Analysis of Temperature Rise and Comparison of Materials of Bus Bar used in the MV Panel Board

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ABSTRACT
The application of mathematical modeling, together with practical designs and efficient fabrication methods, has had considerable impact on the improvement in capital costs of aluminum reduction over the last thirty years. This is particularly the case for the bus bar design, which represents 10-15% of the total pot line cost. Effective bus bar designs must also take account of the many practical needs, including optimization of the bus bar mass (current density), ease of fabrication, and safe electrical isolation. This paper deals with the energy balance equation. Solving the equation the temperature rise with respect to the ampacity of the load condition. Thermal time constant of the particular temperature to reach the steady state are also discussed and tabulated. The Conductor materials such as copper and Aluminum are also compared. The performance of the feeder section has the good agreement between the experimental and calculated values.

Keywords
energy efficiency, heat transfer, ampacity.

1. INTRODUCTION
Material and energy efficiency of bus bar systems are very often conflicting requirements, e.g. if you reduce the cross section of a bus bar system for saving material (increased material efficiency) you increase the resistance and with the resistance the power losses (reduced energy efficiency). The most important requirement is given by the specific industry plant and is different case by case. Nevertheless the other requirements should be respected as much as possible. In most applications there is room for improvements which are easy to realize during engineering and design phase but are difficult and costly afterwards. Therefore it is necessary to have a basic understanding about the working mechanisms of bus bar systems. The design of bus bar systems is not just the calculation of a current density with the nominal current.

2. MATERIAL DESCRIPTION
2.1 Effect of Materials

$$\frac{I_{al}}{I_{cu}} = \sqrt{\frac{61.0}{98.0}} = 78.9\%$$

$$\frac{I_{al}}{I_{cu}} = \sqrt{\frac{57.0}{98.0}} = 76.26\%$$

78.9% for 1350 alloy

76.26% for 6101-T61 alloy

The ratio of currents that will produce the same temperature rise in aluminum and commercial copper bars of same size and same surface conditions.

2.2 Effect of Dimensions
Tests show that for practical purposes, copper bus bar sizes can be converted to aluminum sizes for equal temperature rise by either of the following two methods:

1. Increase the width of the aluminum bar 27 percent. For example, a 5” x ¼ “aluminum bar is equivalent to a 4" x ¼ "copper bar.
2. Increase the thickness of the aluminum bar about 50 percent. A 4" x 3/8" aluminum bar is equivalent to a 4” x ¼ “copper bar.

Increasing the cross-sectional area by increasing the width not only reduces the resistance heating but also substantially increases the area for heat dissipation. A change in thickness of a rectangular bar does not appreciably affect the amount of exposed surface area. For example, increasing the area of a ¼ "-in. bar by changing the width from 4 in. to 8 in. increases the capacity by about 87 percent, but increasing the thickness of a 4-in. bar from ¼ in. to ½ in. increases the capacity by only about 45 percent.

Table 1. Properties of Conductor Materials

Material	**ρex10-8 (K/m)**	**∝ex10-3 (1/oC)**
Hard drawn copper	1.70	3.81
Aluminum	2.82	4.04
Steel	2.155	3.20

3. EXPERIMENTAL SETUP
The most common form of bus conductor is bar stock of rectangular cross section. This shape is inherently easy to fabricate, store, handle and erect. A relatively large surface area can be provided for the dissipation of heat by the use of multiple-bar buses. Joints and taps are readily made by either bolting or welding. Off-sets and 90-degree bends are easily made. Practically, the arrangement of the distribution system from the substation to the load centre has been studied. It was done in two levels of high voltage and low voltage. High rating panel assembly studied in the Textile mill and low tension panel arrangement in a College power house. Load distribution and the thermal properties were analyzed.

3.1 Case study 1
This unit consists of spinning machines. Out of this Long Frame are about 24 nos. and Short Frame 15 nos. Maximum Demand (MD) of this mill is 1600 KVA, of Distribution Transformer and current rating of 3200A. Fig-1.0 shows the

complete section of the panel board. From the 1600 KVA distribution transformer given to the 4P, DO, 65KA, Air Circuit Breaker. To have protection at both ends, earth faultier is located next to the CB unit. The bus bars used are aluminum with laminated having the size of

2R – 150 x 12 mm ALU Phase

1R – 150 x 12 mm ALU Neutral

Figure 1.0 Panel arrangements with display unit

After ACB, bus bar size at the panel 2R x 150 x 12mm Phase 1R x 150 x 12mm N. Total panel rating = 3200A, from 1600KVA. Total load at the panel = 1600 x 0.98 = 1568 KW, 415V. According to the dimension, current rating = 2 x 6 x ½ = 3600A. According to the calculation of KW consumption, current = 2.2KA

3.2 Case study 2:

Hard drawn copper are used in the college premises, having the incoming power of 1000KVA. It consist of various feeders out of these, hostel feeder consume the maximum load. So this area is considered for calculation. Steel is used in the metallic contact of the bus bar. The active power of the power house is 900KW with 0.9 as power factor and 50Hz as frequency. The maximum current flowing through the single bar is 680A. Here the ambient temperature observed as 32oC and operating temperature taken as 40oC. This temperature is taken an assumption due to the high load consumption.

3.3 Observations in Case 1

The mill is 24 hrs running with shift basis. They use only the Aluminum bus bar for both distribution and feeder unit. In the metallic joints also they are using the aluminum. This reduces the cost consumption. The rating the load is at 3000A. But they designed the bus bar of 3200A. So it should withstand the thermal effect and also the short circuit effect. This mill started with the small unit and included other machines. So the panel is split into two sections as 1500A 2 no's, both are taken separately from the transformer. The 24 hours readings are monitored on the display in the panel. They are maintaining the power factor as 0.994.

They observed the temperature rise at one time, by the heat dissipated near the panel. At that condition the temperature is about 70oC. This is 20oC larger than tolerate temperature. The final operating temperature of the bus bar is limited by the temperature withstand capacity of bus bar conductor material itself. For aluminum the final operating temperature is limited to 85oC because the long term deterioration of the conductor, the joints or to the equipment connected to the bus bar. The mechanical strength is reduced at elevated temperature.

Let us know the design calculation of the current rating and the temperature rise calculations. The Dimension of the main bus bar in this textile mill is 2Run 150 x 12mm. As per the standard table of Al the current rating is 4275 Amps. The Ambient correction factor is 0.88. Assume ambient temperature 45oC instead of 35oC the derating factor, k1A is 0.96%. The Enclosure k2 is 0.84%. Correction factor for bus bar material (Al) is 1, Uprating PVC sleeve is 1. Therefore the combined derating =k1 x k1A x k2 x k3 x k4 = 0.88 x 0.96 x 0.84 x 1 x 1 = 0.675%. So the actual rating of considered bus bar = 4275 x 0.675 = 2889 Amps.

Temperature Rise Calculations has the correction factor as 0.88. The I2 is calculated from the dimension of main bus bar as 2 x 150 x 12 = 4275 x 0.88 x 0.91=3423.42 Amps. This current taken as I2.

$$\theta_1 = \left(\frac{3200}{3423.42}\right)^{1.7} \times 40 = 35.66^o C$$

Maximum temperature rise obtained as 35.66oC over and above the ambient temperature of 45oC within the limit. The heating effect of the short circuit current should be obtained. The minimum conductor size for the same short circuit current should be determined. This Al bus bar has the short circuit current of 4.6kA. The maximum SC current mentioned as 65kA, for this the conductor size calculated is about 813.26mm2 for Al. The actual bus bar size for the single phase is 50 x 12mm as 600mm2, so this dimension is to be safe limit. The other readings observed during the work were tabulated in the chapter .The short circuit withstanding capacity of bus bars for a given cross section of bus bar conditions under defined conditions of initial operation temperature of bus bar conductor and final peak operation temperature of bus bar conductors is determined by the following formula (applicable for disconnection times not exceeding 5 seconds).

From the below iterations, the temperature obtained for the Y phase of 280A as 41.277oC as the operating temperature. This temperature became steady state at the time constant of 6595 sec (i.e.,) less than 2 hours. Similarly for the R phase of 228A, temperature obtained as 38.15oCwith the time constant as 2146 sec and for B phase of 263A, temperature obtained as 40.185oC with 2135 sec. Table 5 shows the difference between the observed and calculated readings.

$$T_{i+1} = 41.278(1 - e^{-4.6796e-4t}) + \mathrm{T_i}(e^{-4.6796e-4t})$$

Iteration starts at Ti = 32oC

T1 =19.001 +17.26 = 36.261, τ =1319sec

T2 =29.267 +10.55 = 39.817, τ =2638sec

T3 =34.798 +6.250 = 41.049, τ =3957sec

T4 =37.78 +3.475 = 41.255, τ =5276sec

T5 =39.393 +1.884 = 41.277, τ =6595sec

c). Observations in Case 2

$$T_{i+1} = 34.058(1 - e^{-4.991e-4t}) + \mathrm{T_i}(e^{-4.991e-4t})$$

Iteration starts at Ti = 32oC

T1 = 19.78 + 12.26 = 32.04, τ =1921sec

T2 = 29.05 + 4.709 = 33.759, τ =3842sec

T3 = 32.139 +1.902, = 34.041 τ =5763sec

By the third iteration the theoretical maximum temperature attained. The time constant is about with the 2 hours exactly says 1hr.30min reaches the steady state temperature.

This method is an approximate method to find the maximum temperature. The feeder 1 has the maximum temperature as 36.11oC as 1910 sec as time constant. No.11

Depending upon the rating of the frames the values varies with that percentage. With the maximum utilization say in 800A rating spinning feeder 15 to 19 has the 270A , having 35% of load consumption has the temperature of 37oC on the bus bar and the approx. max temperature of 42oC, with the much less time in seconds as 2006. The seconds noted here is for the one time constant. All the temperature attains its value by the end of 2 time constant (i.e.,) less than two hours accurately 1 hour 30 minutes. The experimental value goes on same with the calculated value with less error as approached positive and negatives. All the temperature of the experimental results stays within 40oC, because there is no full load consumption. The max load is stated as only 40%. If there is full load intake there is a chance for rise in temperature which reduces the time constant.

4. BUS BAR MODELLING

The net heat transfer is the heat generated due to Julian heating (i.e.) I2R (t) and the heat loss due to convection and energy radiated to surroundings. The thermal modeling of the bus bar falls into two categories (i) steady state and (ii) unsteady state. For calculating the steady state and unsteady (or) transient of the bus bar using the thermal model with the equation relating the current to temperature can be derived by applying the conservation of energy.

When analyzing temperature rise, the convection heat flux is

$$q_c = h(T - T_\infty)$$

In the case of radiation

$$q_r = h_r(T - T_\infty)$$

where the radiation heat transfer coefficient is

$$h_r = \varepsilon\sigma(T^2 + T_\infty{}^2)(T + T_\infty)$$

Total heat flux, which is transferred from the model boundary to the atmosphere, is

$$q = q_c + q_r$$

The energy balancing equation is given as

$$\nabla . q = Q - \rho C_p \frac{\partial T}{\partial t}.$$

So, the heat transfer mechanism is governed by

$$\rho CpV \frac{dT}{dt} = I^2 R(t) - hAs(T - T_\infty) - \varepsilon\sigma As(T^4 - T_\infty{}^4)$$

This differential equation can be solved to obtain the steady state result of the temperature by assuming current as the input parameter.

Eq (6) can be solved by

$$\frac{dT}{dt} + a(T) = C$$

Eq (8) be the solution of the above energy balance equation. The [a (T)] part consist of the parameters in which be constant such as surface area, Emissivity, Stefan Boltzmann constant. The denominator part consists of the product of the density of the, material and the specific heat of the material and the volume of the conductor. The ambient temperature (T∞) considered depends on the environmental conditions, (T) is the operating temperature of the bus bar at that conditions. Here these two temperatures assumed as 32oC and 40oC.

In the solution of the differential equation the C part comprises of two terms. It is the sum of Julian losses and the (T∞) part which is taken into account during the calculation. For the sake of calculation, the equation (8) can be written as below

$$T_{i+1} = \frac{c}{a}(1 - e^{-at}) + T_i(e^{-at})$$

The heat transfer mechanism is done by the natural convection and the radiation from the tank to the atmosphere. But it is difficult to know the heat transfer coefficient on the boundaries because it depends on many factors such as material constant and model geometry as well as temperature. In this paper, we introduced the Nusselt number proposed by Churchill and Chu [7] in order to calculate the temperature-dependent heat transfer coefficient exactly. As the bus bar is vertical, the equation of the natural convection is

$$Nu_L = \frac{4}{3}\left[0.508 \Pr^{0.5}(0952 + \Pr)^{-0.25} Gr_L{}^{0.25}\right]$$

where Pr is Prandtl number.

In this equation, the Rayleigh number is defined asRa=Gr.Pr

$$Gr_L = \frac{g\beta(T + T_\infty)L^3}{v^2}$$

where the Pr = 0.699 to 0.7 in the air. Gr_L is Grashop number, g is acceleration of gravity, β is the thermal expansion coefficient, and v is dynamic viscosity and L is the length of the conductor. The convection heat transfer coefficient is

$$h = \frac{K}{L} Nu_L$$

Convection heat transfer coefficient, h depends on the Thermal conductivity of the material in J/Kg.K to the length of the conductor in (m). When the current carrying element decrease in the length the convection heat transfer coefficient increases.

Table 2. Thermal properties of several common conductor materials

Material	ρ (Kg/m3)	Cp (J/Kg.K)	ρ Cpx10-6 (J/m3.K)
Hard drawn copper	8940	384	3.433

Aluminum	2707	894	2.413
Steel	7800	480	3.744

5. NUMERICAL ANALYSIS

The equation for steady ampacity can be written by removing the time derivative term from Eqn.

Since current be the input parameter this can be written in terms of temperature

$$I = \left\{ \frac{hAs(\mathrm{T_{max}} - \mathrm{T_\infty}) + \varepsilon\sigma\,\mathrm{As}(\mathrm{T_{max}}^2 - \mathrm{T_\infty}^2)}{R(\mathrm{T_{max}})} \right\}^{\frac{1}{2}}$$

Before Eqn. 13 can be solved for the bus bar temperature, all terms must be expressed as a function of the component temperature. For example, the electrical resistance can be written as a function of temperature. So the Table 1 shows the electrical resistivity of the different material at 20oC and the temperature coefficient of resistivity for several common material conductors.

6. RESULTS AND DISCUSSIONS

The below tables specifies the comparison between the materials of copper and Al conductor on the performance of the temperature rise due to the ampacity.

There is a small percentage degree of error. This becomes high when the utilization of active power increases. In this feeder the single bus bar carries 400A which explains that 25in x12in carries 400A as per IE rules of Copper Association. The temperature is directly proportional to the current produced in the bus bar. The above tabulated current reading in R phase is 57%, Y phase is 70%, and B phase is 65.75% of total load consumption. So the temperature rises up to the utilized level. When there is increase in the active power then the load consumption will raise causes the rise in the temperature up to 70oC.

The comparisons of the two materials have the high temperature in the cu bus bar as its current rating is high. In the Al material the maximum temperature should be within the limit as per the standard. So the applications are designed to maintain the standards.

Table 3. Comparison of the parameters

Phases	**Current (Amps)**	**Exper Temperature at the bus bar (oC)**	**Calculated Temperature (oC)**	**Error**	**Maximum temperature (oC)**
R	228	35	38.150	-3.150	44.790
Y	280	45	41.277	3.723	51.233
B	263	38	40.185	-2.185	49.020

Table 4. Comparison of the parameters

Phases	**Current (Amps)**	**Exper Temperature at the bus bar (°C)**	**Calculated Temperature (°C)**	**Error**	**Maximum temperature (°C)**
R	180.20	34	34.158	-0.158	36.841
Y	185.90	36	34.295	1.705	37.150
B	181.30	34	34.185	-0.185	36.900

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