)

and for the box $= \dfrac{18.41 \times 1.236}{2}$

$= 11.38 \times 10^{-3}\ \Omega$/1000 m

Active area per phase $= 2 \times 1695$ mm^2

$= 33.9$ cm^2

Skin effect ratio from Figure 28.13(c) for

$$\frac{t}{a} = \frac{8}{127} = 0.06$$

$$\frac{R_{ac}}{R_{dc}} = 1.04 \text{ but considered minimum 1.05}$$

$\therefore\ R_{ac} = 1.05 \times 11.38 \times 10^{-3}$

$= 0.01195\ \Omega$/1000 m

- Proximity effect

From Figure 28.19(c) conductor effective spacing

$$S_e = \sqrt[3]{S_{AB} \cdot S_{BC} \cdot S_{CA}}$$

$S_{AB} = S_{BC} = 302$ mm

and $S_{CA} = 2 \cdot S_{AB} = 604$ mm

$$\therefore\ S_e = \sqrt[3]{302 \times 302 \times 604}$$

$= 380.5$ mm

and X_a from graph of 127 mm channel = 108 $\mu\Omega$/m

= 0.108 Ω/1000 m per phase

- Impedance

$$Z = \sqrt{0.01195^2 + 0.108^2}$$

$$= 0.108\ \Omega/1000\ \text{m}$$

- Voltage drop for 50 m length in phases R and B

$$= 2500 \times 0.108 \times \frac{50}{1000}$$

$$= 13.5\ \text{V}$$

which is 3.25% for a system voltage of 415 V. The system chosen is good up to a length of 50 m. Beyond this the voltage drop may exceed the desirable limits and require either larger channels or a reduced centre spacing S. Reduced spacing S is possible in this instance due to the sufficient margin available in the rating of the channel section chosen.

(viii) ***Effect of proximity on the centre phase Y***

Let us assume a length of 50 m. The voltage drop in phase Y, because of R_{ac}, assuming content of $X_a = 0$

$$= 2500 \times 0.01195 \times \frac{50}{1000}$$

$$= 1.49\ \text{V}$$

$\therefore$ Supply-side voltages of phases R and B

$$= \frac{415}{\sqrt{3}} - 13.5 = 226\ \text{V}$$

and of phase $Y = \frac{415}{\sqrt{3}} - 1.49 = 238$ V

which will provide a reasonably balanced system. To make it more balanced a reactor can be inserted into the middle phase along similar lines to those calculated in Example 28.10 for a reactance of

$$X_a = 0.108 \times \frac{50}{1000} = 5.40 \times 10^{-3}\ \Omega$$

For the rest of the calculations for mechanical suitability of the busbar system the procedure for rectangular sections can be followed.

(C) Tubular sections

Now consider a tubular section for the same requirements.

Choose a tube of size 5″ (standard pipe) from Table 30.8 having the following dimensions,

For phases

Outside diameter (OD) = 141.30 mm = $2 \cdot r_1$

Inside diameter (ID) = 128.20 mm = $2 \cdot r_2$

A = 2724 mm^2

Nominal current rating = 3550 A

For a neutral choose a tube of size 3", having

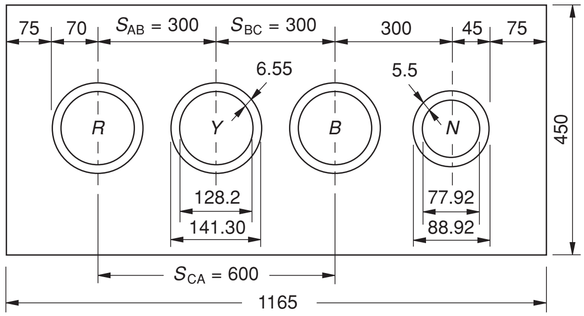
OD = 88.90 mm

and ID = 77.92 mm

A = 1439 mm^2

Arrange them as in Figure 28.39.

Likely deratings:



(All dimensions in mm)

Figure 28.39 Illustrating Example 28.12(c), with tubular bus sections

- For grade of busbars, for E-91E = 1.0
- For ambient temperature = 0.815
- For altitude = 1.0
- For enclosure factor

$$= \frac{3 \times 2724 + 1 \times 1439}{450 \times 1165}$$

$$= 1.83\%$$

$\therefore$ derating $\simeq$ 0.83 (Table 28.6)

- For proximity $\simeq$ 0.9 (such sections, because of their shape, would have a low proximity effect as noted later)

$\therefore$ Total derating = $1 \times 0.815 \times 1 \times 0.83 \times 0.9$

= 0.609

Actual current rating = 0.609×3550

= 2162 A

The busbars and the inside of the enclosure may be painted with matt finish black paint to make this section suitable for

= 1.2×2162

= 2594 A

If voltage variation is also to be considered, then one may have to choose the next higher size. As in Table 30.8, one can choose an extra-heavy pipe of 5″ size.

Voltage drop

For skin effect:

d.c. resistance $R_{dc20} = 11.3\ \mu\Omega$/m from Table 30.8

$\therefore$ $R_{dc85} = 11.3 \times 1.236$ (refer to step (iv) above)

$= 13.97\ \mu\Omega$/m

Active area per phase = 2724 mm^2

$\therefore$ skin effect ratio from Figure 28.13(b) for

$$\frac{t}{d} = \frac{6.55}{141.3} = 0.046 \quad \left[t = \frac{141.3 - 128.2}{2} = 6.55\right]$$

$$\frac{R_{ac}}{R_{dc}} \simeq 1$$

$\therefore$ $R_{ac85} \simeq R_{dc85} = 13.97\ \mu\Omega$/m

$= 0.01397\ \Omega/1000$ m

For proximity effect:

From Figure 28.21 $\frac{r_2}{r_1} = \frac{128.2}{2} \div \frac{141.3}{2}$

$= 0.907$

Corresponding to this $D_s/r_1 = 0.967$

$\therefore D_s = 0.967 \times \frac{141.3}{2} = 68.3$ mm

and $S_e = \sqrt[3]{S_{AB} \cdot S_{BC} \cdot S_{CA}}$

(refer to Figure 28.39)

$= \sqrt[3]{300 \times 300 \times 600}$

$= 1.26 \times 300$

$= 378$ mm

Corresponding to this, the reactance from Figure 28.19(b) can be determined by extrapolation. We have assumed it to be 0.06 Ω/1000 m per phase.

- Impedance $Z = \sqrt{0.01397^2 + 0.06^2}$

$= 0.0616\Omega/1000$ m

- Voltage drop for 50 m length in phases R and B

$= 2500 \times 0.0616 \times \frac{50}{1000}$

$= 7.7$ V

which is only 1.86% for a system voltage of 415 V, and is satisfactory.

Effect of proximity on the centre phase Y

The voltage drop in this phase, assuming $X_a = 0$

$= 2500 \times 0.01397 \times \frac{50}{1000}$

$= 1.75$ V

which is only 0.4% of the system voltage. This bus system will thus provide a near-balanced system.

For the rest of the calculations for the mechanical suitability of a busbar system the procedure for rectangular sections can be followed.

Note

Since basic properties of copper are similar to that of aluminium, the design parameters and service condition considerations in selecting the size of conductor and enclosure for copper busbars will also remain same as for aluminium busbars.

Relevant Standards

IEC	*Title*	*IS*	*BS*	*ISO*
60059/1999	Standard current ratings (based on Renald Series R-10 of ISO-3).	1076-1 to 3/2000	BS 2045/1982	3/1973
60439-1/2004	Low voltage switchgear and controlgear assemblies. Requirements for type-tested and partially type tested assemblies.	8623-1/1998	BS EN 60439-1/1999	—
60439-2/2000	Low voltage switchgear and controlgear assemblies. Particular requirements for busbar trunking systems.	8623-2/1998	BS EN 60439-2/2000	—
–	Hexagon head bolts. Product grade C.	1363-1/2002	BS EN 24016/1992	4016/2001
–	Hexagon head screws. Product grade C.	1363-2/2002	BS EN 24018/1992	4018/1999
–	Hexagon nuts. Product grade C.	1363-3/1998	BS EN 24034/1992	4034/1999
–	Hexagon head bolts. Product grades A and B.	1364-1/2002	BS EN 24014/1992	4014/1999
–	Hexagon head screws. Product grades A and B.	1364-2/2002	BS EN 24017/1992	4017/1999
–	Hexagon nuts, style 1. Product grades A and B.	1364-3/2002	BS EN 24032/1992	4032/1999
–	Hexagon thin nuts (chamfered). Product grades A and B.	1364-4/2003	BS EN 24035/1992	4035/1999
–	Hexagon thin nuts. Product grade B.	1364-5/1992	BS EN 24036/1992	4036/1999
–	Mechanical properties of fasteners.	1367-20/2001	BS EN 20898-2,7	898-1,2,7
–	Criteria for earthquake resistant design of structures. General provisions and buildings.	1893-1/2002	DD ENV 1998 (1 to 5)	–
–	Plain washers.	2016/2001	–	–
–	Interconnecting busbars for a.c. voltage above 1kV up to and including 36 kV.	8084/2002	BS 159/1992	–
–	Fire resistance tests – Elements of building construction.	–	–	834/2000

Relevant US Standards ANSI/NEMA and IEEE

ANSI/IEEE-C37.20.1/2002	Standard for metal enclosed LV power circuit breakers.
ANSI/IEEE-C37.23/1992	Metal enclosed bus and Guide for calculating losses in isolated phase bus.

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

Short-circuit effects

(1) Thermal effects

$$\theta_t = \frac{k}{100} \cdot \left(\frac{I_{sc}}{A}\right)^2 \cdot (1 + \alpha_{20}\theta) \cdot t \qquad (28.1)$$

θ_t = temperature rise in °C
I_{sc} = symmetrical fault current r.m.s. in Amp
A = cross-sectional area of the conductor in mm^2
α_{20} = temperature coefficient of resistance at 20°C/°C
θ = operating temperature of the conductor at which the fault occurs in °C
k = 1.166 for aluminium and 0.52 for copper
t = duration of fault in seconds

or $\frac{I_{sc}}{A} \times \sqrt{t}$ = 0.0799 for aluminium for an operating temperature at 85°C and end temperature at 185°C (28.2)

$\frac{I_{sc}}{A} \sqrt{t}$ = 0.12 for copper for an operating temperature at 85°C and end temperature at 185°C (28.3)

(2) Electrodynamic effects

$$F_m = k \cdot \frac{16 \cdot I_{sc}^2}{S} \times 10^{-4} \text{ N/m} \qquad (28.4)$$

F_m = maximum dynamic force that may develop on a fault
I_{sc} = r.m.s. value of the symmetrical fault current in Amps
k = space factor
S = centre spacing between two phases in mm

Skin effect

Effect on current-carrying capacity

$$I_{ac} = I_{dc} \cdot \sqrt{\frac{R_{dc}}{R_{ac}}} \qquad (28.5)$$

I_{ac} = permissible current capacity of the system
R_{dc} = d.c. resistance
R_{ac} = a.c. resistance
I_{dc} = d.c. current

Conductor resistance at higher temperature

$$R_{dc} \text{ at } 85°C = R_{dc20}\,[1 + \alpha_{20}(\theta_2 - \theta_1)] \qquad (28.6)$$

α_{20} = temperature coefficient of resistance at 20°C per °C
R_{dc20} = d.c. resistance at 20°C
θ_2 = operating temperature = 85°C
θ_1 = since the value of R_{dc} is available at 20°C therefore, θ_1 = 20°C

Proximity effect in terms of busbar reactance

$$S_e = (S_a \cdot S_b \cdot S_c)^{1/3} \qquad (28.7)$$

S_e = effective or geometric mean spacing
S_a, S_b, and S_c = spacing between conductors

Use of saturable reactor to balance a large unbalanced power distribution system

To determine size

$$X_p = V_{ph}\left(\frac{1}{I_r} - \frac{1}{I_y}\right) = 2\,\pi \cdot f \cdot L \qquad (28.8)$$

X_p = lost reactance of Y phase
L = inductance of X_p
I_r = current in R or B phase
I_y = current in Y phase

Reluctance of the magnetic path

$$R_l = \frac{2\,\ell_g}{\mu_o \cdot A} + \frac{k - 2\ell_g}{\mu_o \cdot \mu_r \cdot A} \qquad (28.9)$$

ℓ_g = length of the air gap in metres
μ_o = permeability of air (free space) = $4\pi \cdot 10^{-7}$ H/m
μ_r = relative permeability of the silicon steel used for the laminates in H/m
A = area of cross-section of core in square metres
k = total length of the magnetic circuit in metres

Calculating stresses on a fault

Bending stress on busbars at section

$$x - x = \frac{F_m \cdot \ell}{12 \cdot M \cdot N} = \text{kg/cm}^2 \qquad (28.10)$$

F_m = maximum electrodynamic forces acting on each support in the event of a fault
ℓ = centre distance between two busbar supports in cm
M = sectional modulus of each busbar at section $x - x$
$= \frac{1}{6}\, a \cdot b^2$ in cm^3
N = number of busbars per phase

Further Reading

1 ERDA, 'Study on feasibility of upgrading the operating temperature of Al busbars without plating'.
2 Golding, E.W., *Electrical Measurements and Measuring Instruments.*
3 Lynthall, R.T., *The J & P Switchgear Book.* Butterworth, London.
4 Thomas, A.G. and Rata, P.J.H., *Aluminium Busbar.* Hutchinson Scientific and Technical for Alcan Industries Ltd.
5 *Copper for Busbar,* (available in FPS and MKS systems), Pub. No. 22, Copper Development Association, U.K.