Brief Notes and Practice Examples For Bus Bar Calculations.

Steps in bus bar design for substation:

The cross section of conductors is designed on the basis of rated normal current and permissible temperature rise.

The value of cross section so obtained is verified for temperature rise under short time short circuit current.

The busbars can be broadly classified in the following categories at substations:
1. outdoor - rigid tubular busbars
2. outdoor - flexible ACSR or Aluminimum alloy busbars
3. indoor - indoor busbars in switchboards etc

Steps in bus bar design:

1. Choice of cross section of conductor based on nomral current, ambient temperature, specified permissible temperature rise
2. Calculation of temperature rise under short time current to confirm it is within safe limits
3. Calculation of electro dynamic forces per meter per given short circuit current
4. Calculation of choice of support insulators on the basis of bending moment withstand value
5. Calculation of span of support insulators on the basis of the force, bending strength of insulators, and factor of safety
6. Design of insulator system, phase to phase clearance, phase to earth clearance, creepage
7. Design of support structures
8. Design of clamps and connectors, flexible joints
9. Manufacture full scale prototypes having adequate length, typical bends, typical joints, connectors
10. Subjecting bus bar system to type tests (per standard for type tests)
11. Subjecting a typical busbar to field trials (the bus bar design is manufactured and put under tests similar to actual installation conditions)
12. Regular maintenance and routine tests

The above steps also apply to bus bars in switchboards. F
For under 1kV bus bars the steps are similar and require standards applicable at <1kV.

Figures of substation yard and busbars:

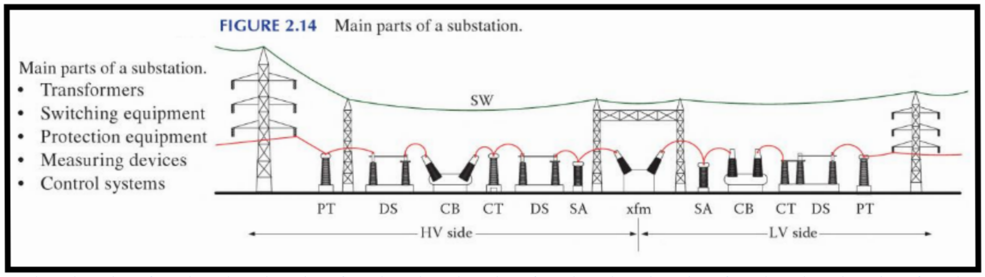

FIGURE 2.14 Main parts of a substation.

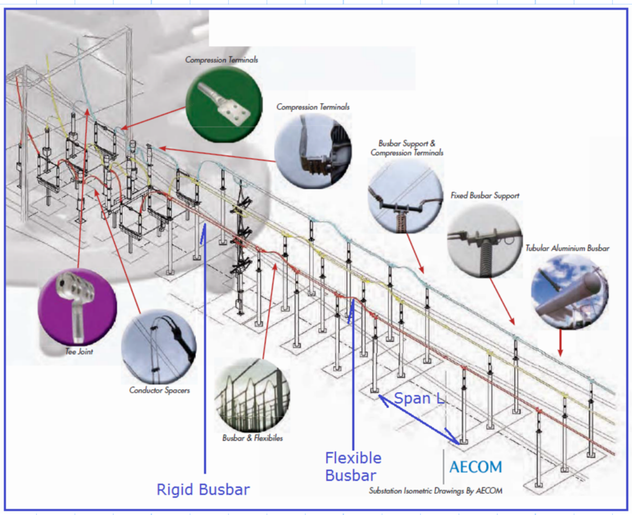

Fig. 3.1-14: **H-arrangement, 110 kV, Germany**

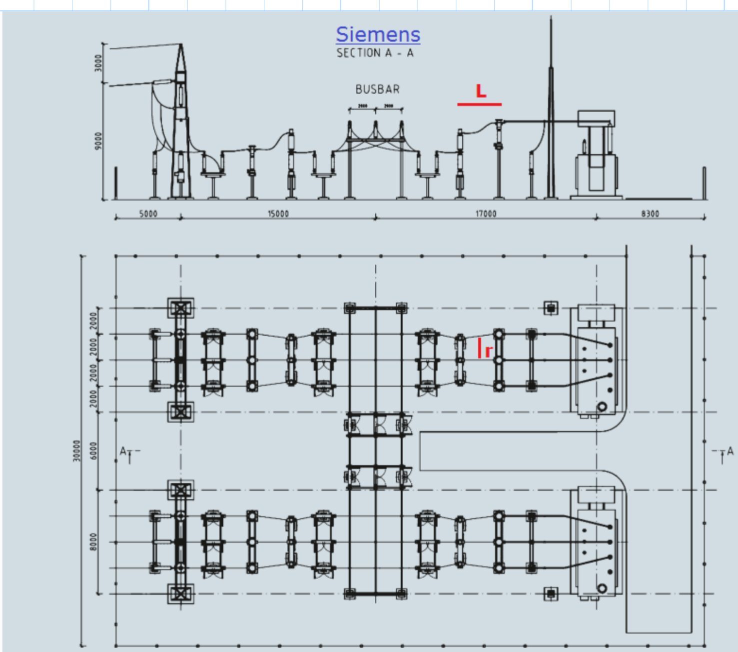

Fig. 3.1-13: **H-arrangement 110 kV**

L - the distance between insulator post (span)

r - the distance between conductors (phase to phase distance)

Main requirements of conductors, bus bars, connectors, and current carrying parts of the equipment in the substation include the following:

- normal current rating
- short time current rating (for a period of 1 second)
- low electrical resistance (wrt busbars, clamps, connectors, joints, etc.)
- mechanical strength (experienced by the conductor as shown below):
  a. dead weight of the conductor and associated components
  b. short circuit forces during peak of first major current loop/cycle of short circuit
  c. wind loading, ice loading
  d. vibrations
- conductive material (cond., conn., associated hardware) free from radio interference, and television interference
- conductor system has minimum number of joints (each joint shall have a resistance below 15 micro ohms, this is to avoid local overheating)
- conductor system has adequate number of insulators
- conductor system should be economical
- conductor system should be fully reliable

Some theory on bus bar installation:

Isolated phase busduct (IPB) system:

Is one in which an aluminium conductor in the form of a rectangular/tubular/ octagonal of each phase is enclosed in a hollow tubular aluminium enclosure. One phase in one tubular enclosure.

Conductor is supported on epoxy insulators.

The enclosures of the three phases are star connected and earthed at each end.
3 enclosures connected in star at each end, and earthed at each end.

Enduced currents flow in each enclosure. Due to three phase 120 degs apart, the magnetic field outside the enclosure cancels out.

Therefore the forces between the conductors during the short-circuit current flow are negligibly small. The enclosure gives magnetic sheilding.

The forces on the insulators during short circuit are reduced to about 10% due to interaction between magnetic fields of the induced enclosure current and magnetic field of the main conductor current.

So IPB installation method is safe and reliable, and is usually used universally for generator and transformer connections. The cables from the generator are installed in IPB system to the transformer. From the transformer to the generation substation dependent on distance suitable methods installations are used including IPB.

Mechanical areas related to busbar installation:

- a substation has a combination of rigid and flexible busbars
- types of enclosed bus bars
  a. enclosed busbars - busbars enclosed in aluminium or steel sheets
  b. non-segregated bus ducts - conductors of 3 phases are in a common metal enclosures without any barrier between them
  c. segregated bus ducts - with metal/insulator seperation between phases
  d. isolated phase bus system - each phase in seperate metal enclosure
  e. isolated phase bus system of discontinous type - enclosures unit lengths are not electrically connected
  f. isolated phase bus sytem of continous type - enclosures electrically continous through out length, with the 3 enclosures star and earthed at each end

Ratings for busbars:

1. rated current
2. rated voltage
3. rated frequency
4. rated short time current
5. rated insulation level

Other areas:

1. permissible temperatur rise values material type (cu/al), over ambient, hot-spot temp rise
2. temperature rise due to
   - material resistivity, cross section of conductor, size shape of conductor, skin effect, proximity effect, type of enclosure or open, heating due to solar radiation, ambient temperature, wind, etc.
3. thermal expansion - use expansion joints, also vibration related to expansion
4. methods of jointing - clamps, welding, etc.
5. type of clamps and connectors, and their fit - current carrying parts, ratings, etc. also choice of right types of clamps and connectors (tee, grove, sliding, etc.), and related hardware.
6. bimetal jointing - use appropriate connector between equipment terminal and conductor
7. oxidation of layer - use of emery paper and wire brush to remove thin oxidation layer, application of oxidation inhibiting grease

Examples next page.

Example 1: Maximum force on a conductor and span of insulators

The busbars are having phase to phase spacing of 24 cm.
Their short circuit current rating is kA rms

Determine the maximum force on conductors during short circuit conditions and span L.
Check the units in the progression of the calculation.

Solution:

Force F = 2.04 x is^2 x (L/r) x 10^-2 kgf
F = force between conductors
is = peak value of making current kA
L = distance between insulator supports cm (center to center dist)
(the conductor runs on top of the insulators and the insulator span L in cm)
r = separation between conductors cm (side to side dist.)

is = Irms x sqrt(2) x 1.8
1.8 is a factor for assymmetry

$Asy_{factor} := 1.8$
$I_{rms} := 1.0$ set as unity

$i_{s\_Irms} := I_{rms} \cdot \sqrt{2} \cdot Asy_{factor}$

$i_{s\_Irms} = 2.5456$ in Irms

Let short circuit current = 25kA rms

$I_{sc} := 25$ kA rms

So peak short circuit current is

$i_s := i_{s\_Irms} \cdot I_{sc} = 63.64$ A

$i_s^{\,2} = 4050$ kA (units in Kiloamperes)

Distances:

$L := 100$ cm - NOT given so set as unity ie 1 meter dist between insulator supports
$r := 24$ cm - spacing between

$L_{over}r := \frac{L}{r} = 4.1667$

In the force F equation multiply by 10^-2 for conversion of L/r dist to meters, and the answer is given in kilograms force since the current is in kA.

Force F on busbars per meter length:

$F := 2.04 \cdot i_s^{2} \cdot \left(L_{over} r\right) \cdot 10^{-2} = 344.25$

344.25 kgf per meter
kilogram force per meter

Cantilever load on on insulator is:
F x H kg-meter
F is force per span of length
H is height of insulator in meter

Assume insulator height is 13cm = 0.13m
Sk = cantilever strength of insulator (cantilever - a member fastened to a structure)

F x H x L = cantilever load per span length of insulator, L is span of insulators

F x H x L = Sk / (Factor of safety)

Set the variables:

$H := 0.13$ m
$S_k := 500$ kg-m
$S_{factor} := 4.0$ factor of safety

Calculate span L:

$L_m := \frac{S_k}{\left(S_{factor} \cdot F \cdot H\right)} = 2.79314$ m

$L_m = 2.79$ meters

Let span L = 2.8 meters

Answer - length of busbar or flexible bus between 2 insulators mounted on posts

Example 2: Design the busbar system per the given specifications

Design the busbar sysem for the following specifications:
Rated voltage: 400kV
Rated normal current: 2000A
Rated short circuit current: 40kA rms
Type of bus bars: Rigid

Solution:

Review the steps in bus bar design provided in notes earlier.

The busbar solution is carried out in 3 steps:

1.
Determine the conductor cross section.
On the basis of current density and normal current rating,
and checking it for temperature rise under short circuit condition.

2.
Determination of phase to phase clearance and phase to ground clearance of busbars from specifications.

3.
Determination of force on support insulator.
Select suitable post insulators.
Determine the span of support insulators.

Step 1:

Cross sectional area based on normal current rating and permissible temperature rise. Normal current rating = 2000 A

$I_{nor} := 2000$

Current density for Aluminium busbar = 120A/cm^2 (open busbar condition NOT enclosed)

$I_{den} := 120$

Cross sectional area = normal current / current density of material

$$CSA := \frac{I_{nor}}{I_{den}} = 16.6667 \qquad cm^2$$

Select a 4inch (100mm) diameter aluminium pipe (rigid) with a cross section area greater than CSA above. Pipe has inner and outer diameter, the solid part area to be greater than CSA above.

Step 2:

Phase to phase clearance for 400kV = 4 m (from table)
Phase to ground clearance for 400kV = 3.5 m (from table)

Creepage distance:
Atmospheric dust sticks to the insulators forming a conducting layer. The leakage currents flow from live conductor to the earth through such a dust surface layers.

The leakage properties (creepage properties) of an insulator are characterised by the length of the leakage path.

The leakage path or creepage path, is the shortest distance along the insulator surface, between the metal parts at each end of the insulator.

Both ends of the insulator supporting the conductor has a contact distance to the phase conductor, and the supporting post is also metalic beneath the insulator, dust collects on the insulator surface, creating a closed path to the metal parts. This is not desirable because it creates a conducting path. Distance used in design depends on rated phase to earth voltage, and degree of pollution in the area.

Heavily polluted areas for example maybe 24mm per kV distance. There are also tables for creepage distances.

$Crep_{perkV} := 24$

Use highest system voltage 420kV instead of nominal 400kV, this gives a greater creepage distance.

$V_{nom} := 420 \cdot 10^3$

$$Creepage := Crep_{perkV} \cdot \frac{\left(420 \cdot 10^3\right)}{10^3}$$

$Creepage = 10080$ mm

Step 3:

Use post insulator stack formed by 10 numbers of 33kV post insulators.
From the table 9.6 page 176 the cantilever strength is 0.3 kilo - kg m.

Calculate the span of post insulators as in example 1 above.

Force F = 2.04 x is^2 x (L/r) x 10^-2 kgf
F = force between conductors
is = peak value of making current kA
L = distance between insulator supports cm (center to center dist)
(the conductor runs on top of the insulators and the insulator span L in cm)
r = separation between conductors cm (side to side dist.)

is = Irms x sqrt(2) x 1.8
1.8 is a factor for assymmetry

$Asy_{factor} := 1.8$

$I_{rms} := 1.0$ set as unity

$i_{s\_Irms} := I_{rms} \cdot \sqrt{2} \cdot Asy_{factor}$

$i_{s\_Irms} = 2.5456$ in Irms

Let short circuit current = 40kA rms

$I_{sc} := 40$ kA rms

So peak short circuit current is

$i_s := i_{s\_Irms} \cdot I_{sc} = 101.82$ kA

$i_s^2 = 10.368 \cdot 10^3$ kA

Distances:

$L := 100$ cm - NOT given so set as unity ie 1 meter dist between insulator supports

$r := 400$ cm - spacing between phase to phase per table or standard

$L_{over}r := \frac{L}{r} = 0.25$

Force F on busbars per meter length:

$F := 2.04 \cdot i_s^2 \cdot (L_{over}r) \cdot 10^{-2} = 52.88$ kgf per meter
kilogram force per meter

Cantilever load on on insulator is:
F x H kg-meter
F is force per span of length, kgf
H is height of insulator in meter

Sk = cantilever strength of insulator (cantilever - a member fastened to a structure)

F x H x L = cantilever load per span length of insulator, L is span of insulators
F x H x L = Sk / (Factor of safety)

Set the variables:

$H_{post\_ins\_5units} := 2.208$ m height of a set of 5 post insulators

$H := 2 \cdot H_{post\_ins\_5units} = 4.416$ m, height of 10 post insulators (stacked)

$S_{k\_each} := 0.3 \cdot 10^3$ kg-m

$S_k := 10 \cdot S_{k\_each} = 3000$ for 10 sacked units of post insulators

$S_{factor} := 4.0$ factor of safety

Picture of post insulator; stacks of insulators mounted on a post

Calculate span L:

$$L_m := \frac{S_k}{(S_{factor} \cdot F \cdot H)} = 3.21194 \quad \text{m}$$

$L_m = 3.21$ meters

Let span L = 3.2 meters Answer

<u>Description of the bus bar system:</u>

Conductor: Aluminium tubular 4 inch diameter
csa 16.67 cm^2 (adj to 18.9 cm^2 for temp rise see calc below)
Clearance: Phase to phase - 4 m
Phase to earth - 3.2 m
Insulator: Cantilever strength = 0.3 x 10^3 kgm
Span of insulator: 3.25 m
Height of insulator stack: 4.16 m
Creepage distance: 10,800 mm

<u>For the above example calculate temperature rise during short circuit conditions</u>

T = temperature rise per sec, during short circuit conditions (C deg)
C = 0.54 for Cu
1.17 for Al
I = rms value of short circuit current
A = csa in mm^2
alpha = temperature coefficient of resistivity at 20 C deg
0.00393 for copper
0.04003 for aluminium
0.00364 for aluminium alloy
theta = temperature at instant of short circuit
this is the ambient temperature plus permissible temperature rise

$C_{al} := 1.17$

$I_{rms} := 40 \cdot 10^3$

$A_{mm} := CSA \cdot 10^2$ $\qquad A_{mm} = 1666.67$

$\alpha_{al} := 0.04003$

$\theta_{amb} := 35$ $\qquad \theta_{perm\_rise} := 40$ $\qquad \theta := \theta_{amb} + \theta_{perm\_rise} = 75$

$$T := C_{al} \cdot \left(\frac{I_{rms}}{A_{mm}}\right)^2 \cdot (1 + \alpha_{al} \cdot \theta) \cdot 10^{-2}$$

$T = 26.972$ temperature rise per second during short circuit condition

At temperature above 160C deg aluminium becomes soft and
losses its mechanical strength.

<u>Derating factor based on temperature:</u>

Check your local or international standards on temperature derating for busbars

Here we will use one of the temperature rise condition as follows:
Temp rise of 40 C deg, ambient 35C deg - derating factor of 0.88

To adjust the size of the aluminium CSA, upsize the
CSA by dividing it by the derating factor

$DF_{temp\_al} := 0.88$

$CSA_{adj} := \frac{CSA}{DF_{temp\_al}}$ $\qquad CSA_{adj} = 18.9394$ cm^2

Plugging it back into the equation for T above:
$A_{mm\_adj} := CSA_{adj} \cdot 10^2$ $\qquad A_{mm\_adj} = 1893.94$ mm^2

$$T_{adj} := C_{al} \cdot \left(\frac{I_{rms}}{A_{mm\_adj}}\right)^2 \cdot (1 + \alpha_{al} \cdot \theta) \cdot 10^{-2}$$

$T_{adj} = 20.8871$ reduced temperature rise per second during short circuit condition
dependent on standard requirements the size of the busbar is
increased to offset the temperature rise
- in this case it resulted with a 6C deg decrease in temp rise
- upsize the busbar conductor per adjusted CSA