

Experimental and Analytical Study on the Bus Duct System for the Prediction of Temperature Variations Due To the Fluctuation of Load

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Abstract – In this paper, a thermal model is developed for the bus bar system to predict the temperature variation during the transient time period and to calculate both the steady-state and transient electrical current carrying capacity (ampacity) of bus bar. The bus bar system installed in the power house of Kumaraguru College of Technology, Coimbatore has been considered. Temperature variation predicted in the modelling is validated by observing the current and steady state temperatures in different feeders of the bus bar. Magnetic field of the extreme phases R and B induces more current in the middle phase Y. Hence, the steady state temperature in the phase Y is greater than other two phases. The transient capabilities of the bus bar are illustrated by calculating the variations in the bus bar temperature when it is subjected to a step change in current during the peak hours due to increase in hostel utilities and facilities (5.30 pm to 10.30 pm). The physical and geometrical properties of the bus bar and temperature variation in the bus bar are used to estimate the thermal time constants for common bus bar cross-sections. An analytical expression for the time constant of the bus bar is derived.

Keywords: Air insulated bus bar, Heat transfer, Temperature rise, Current carrying capacity, Mathematical model development

1. Introduction

Bus bar is one of the most primary elements of a power system connecting a variety of elements like generators, transmission lines and loads. Bus bars have been traditionally used in switchgears, control gear assemblies and for power distribution in buildings. Bus bar provides a wide variety of interconnection methods and improves thermal characteristics. The temperature rise of bus bar system is a vital factor that has an adverse effect on its performance. The amperage, cross sectional dimensions, layout and conductivity of the bus bar are the factors that determine the rate of heat generated in the bus bar. A fault in the bus bar due to increase in temperature leads to loss of all the components connected to it. The protection scheme of bus bar should be fast, reliable and stable. In order to design a power apparatus such as the bus bar, the current carrying capacity (or ampacity) should be exactly valued since it is limited by maximum operating temperature. Finite-element method was used to solve the governing thermal equations.

Contact resistance between copper conductors and corresponding temperature rise was measured. It was found that there was very little difference between the

temperature rises at the measuring positions in the same phase. The bus bar temperature increases linearly with the increase in the insulation material thickness [1]. Harmonic eddy current analysis is carried out and the power losses are calculated in the conductor and enclosure tank. The accuracy of both methods is verified by the comparison of the measured and calculated temperature in a single phase and three-phase GIB [2]. The analysis used to calculate the temperature rise in the bus bars of switch gear using CFD (Computational Fluid Dynamics) techniques. The values obtained by computational analysis compared with experimental results. These results can be employed while designing the switch gear to minimize the bus bar chamber. [3].

A new technique has been developed that can be used to estimate the temperature rise in the extra high voltage bus bar. The heat transfer coefficient was calculated according to the model geometry and varying temperature coupled with the finite element method [4]. Evaluation of the impedance of bus bar systems with ferromagnetic enclosures, impedance was modelled by averaging phase resistance and effective reactance obtained from the measured data. It was found that the discrepancy of impedance was very small and it was less than 2% [5].

The parametrical analysis of rigid bus bar short circuit calculation has been compared to those obtained from the corresponding IEC 865/1993 standard. The results showed minimal differences between the two methods [6]. Magneto fluid-thermal fields of 3-phase/4-pole air-insulated bus bar trunking system, was non-ventilated and

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enclosed by steel shielding.

It was found that the maximum error of temperatures between simulation results and experiment results was about 9.5°C. Moreover, bigger the size of the steel shielding, lower is the temperature rise of the bus bar [7]. By applying the Nusselt number considering material constant and model geometry for natural convection, the temperature predicted by coupled magneto thermal analysis showed good agreement with the experimental data [8]. The analysis used to calculate the temperature rise in the bus bars of switch gear. The values obtained by computational analysis compared with experimental results. These results can be employed while designing the switch gear to minimize the bus bar chamber [9].

In most of the research publications, temperature rise in bus bar system are studied and discussed for the general configuration like rectangular, square and cylinder. In this Paper, temperature rise in the bus bar which is used in panel board of an educational Institution in which load variation is very much as it distributes the power for both laboratories of different branches, hostel and quarter facilities. This paper deals with a practical application and study the temperature variations dynamically both during base load and peak load conditions.

2. Magnetic Field Analysis

2.1 Magneto static governing equation

When steady state source current flows through the three phases of the bus bar system. To analyse the losses and study the temperature rise in the bus bar, magnetic analysis is necessary to study the eddy current developed in the nearby conducting material. Magneto static governing equation is given as

$$\nabla \times \vec{H} = \vec{J} \quad (1)$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad (2)$$

$$\nabla \cdot \vec{B} = 0 \quad (3)$$

Magnetic vector potential \vec{A} is

$$\vec{B} = \nabla \times \vec{A} \quad (4)$$

$$\nabla \times \vec{A} = \mu \vec{H} \quad (5)$$

Then Eq. (1) is written as

$$\nabla \times \frac{1}{\mu} (\nabla \times \vec{A}) = \vec{J} = \vec{J}_s + \vec{J}_e \quad (6)$$

Where \vec{J}_s is source current and \vec{J}_e is eddy current. The eddy current in the conducting material is

$$\vec{J}_e = \sigma_e \vec{E} = -\sigma_e \frac{\partial \vec{A}}{\partial t} \quad (7)$$

From the above equation, we can write the governing equation as

$$\nabla \times \frac{1}{\mu} (\nabla \times \vec{A}) = \vec{J} - \sigma_e \frac{\partial \vec{A}}{\partial t} \quad (8)$$

Considering the z-directional current, we write the governing Eq. (1) as

$$\frac{\partial}{\partial x} \left(g_y \frac{\partial A}{\partial x} \right) + \frac{\partial}{\partial y} \left(g_x \frac{\partial A}{\partial y} \right) = -\vec{J}_s + j\omega \sigma_e \vec{A} \quad (9)$$

2.2 Eddy current

Eddy current in the conducting material is induced due to the time varying source current flowing in the three phase of the bus bar. The phase Y is in between R&B hence magnetic field forming around the R and B induces the eddy current in the nearby phase Y. Therefore the power losses due to eddy current in the phase Y will be greater than other two phases.

2.3 Power losses

Power losses are caused by the both source current and induced eddy current in the phases. When the power losses are calculated exactly these can be used as input for predicting temperature rise in the bus bar, power losses in the bus bar unit length is

$$P = \int \frac{J^2}{\sigma} ds$$

3. Thermal Analysis

3.1 Bus bar panel arrangement in the power house

The experimental observations have been taken in the power house of Kumaraguru College of Technology, Coimbatore.

The power house has the capacity of 500A rating and 1000 KVA transformer substation. In the transformer the voltage is step down to 440V for distributing to the load centres. These arrangements are done in an enclosed chamber made of steel with minimum amount of ventilation. Low tension voltage is drawn from the transformer using high stranded cable to the panel underground. The conductor used in the panel board is copper. The power from the panel is given to various sub stations. The current rating of the bus bar depends on the volt ampere rating.

3.2 Mathematical modelling

The net heat transfer in the bus bar is the heat generated due to Julian heating and the heat loss due to convection and radiation. By considering the energy balance, the thermal modelling of the bus bar under steady and unsteady state can be developed. During temperature rise, the convection heat flux is given in Eq. (10) and radiation is given in Eq. (11).

$$q_c = h(T - T_\infty) \quad (10)$$

$$q_r = h_r(T - T_\infty) \quad (11)$$

In the Eq. (11), h_r is the radiation heat transfer coefficient and is expressed as

$$h_r = \varepsilon\sigma(T^2 - T_\infty^2)(T + T_\infty) \quad (12)$$

Total heat flux transferred from the bus bar to the atmosphere is

$$q = q_c + q_r \quad (13)$$

Heat generation due to the resistance to the current flow is $Q = I^2R(t)$. The current carrying capacity of the bus bar is limited by the maximum operating temperature.

Energy balance equation can be written as

$$Q = I^2R(t) = \text{Rate of heat sorted in the bus bar} + \text{Rate of heat dissipated from the bus bar from convection and radiation} \quad (14)$$

Then energy balance equation is developed as

$$\rho C_p V \frac{dT}{dt} = I^2R(t) - hA_s(T - T_\infty) - \varepsilon\sigma A_s(T^4 - T_\infty^4) \quad (15)$$

This differential equation shown in Eq. (15) can be solved to obtain the steady state result of the temperature by assuming current as the input parameter.

$$\rho C_p V = I^2R(t) - hA_s(T - T_\infty) - \varepsilon\sigma A_s(T - T_\infty)(T + T_\infty)(T^2 + T_\infty^2) \quad (16)$$

Eq. (16) is simplified and given as

$$\frac{dT}{dt} + \left[\frac{hA_s\varepsilon\sigma A_s(T + T_\infty)(T^2 - T_\infty^2)}{\rho C_p V} \right] (T) = \left[\frac{I^2R(t)}{\rho C_p V} \right] + \left[\frac{hA_s\varepsilon\sigma A_s(T + T_\infty)(T^2 - T_\infty^2)}{\rho C_p V} \right] (T_\infty) \quad (17)$$

Eq. (17) is similar to the differential equation.

$$\frac{dT}{dt} + a(T) = C \quad (18)$$

Solution for the above given differential equation is

$$T_{i+1} = \frac{C}{a}(1 - e^{-at}) + T_i(e^{-at}) \quad (19)$$

Where

$$C = \left[\frac{I^2R(t)}{\rho C_p V} \right] + \left[\frac{hA_s\varepsilon\sigma A_s(T + T_\infty)(T^2 + T_\infty^2)}{\rho C_p V} \right] (T_\infty)$$

$$a = \left[\frac{hA_s\varepsilon\sigma A_s(T + T_\infty)(T + T_\infty^2)}{\rho C_p V} \right] (T)$$

Bus bar with rectangular shape cross section is being used in the panel board. The size of the bus bars is a two run 25×12 mm Copper for Phases (RYB) and single run 25×12 mm Copper for Neutral. It passes horizontally along the length of the panel board. During the distribution to load centre the ratings of the bus bar decreases. Fig. 1 shows the arrangement of three phases RYB and neutral of the bus bar conductor. The spacing between the conductors is 35 mm. The Fig. 1 also shows the cross sectional view of the bus bar. The transient temperature of the bus is

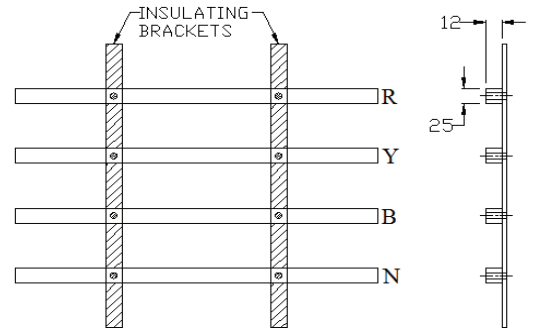


Fig. 1 Bus bar arrangement

Table 1. Parameters used in thermal model

Bus bar dimensions in (mm)	Width-25; Thickness-12; Length-304.8	
Surface area (A_s) m^2	22.5×10^{-3}	
Volume (V) m^3	9.144×10^{-5}	
Convective heat transfer coefficient, (h) $W/m^2 K$	3.123	
Emissivity (s)	0.5	
Stefan boltzmann constant (σ) W/m^2K^4	5.7×10^{-8}	
ρC_p $J/Kg K$	3411×10^3	
Ambient temperature (K)	305	
Operating temperature (K)	313	
Resistance of the conductor (Ω)	1.7272×10^{-5}	
Current (Amps)	R phase - 228	R phase - 392
	Y phase - 280	Y phase - 412
	B phase - 263	B phase - 402

determined by solving the differential Eq. (17).

A less complex approach for the calculation of the transient temperature exists, but it has several limitations that restrict its application and accuracy. Parameters considered in the Eq. (17) are calculated and tabulated in the Table 1.

With the parameters given in the Table 1 and numerical analysis is performed for the Y phase with current rating of 280 Amps hence Eq. (17) is simplified in terms of time as given below.

$$T_{i+1} = 41.278(1 - e^{-4.6796-4\tau}) + T_i(e^{-4.6796-4\tau}) \quad (20)$$

For these restrictive assumptions, the temperature of bus bar material can be expressed in terms of a thermal time constant

$$\frac{T(t) - T_1}{T_2 - T_1} = 1 - e^{-\frac{t}{\tau}} \quad (21)$$

The thermal time constant “ τ ” in equation can be denoted as a function of the thermal capacitance of the bus and both the radiative and convective thermal resistances from the surface of the bus bar.

The thermal time Constant is,

$$\tau = \frac{\rho C_p (V/A_s)}{h + \varepsilon \sigma (T^2 - T_\infty^2)(T - T_\infty)} \quad (22)$$

Where T is a fixed reference temperature used to calculate the radiative resistance whose value can be estimated for the average temperature of $(T + T_\infty)/2$. Eq. (22) shows that the thermal time constant is a function of the convective heat transfer coefficient (h), the geometry of the bus (V/A_s) , the ambient temperature T_∞ . Also it is the function of the reference radiative temperature (steady state temperature) T, the bus emissivity ε and the thermal capacity ρC_p . Conditions which lead to a smaller heat loss from the surface and bus design with a larger ratio of volume to surface area (or ratio of cross-sectional area to perimeter) will lead to longer time constants. By substituting the above said parameters and one time constant τ is calculated as $\tau = 2077$ seconds. Transient temperature rise for multiples of time constant τ , 2τ , 3τ , 4τ etc are found from the Eq. (20). Iteration starts at $T_i = 32^\circ\text{C}$

$$\begin{aligned} T_1 &= 37.768, \tau = 2077\text{sec} \\ T_2 &= 40.775, \tau = 4154\text{sec} \\ T_3 &= 41.208, \tau = 6231\text{sec} \\ T_4 &= 41.277, \tau = 8308\text{sec} \end{aligned}$$

From the above iterations, it is found that the steady state temperature for the Y phase of the bus bar which carries 280A is 41.277°C . This temperature attained the steady state at the time of 4τ i.e. (8308 sec) which is more

Table 2. Comparison of observed and calculated steady state temperatures for base load current

Phases	Current (Amps)	Observed Temperature at the bus bar ($^\circ\text{C}$)	Calculated Temperature at the bus bar ($^\circ\text{C}$)	Error in %	Time Constant (seconds) for attain steady state
R	228	35	38.151	9.0	4τ (8308)
Y	280	45	41.277	8.3	4τ (8308)
B	263	38	40.185	5.8	4τ (8308)

Table 3. Comparison of observed and calculated steady state temperatures for peak load current

Phases	Current (Amps)	Observed temperature at the bus bar ($^\circ\text{C}$)	Calculated temperature at the bus bar ($^\circ\text{C}$)	Error In %	Time constant (seconds) for attain steady state
R	392	48	50.182	4.5	4τ (8308)
Y	412	51	52.085	2.1	4τ (8308)
B	402	50	51.122	2.2	4τ (8308)

than 2 hours. Similarly for the R phase and B phase which are carrying current of 228A and 263A respectively, the steady state temperatures calculated from modelling and from the observations are given in the Table 2.

Sudden change in the load during peak hours (5.30 pm to 10.30 p m) causes the step change in current rating as follows, in R phase it is 392 A, in Y phase it is 412 A and in B phase it is 402 A. For these new current rating in all the three phases during the peak hours, analysis have been carried out with the Eqs. (17), (19) and (20).

Steady state temperatures attained by the bus bar with corresponding time constants and experimentally observed steady state temperature in three phases are given in the Table 3.

4. Result and Discussion

Temperature variations in the Y phase bus bar from the transient to steady state condition for the current rating of 280A and for the step changing current of 412A for a day starting from 6 am is shown in the Fig. 2. Transient

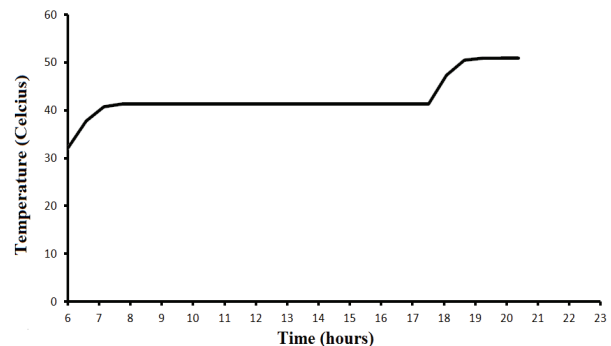


Fig. 2. Temperature variations from transient to steady state condition

temperature changes for the current rating of 280A reaches the steady state temperature of 41.277°C within a time of 4τ (8308 seconds) and remain constant till the time of 16.50 hours. It is observed that step changing current of 392 A in R phase, 412 A in Y phase and 402 A in B phase at 17.50 hours causes the change in temperature and attain the new steady state temperature of 50.182°C in R phase, 52.085°C in Y phase and 51.122°C in the B phase at 22.50 hours within a time of 4τ (8308 seconds) and remains constant thereafter. Fig. 1 shows the arrangement of bus bar R, Y, B and N in panel. R phase is situated in the outer layer, Y phase bus bar is kept in between R and B bus bars. Hence from this arrangement, it is understood that Y phase will have the increased effect of eddy current due to the magnetic field of R and B phase bus bars. Therefore current flow through the Y phase bus bar (280A) is greater than the R phase bus bar (228A) and B phase bus bar (263A). R phase bus bar is in the outer layer which will have lesser effect of the eddy current. Hence current rating and temperature of the R phase bus bar is lower than the B phase bus bar. It is proved from the experimental observations and calculated values of the temperature changes in the R, Y, and B phases of the bus bar given in table.2. Temperature of the Y phase bus bar is greater than the other two phases of the bus bar.

R phase bus bar is in the outer layer and therefore is exposed to the atmosphere. Hence the current rating and temperature of the R phase is comparatively lower than the other bus bars. From the Table 2, it is understood that the calculated steady state temperatures of the R, Y and B phase bus bars from the modelling are in good agreement with the observed steady state temperatures of the R, Y and B phase bus bars respectively. From the mathematical modelling, steady state temperatures of R, Y and B phase bus bars for the full load current rating of 392 A in R phase, 412 A in Y phase and 402 A in B phase are calculated. The maximum steady state temperature attained in the bus bar is 52.085°C .

This bus bar could withstand the temperature of steady state value for about four hours. This high level is attained at the interval between 5.30 pm and 10.30 pm. The bus bar has been made of copper which can withstand even at the high temperatures of about 100°C . But due to high temperature there is a chance of the material being corroded and the change in the color of the bar due to excessive oxidation at the bolted joints. From the observed and calculated results it is discussed that the rating of the bus bar dimensions should be changed to the next recommended dimensions to keep the bus bar within the safe limit. Otherwise more ventilation needs to be provided in the feeder section for the circulation of air at the high temperature bolted joints. The observations are carried out in the panel board for the institution power distribution system (for both institution and hostel facilities) in which load variation suddenly increases to maximum current rating in the evening hours (5.30 to 10.30 pm).

Hence it is necessary to study the transient temperature variation and maximum steady state temperature of the bus bar conductor.

Also it is necessary to study the temperature variation in different phases. Phase R in extreme outside is exposed to the atmospheric air where as Y phase in between the phases R and B. Hence phase Y will be affected by the electromagnetic field of the phase R and B and convection heat dissipation from the phase Y will be less compare to phase R.

From this study, it is concluded that bus bar conductor which is in between the other two phases will have the higher thermal stresses and also affected by the eddy current.

5. Conclusion

In this study, simplified mathematical model has been developed by considering the thermo physical properties and convective heat transfer coefficient of all three phases of the bus bar and also involve the time constant. Results obtained from the modelling shows the temperature variation in different phases of the bus bar for different current rating in each phase which consistently matches with the observed values. The model can be simulated for different configuration of bus bar sizes. (width and thickness of the bus bar) so that size of the bus bar can be optimized. The simplified expression can be used to estimate the transient thermal behaviour of the bus bar when it experiences step change in current due to the load variation in terms of time constant.

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