TECHNICAL REPORT

ALUMINIUM TUBULAR BUSBARS FOR HV SUBSTATIONS

In many instances HV outdoor substations with a high current rating are constructed more economically with aluminium tubular busbars rather than with stranded conductors. The advantages realised by using aluminium tubular busbars are:

- Busbars are lighter in weight and have a greater stiffness than stranded conductors with the same current transfer capacity.
  - This facilitates larger free spans;
  - Which require fewer points of supports and foundations;
- impose a lower mechanical load on the foundation points and circuit equipment than stranded cables do under short circuit conditions;
- are good electrical conductors due to the skin effect: the busbar surface has a current density that is relatively lower than that of a stranded conductor;
- are permanently corrosion resistant;
- possess excellent electric conductance properties;
- have a smooth surface;
- maintenance free;
- have a very long life span.

Tubular busbars can be welded together to provide a total length of about 140 meters.

In Southern Africa aluminium tubular busbars up to a nominal diameter of 160mm with a wall thickness of 8mm can be locally manufactured and provided up to maximum lengths of 12 metres. Larger diameter lengths of tube are supplied by the company out of recognised foreign manufacturers.

The following information relates to imported aluminium tubular busbars manufactured in accordance with Standard EN 755-2.

Using the information detailed hereunder, you can calculate which specifications the aluminium tubular busbars used in your projects must meet. The guidelines and methods of calculation detailed have been determined by KEMA of the Netherlands.

It is assumed that the client knows the following details:
The nominal current during normal operation.
The required short-circuit current.
The applicable centre-line distance between busbars.
The Maximum span between two busbars supports.

Based on these details a correct choice of busbar diameter and wall thickness can be made using the method described below.

The dimensions of a busbar are mainly determined by two physical loads, i.e. the thermal and mechanical loads on the busbar.

MATERIAL PROPERTIES

The alloys listed below, which comply with EN 755-2, are those most commonly used for electrical busbars. Alloy 6101B T6 has more mechanical strength but less electrical conductivity. If higher electrical conductivity is required, alloy 6101B T7 can be used. However, this alloy has less mechanical strength. Of course busbars made of other alloys can also be supplied.

Property	Unit	Alloy	
		6101BT6	**6101BT7**
Specific gravity p	Kg/m^3	2, 700	2, 700
Young's modulus E	N/mm^2	70, 000	70, 000
Stress corresponding to the yield point (R_p)	N/mm^2	160	120
Ultimate tensile strength (R_M)	N/mm^2	215	170
Elongation	%	8	12
Coefficient of linear expansion ∂ (0 - 100ºC)	K^{-1}	23.5×10^{-6}	23.5×10^{-6}
Electrical conductivity (at 20ºC)	MS/m ($m/\Omega mm^2$	30	32

THERMAL CAPACITY OF BUSBARS

The thermal capacity of a busbar is mainly determined by:

- the environment: temperature and solar radiation;
- the nominal current;
- the maximum busbar temperature as determined by the client.

When the amount of heat absorbed by the busbar is the same as the amount of heat it emits, equilibrium is reached. In this situation the busbar temperature will remain constant. The current at this point of equilibrium is the current-carrying capacity of the busbar.

This heat balance must be considered under normal operating conditions and under the extreme condition of a short-circuit. During a short-circuit extra heating of the busbars may occur in a short space of time.

Normal operating conditions:

In this documentation the allowable current was calculated in accordance with DIN43 670 with an ambient temperature or 35ºC, a final busbar temperature of 80ºC, an absorption coefficient of 0.6 and a solar radiation of 600 W/m^2.

The allowable current for the busbar dimensions and standard aluminium alloys available are given in table 2 and table 3.

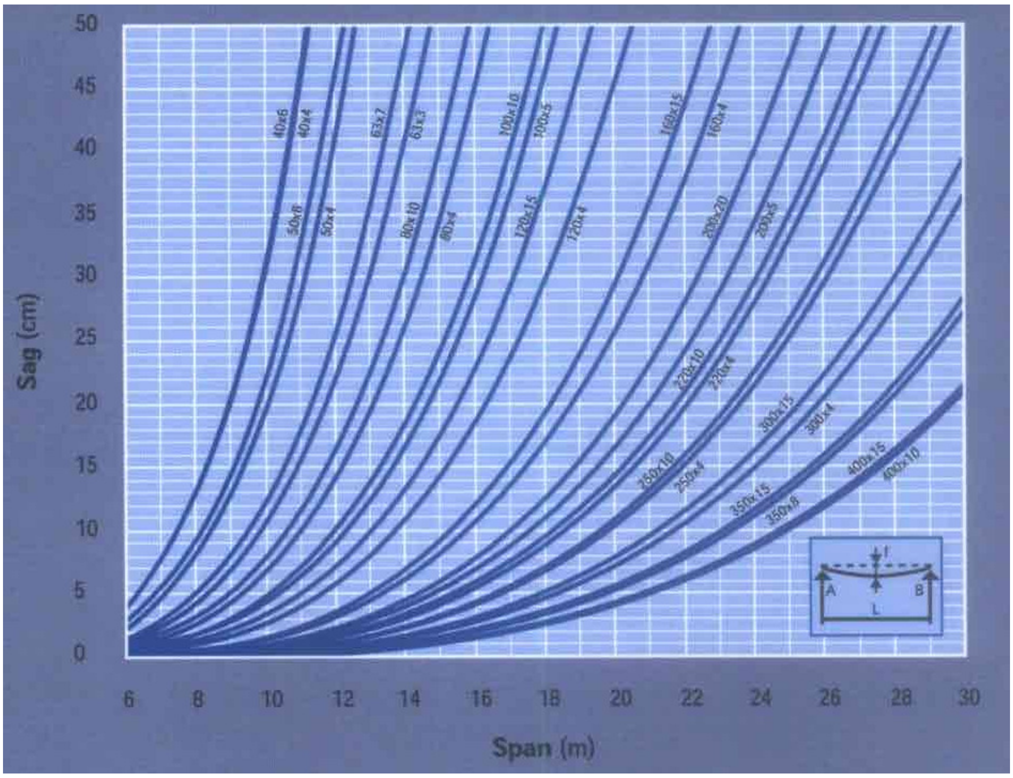
It can be seen from the tables that when using aluminium alloy 6101B T7 for a current carrying capacity of 3000A, the minimum busbar dimensions (diameter/wall thickness) of 100/10, 120/6 or 160/4 are acceptable.

For different ambient temperatures or final busbar temperatures the current carrying capacity can be determined using the load factor from figure 1.

Example:
At an ambient temperature of 30ºC and a final busbar temperature of 65ºC, the current carrying capacity from table 2 or 3 has to be multiplied by a factor 0.86.

If, under these conditions, a busbar has to be selected for a nominal current of 3000A, the method is as follows:
The effective load on the busbar is 3000 : 0.86 = 3488 A.
From the table (6101B T7) it can be seen that possible choices for busbar dimensions are 120/10 or 160/5.

Figure 1. Current carrying capacity as function of ambient temperature and final busbar temperature



Short-circuit

Under short-circuit conditions the final busbar temperature must not exceed 200ºC, based on an initial temperature of 80ºC. Higher temperatures can affect the structure of the aluminium alloy, which results in changes in its mechanical properties. During short-circuits the temperature will generally remain below the allowable temperatures of 200ºC, based on a busbar temperature of 80ºC during normal operation.

After determining the busbar cross-section the current density during a short-circuit can be determined. This current density (J) can be determined from the short-circuit 1_K and the cross-section of the busbar.

Table 1. Current density (J) as a function of material type and duration of the short-circuit current.

Duration of the short-circuit current (s)	6101BT6	6101BT7
	J_{eff} (Amp./mm^2)	J_{eff} (Amp./mm^2)
0.5	118	122
1.0	83	86
1.5	68	70
2.0	59	61
3.0	48	50
5.0	37	38

MECHANICAL CAPACITY OF BUSBARS

The busbar's diameter and wall thickness are not determined on the basis of the current carrying capacity only. The sag as a result of normal and exceptional loads must also be taken into account.

In accordance with the harmonisation document "HD 637 Power installations exceeding 1kV a.c.", busbars must meet mechanical requirements that have been derived from the following loads and operating conditions:-

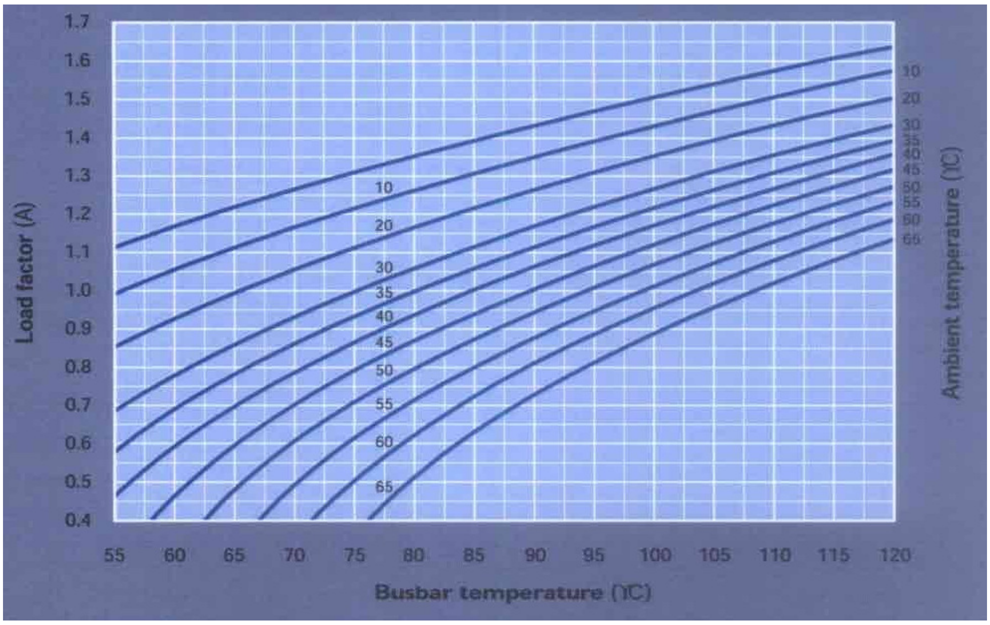
Normal loads taking into account:
- the busbar's mass
- ice load

- wind load

These loads determine the sag of the busbar under normal operating conditions. The amount of sag depends on the stiffness of the busbar. If the busbar's diameter and wall thickness are determined, the sag under normal operating conditions can be determined. This can be important for the design of a switchyard.

The sag resulting from the mass and span length of the busbar can be determined from figure 2.

Figure 2. Busbar sag as function of span length (as a result of the mass of the busbar itself)



Exceptional loads, taking into account:
- short-circuit forces
- switching forces.

Only forces on the busbar during short-circuits are considered below, since these forces are the determining factor in most cases.

In a three-phase system with three busbars in the same plane, the greatest force during short-circuits will occur in the centre busbar. Electromagnetic forces will occur between the conductors as a result of the short-circuit current. The busbar must have a certain stiffness to absorb these forces. The required section modulus was determined in accordance with the simplified calculation method of IEC 865.

Based on the required short-circuit current and phase-to-phase distance, the electromagnetic force per metre busbar can be determined using figure 3 and figure 4 (depending on the alloy used). With this data and the required span length the required section modulus can be seen.

The calculations are based on:
- a two-point support for the busbar
- a factor of plasticity of 1.4
- automatic re-closing after the short-circuit.

<u>DETERMINING THE BUSBAR DIAMETER AND CROSS-SECTION</u>

With the required nominal current-carrying capacity and the required section modulus one or more suitable busbar dimensions that meet both requirements can be found in table 2 or 3.

Example of determining a busbar dimension:

<u>Criteria</u>

I_{normal}	:	4000A	nominal current during operation
I_k	:	50kA	short-circuit current
$a_{phase\text{-}phase}$	:	4m	phase-phase distance
L_{max}	:	12m	span length, distance between supports
Al alloy	:	6101BT6	

The following busbar dimensions (diameter/wall thickness) are acceptable for the required nominal current of 4000 A:120/15, 160/8, 200/5 and 220/4 (see table 2).

Using figure 3 it can be determined that, at the given short-circuit current, phase-to-phase distance and span length, the required section modulus is approximately 100cm³. Among others, the following busbar dimensions meet this requirement: 120/12, 160/6, 200/5 and 220/4.

Busbars 120/15, 160/8, 200/5 and 220/4 meet both the current carrying capacity requirements and the requirements from the dynamic short-circuit load. Busbar 220/4 is the lightest in weight but is vulnerable due to its small wall thickness. Therefore a choice should be made between 120/15, 160/8 or 200/5.

After determining the diameter and wall thickness, the client's choice of busbar may be based on the following:

- weight saving
- standardisation of busbars to be used (possibly a preference for 120mm type)
- sag of the busbar as a result of busbar mass (see figure 2)
- current density in the busbar as a result of short-circuits (see table 1)
- ease of working on the busbar (it is easier to weld termination pieces to busbars with greater wall thickness.)

Changing assumptions or parameters can be discussed with KEMA, if required. Optimisation can lead to significant savings, not just on busbar material but also on supports, e.g. lighter insulators, support structures and foundations. To this end, KEMA has advanced calculation methods and tools at its disposal.

TUBE OPERATIONS

Aluminium tubular busbars are subject to wind-generated vibration and oscillation. Because of the low self-damping of tubular busbars very slight excitation forces will suffice to excite the tubes to vibration amplitudes of the order of the tube diameter, when there is a resilience of the excitation force with a natural frequency of the tube. These high amplitudes produce additional dynamic stresses inside all structural parts and it is often necessary to dampen this tube oscillation by the insertion of AAC conductor into the busbar. The increased self damping provided by the insertion of damping conductor delays the onset of resilience build-up and this limits the maximum amplitudes created by a given excitation force.

As a rule it is normally sufficient to insert one conductor into a tube, but in order to increase the safety and to maintain maximum damping effect it is advisable to insert tow conductors into the tube (one at each end running for 2/3 of the tube length). The following table shows recommended damping conductor sizes. A drain hole of 10mm diameter should be drilled at bottom centre point of tubes to facilitate drainage of condensate moisture.

Recommended Damping Cables		
Tube-Ø mm	Al-cable mm	Permissible spacing between supports without damping cables m (normal values)
63	120	3.0
80	150	3.5
100	240	4.5
120	300	5.5
160	500	7.5
200	625	9.5
250	625	12.0