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Experimental and Analytical Study of Effect of Forced Convectional Cooling of Bus Duct System in the Prediction of Temperature Rise

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Abstract

In this research article, temperature rise on the bus duct system installed in sangeeth textiles Coimbatore, India, is analyzed both experimentally and theoretically by developing a thermal model. Presently heat dissipation from the bus duct system is in natural convection mode. In this paper, the temperature rise in the bus duct system has been predicted in both natural and forced convection mode. Temperature variation predicted in the modeling is validated by experimental observations in both natural and forced convection modes. Thermal time constant was also predicted to find the steady state temperature of the bus duct system in both natural and forced convection mode. From the study, it is understood that about 45 % of the temperature rise is reduced. Hence, power loss due to heat generation is also reduced.

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

Introduction

In the electrical sense, the term bus is used to describe a junction or circuit, usually in the form of a small number of inputs and many outputs. Bus bar indicates the form the bus system consists of, which are mainly bars of conducting material. Bus bars are used within electrical insulations for distributing power from a supply point to a number of output circuits. They may be used in a variety of configuration ratings from vertical risers carrying current to each floor of a multi-storey building to bars which are used extremely within distribution panels or within an industrial process. In any electrical circuit some electrical energy is lost as heat which, if not kept within safe limits, will impair the performance of the power distribution system. This energy loss also leads to financial loss over a period of time and is proportional to the effective resistance of the conductor and square of the current flow through it. A higher working temperature means that the energy passing through is being wasted. Designing a system with lower energy losses requires the use of more conductor material (i.e., larger cross section areas). This results in more reliable operation due to the lower working temperature and also, since the cost of lifetime energy losses is far greater than the cost of first installation this results in lower lifetime costs [1].

2. Current-Carrying Capacity of Bus bars

The current-carrying capacity of a bus bar is limited by the maximum acceptable working temperature of the system, taking into account the properties of the conductor material, the materials used for mounting the bars, the limitations of the cables (including their insulation) and devices connected to the bars. Continuous maximum rating (CMR) and permissible temperature rise is the maximum r.m.s. current that the bus system can carry continuously without exceeding temperature rise limits [2-3].

2.1 Thermal effects

In power distribution 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 [4].

Aluminium and copper conductors are susceptible to oxidation and corrosion at elevated temperatures above 85–90ºC. Universal practice is to restrict the operating temperature of the bus conductors made up of aluminum or copper to 85–90ºC for all ratings, at least in the medium range of current flow up to 3200A. Currents are more difficult to handle than voltages due to mutual induction between the conductors and between the conductor and the enclosure. Bus bars 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, which are simpler to use and can meet most current requirements on an LV or HV systems. Further mitigation of skin and proximity effects in large ratings can be done using two bus bars or more [5].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 [6].

2.2 Skin and proximity effects on a current carrying conductor

In a bus conductor which carries a.c. induces an electric field which in turn 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) [3].

The induced e.m.f. is produced in the conductor by its own electric field cutting the conductor. It is denser 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. it's '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 analyzing the skin effect. 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 leading to increase of heat loss and hence power loss. 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'. Since the skin effect results in an increase in the effective resistance of the bus bar system it directly influences the heating and the voltage drop of the conductor and indirectly reduces its current carrying capacity [7-11].

2.3 Electromagnetic analysis of bus bar:

To analyze 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. Eddy current in the conducting material is induced due to the time varying source current flowing in the three phase of the bus bar. Power losses are caused by both the 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 [2].

3. Thermal Analysis on the prediction of temperature rise of the Bus bar

3.1 With natural convection

The observations have been noted down from the power house of Sangeeth textiles mill, Coimbatore, which has the capacity of 2500A rating and 1500 KVA transformer substation. In the transformer, the voltage is stepped down to 440V for distribution to the load centers. These arrangements are done in an enclosed chamber made of steel with minimum amount of ventilation with natural or free convectional heat dissipation. Low tension voltage is drawn from the transformer using high standard cable to the panel underground. The panel arrangement is shown in Figure1. Arrangement of bus bar is shown in Figure 2.The conductor used in the panel board is copper. In this textile mill, there are 8 sections consisting of 2 Spinners, 2 Auto cones and 2 Drawers, one each of guarding and lighting. The power from the panel passes through the main bus bar and is distributed through various sub stations to the different sections of the mill. The current rating of the bus bar depends on the volt ampere rating. Bus bar with rectangular shape cross section is being used in the panel board. The sizes of the main bus bars are 100 × 6 mm with 3 runs per phase and with a single run of 100 × 6 mm for the Neutral. It passes horizontally along the length of the panel board. During the distribution to load centre the ratings of the bus bar decreases.

Figure 1 Panel arrangement in the power House

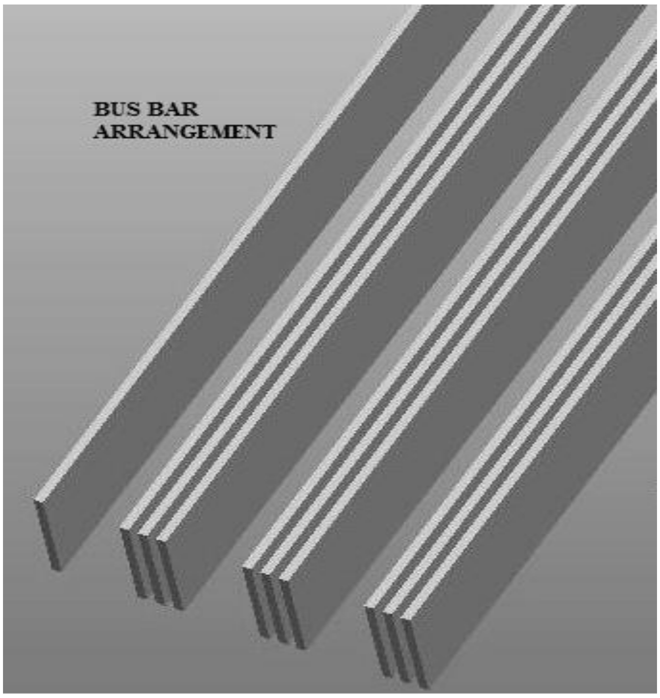

Figure.2 Bus bar with 3 conductors per phase

In the arrangement of bus bar, R phase is situated in the outer layer; Y phase bus bar is kept in between the 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 (1800 A) is greater than the R phase bus bar (1600 A) and B phase bus bar (1700 A). R phase bus bar lies in the outer layer which will have lesser effect on the eddy current. Hence current rating and temperature of the R phase bus bar is lower than the B phase 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.

3.2 Mathematical Modeling for the prediction of temperature rise under the Natural Convection:

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. In this first consider the heat dissipation by natural or free convection mode. Where outdoor bus bar systems are concerned, calculations should always be treated as in still air (i.e. without wind effect) unless specific information is given to the contrary. By considering the energy balance, the thermal modelling of the bus bar under steady and unsteady state conditions can be developed [1]. During temperature rise, the convection heat flux is given in Equation (1) and radiation is given in Equation (2).

$$q_c = h(T - T_\infty) \quad (1)$$

$$q_r = h_r(T - T_\infty) \quad (2)$$

h_r is the radiation heat transfer coefficient and is expressed as

$$h_r = \varepsilon\sigma(T^2 + T_\infty^2)(T + T_\infty) \quad (3)$$

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

$$q = q_c + q_r \quad (4)$$

Heat generation due to the resistance to the current flow is Q = I^2 R(t). The current carrying capacity or ampacity of the bus bar is limited by the maximum operating temperature.
Energy balance equation can be written as Q = I^2 R(t) = Rate of heat sorted in the bus bar + Rate of heat dissipated from the bus bar from convection and radiation (5)

Then energy balance equation is developed as

$$\rho C_p V \frac{dT}{dT} = I^2 R(t) - hA_s(T - T_\infty) - \varepsilon\sigma A_s(T^4 - T^4) \quad (6)$$

$$Nu_x = 0.508\Pr^{0.5}(0.952 + \Pr)^{-0.25} Gr_x^{0.25} \quad (7)$$

$$Gr_x = \frac{g\beta(T - T_\infty)L^3}{\nu^2}$$

$$h = \left(\frac{k}{X}\right)Nu \quad (8)$$

This differential equation shown in Equation (6) can be solved to obtain the steady state result of the temperature by assuming current as the input parameter.

$$\rho C_p V \frac{dT}{dT} = I^2 R(t) - hA_s(T - T_\infty) - \varepsilon\sigma A_s(T - T_\infty)(T^2 + T_\infty^2) \quad (9)$$

Equation (9) is simplified and given as

$$\frac{dT}{dt} + \left[\frac{hA_s\varepsilon\sigma A_s(T + T_\infty)(T^2 + T_\infty^2)}{\rho C_p V}\right](T) = \left[\frac{I^2R(t)}{\rho C_p V}\right] + \left[\frac{hA_s\varepsilon\sigma A_s(T + T_\infty)(T^2 + T_\infty^2)}{\rho C_p V}\right](T_\infty) \quad (10)$$

Equation (10) is similar to the differential equation

$$\frac{dT}{dt} + a(T) = C \quad (11)$$

Solution for the above given differential equation is

$$T_{i+1} = \frac{c}{a}(1 - e^{-at}) + T_i(e^{-at}) \quad (12)$$

Where

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

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

Table 1 Parameters used in thermal model

S.No	Parameters	Natural convection	Forced convection	
			Perpendicular to bus bar axis	Parallel to bus bar axis
1	Bus bar dimensions in mm	Width-100; Thickness-06; Length-1000	Width-100; Thickness-06; Length-1000	Width-100; Thickness-06; Length-1000
2	Surface Area (A_s) m^2	0.2132	0.2132	0.2132
3	Volume (V) m^3	6×10^{-4}	6×10^{-4}	6×10^{-4}
4	Convective heat transfer coefficient, (h) $Wm^{-2}K^{-1}$	4.3	43.67	18.64
5	Emissivity (s)	0.5	0.5	0.5

6	Stefan Boltzmann Constant (σ) $Wm^{-2}K^{-4}$	5.7×10^{-8}	5.7×10^{-8}	5.7×10^{-8}
7	$\rho C_p\ Jm^{-3}K^{-1}$	3411×10^{3}	3411×10^{3}	3411×10^{3}
8	Ambient Temperature (K)	305	305	305
9	Operating Temperature (K)	333	313	318
10	Resistance of the conductor (Ω)	1.7272×10^{-5}	1.7272×10^{-5}	1.7272×10^{-5}
11	Current (Amps)	R phase - 1600 Y phase - 1800 B phase – 1700	R phase - 1600 Y phase - 1800 B phase – 1700	R phase - 1600 Y phase - 1800 B phase – 1700

Table 2 Experimental Observation of Temperature rise in Natural convection

Phase	Current (A)	Temperature measured at different points in the main bus bar under the Natural Convection in °C				
		Pt 1	Pt 2	Pt 3	Pt 4	Average
R	1600	54	53	54	54	54
Y	1800	61	60	61	61	61
B	1700	57	58	58	58	58

The transient temperature of the bus is determined by solving the differential equation (10). Parameters considered in the Equation (10) 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 1800 Amps. Table 2 shows experimental observation of temperature rise under natural convection hence Equation (10) is simplified in terms of time as given below

$$T_{i+1} = 65.12(1-e^{-8.3\times10^{-4}(t)}) + T_i e^{-8.3\times10^{-4}(t)} \qquad (13)$$

Equation (13) gives the temperature variation in the Y phase bus bar with the time until the system attains the steady state condition. For the transition condition, the temperature of bus bar material can be expressed in terms of a thermal time constant. Time constant is the response time for the transition system when it attains 63.2 % of the final steady state temperature. Hence number of time constant is to be calculated for calculating the final steady state temperature. Thermal time constant is the function of geometrical, physical and thermal properties of the bus bar material.

$$\frac{T(t)-T_1}{T_2-T_1} = 1-e^{\frac{t}{\tau}} \qquad (14)$$

The thermal time constant is,

$$\tau = \frac{\rho C_p \left(V/A_s \right)}{h+\varepsilon\sigma(T^2 - T_\infty{}^2)(T - T_\infty)} \qquad (15)$$

Where, T is a fixed reference temperature used to calculate the radiative resistance whose value can be estimated for the average temperature of $(T + T_\infty)/2$. Equation (15) shows that the thermal time constant is a function of the convective heat transfer coefficient (h), the geometry of the bus (V/A_s) and 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, the onetime constant τ is calculated as τ = 1199 seconds. Transient temperature rise for multiples of time constant τ, 2τ, 3τ, 4τ etc are found from the Equation (13). Iteration starts at initial temperature of T_i = 32°C, temperature variation in the Y Phase of the main bus bar as given below:

τ = 1199 sec for T_1 = 52.82°C
2τ = 2398 sec for T_2 = 63.44°C
3τ = 3597 sec for T_3 = 65.03°C
4τ = 4796 sec for T_4 = 65.11°C
5τ = 5995 sec for T_5 = 65.11°C

Hence, steady state temperature of the Y Phase bus bar calculated from mathematical modelling is 65.11°C.

3.3 Mathematical Modelling for the prediction of temperature rise under the Forced Convection arrangement in enclosure:

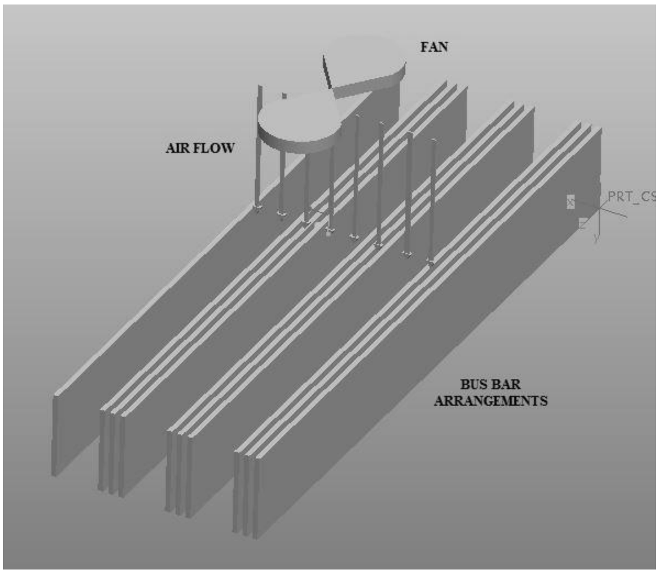

Figure 3 Air flow perpendicular to bus bar axis

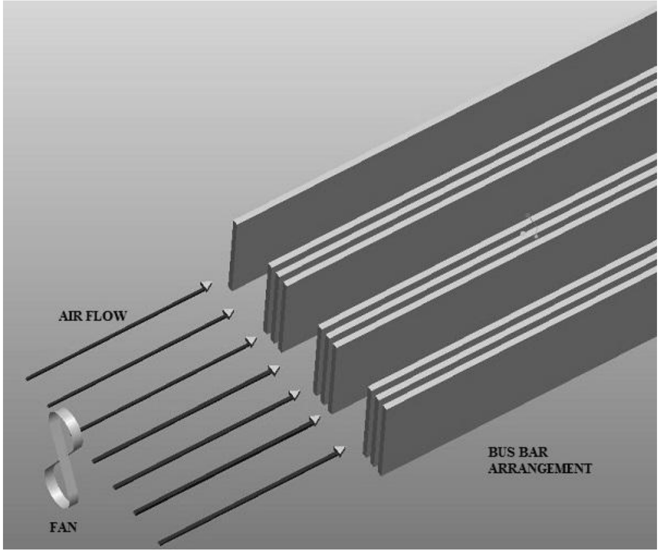

Figure 4 Air flow parallel to bus bar axis

The heat dissipated per unit area by convection depends on the shape and size of the conductor and its temperature rise above ambient temperature. This value is usually calculated for still air conditions but can be increased greatly if there is forced air-cooling. In this study, experiments are conducted in the main bus bar to find the effect of forced cooling arrangement by providing the circulation of air in two different directions. Figure 3 shows air flow perpendicular to bus bar axis and Figure 4 shows air flow parallel to bus bar axis.

Table 3 Experimental Observation of Temperature rise in Forced convection

Phase	Current (A)	Temperature measured at different points in the main bus bar in °C for forced convection									
		Air flow direction perpendicular to the bus bar axis					Air flow direction parallel to the bus bar axis				
		Pt 1	Pt 2	Pt 3	Pt 4	Average	Pt 1	Pt 2	Pt 3	Pt 4	Average
R	1600	38	38	39	38	38	42	42	42	43	43
Y	1800	41	41	41	40	41	45	45	44	45	45
B	1700	40	40	40	39	40	44	44	43	44	44

Observations are carried out for the forced air in the direction perpendicular to the main bus bar axis and air is blown along (parallel to) the axis. Table 3 show the experimental observation of temperature rise under forced convection. Thermal modelling for the prediction of temperature rise under the forced convection mode is carried out in the same procedure of natural convection mode except that of the value of h_c convective coefficient. For the forced convection, heat transfer correlations consist of Nusselt number, Prandtl number and Reynolds number as given below:
For the air flow direction perpendicular to the bus bar axis,

$$Nu_x = 0.205\,\mathrm{Re}_x^{0.731}\,\mathrm{Pr}^{\frac{1}{3}} \tag{16}$$

For the air flow direction parallel to the bus bar axis,

$$Nu_x = 0.664\,\mathrm{Re}_x^{\frac{1}{2}}\,r^{\frac{1}{3}} \tag{17}$$

When air flows in the direction perpendicular to the bus bar axis

$$T_{i+1} = 37.55\left(1-e^{-4.9\times10^{-3}t}\right)+T_i e^{-4.9\times10^{-3}t} \tag{18}$$

When air flows in the direction parallel to the bus bar axis

$$T_{i+1} = 43.97\left(1-e^{-2.29\times10^{-3}t}\right)+T_i e^{-2.29\times10^{-3}t} \tag{19}$$

Thermal time constant for both types of forced cooling arrangement are calculated from the equation (15) and iteration starts at the initial temperature of T_i = 32°C. Temperature variation in the Y Phase of the main bus bar as given below:

Air flow Perpendicular
τ = 216secfor T_1 = 35.62°C
2τ = 432secfor T_2 = 37.32°C
3τ = 648sec for T_3 = 37.54°C
4τ = 864sec for T_4 = 37.54°C
5τ = 1080sec for T_5 = 37.54°C

Air flow Parallel
τ = 436 sec for T_1 = 39.56°C
2τ = 872 sec for T_2 = 43.37°C
3τ = 1308 sec for T_3 = 43.94°C
4τ = 1744 sec for T_4 = 43.94°C
5τ = 2180 sec for T_5 = 43.94°C

4. Result and Discussion

From the below tables 4, 5, & 6, it is understood that heat dissipation is less in the natural convectional mode. The difference of temperature between the phases due to magnetic field and eddy current effect is very high in the natural convectional mode of heat dissipation compared with the forced convectional mode. In the natural convectional mode, thermal time constant (response time) τ is very high compared with the forced convectional heat dissipation. Hence, duration of transient condition in the natural convection mode is very high about 4796 seconds. Where as in the forced convectional heat dissipation, the steady state condition is attained in shorter duration of about 648 seconds and 1038 seconds for air flows which are perpendicular and parallel to the bus bar axis respectively

Table 4 Comparison of experimental and theoretical temperature rise under the Natural Convection

Phases	Current (Amps)	Experimentally Observed Temperature at the bus bar (^oC)	Theoretically Calculated Temperature at the bus bar (^oC)	Error In %	Time Constant (seconds) for attain steady state
R	1600	54	58.20	7.2	4τ (4796)
Y	1800	61	65.11	4.11	4τ (4796)
B	1700	58	61.56	5.7	4τ (4796)

Table 5 comparison of experimental and theoretical temperature rise under the under forced convection with air flows perpendicular to the bus bar

Phases	Current (Amps)	Observed Temperature at the bus bar (^oC)	Calculated Temperature at the bus bar (^oC)	Error In %	Time Constant (seconds) for attain steady state
R	1600	38	36.52	3.8	3τ(648)
Y	1800	41	37.54	8.4	3τ(648)
B	1700	40	36.92	7.7	3τ(648)

Table 6 Comparison of experimental and theoretical temperature rise under the under Forced Convection with air flows parallel to the bus bar

Phases	Current (Amps)	Observed Temperature at the bus bar (^oC)	Calculated Temperature at the bus bar (^oC)	Error in %	Time Constant (seconds) for attain steady state
R	1600	42	41.46	1.2	3τ(1308)
Y	1800	45	43.94	2.3	3τ(1308)
B	1700	44	42.67	3	3τ(1308)

Table 7 Comparison of temperature rise under natural and forced convection with for various times constant

Time Constant(τ)	Temperature rise °C		
	Natural convection	Forced convectional air flow perpendicular to bus bar axis	Forced convectional air flow parallel to bus bar axis
1 τ	54.12	35.62	39.56
2 τ	65.29	37.32	43.37
3 τ	66.96	37.54	43.94
4 τ	67.05	37.54	43.94
5 τ	67.05	37.54 (44%)	43.94 (34%)

Table: 8 Comparison of time taken in seconds under natural and forced convection till steady state attained

Time constant(τ)	Time in seconds		
	Natural convection	Forced convectional air flow perpendicular to bus bar axis	Forced convectional air flow parallel to bus bar axis
1 τ	1278	216	436
2 τ	2556	432	872
3 τ	3834	648	1308
4 τ	5112	864	1744
5 τ	6390	1080	2180

From the Table 7, it is understood that with the forced convectional heat dissipation the temperature rise will be reduced about 45 % when air blows perpendicular to bus bar whereas it is reduced about 35 % when air blows parallel to bus bar. Table 8 gives the time constant and number of time constant required attaining the steady state temperature in the bus bar. In Natural convectional heat dissipation, steady state temperature will be attained after a long period of about 6390 seconds with 5 time constants compared to forced convectional heat dissipation in which the bus bar attained the steady state temperature in the period of about 1080 seconds and 2180 seconds when air blows perpendicular and parallel to the bus bar respectively.

Figure 5 shows the temperature rise in the bus bar in all three, namely natural convection, forced convection with air blowing perpendicular and parallel to the bus bar respectively. Figure 6shows the time required to attain the steady state in the bus bar in all three namely natural convection, forced convection with air blowing perpendicular and parallel to the bus bar respectively.

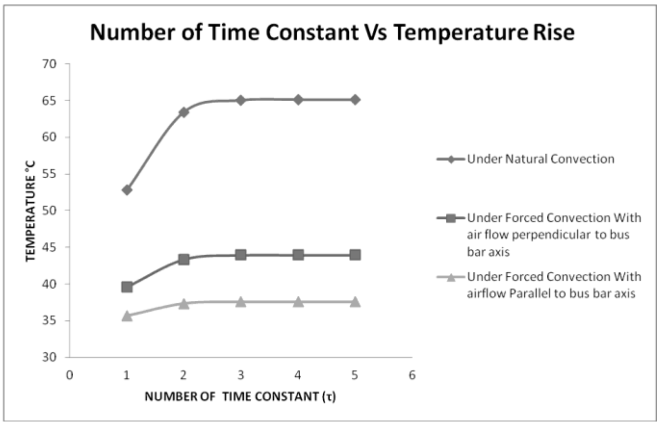

Figure.5 Temperature variation with time constant

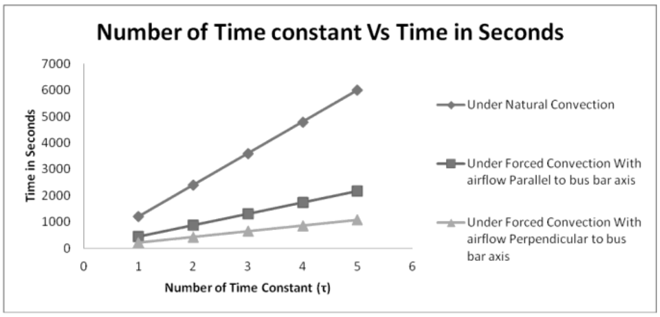

Figure.6 Time constant with time

5. Conclusion

In this research article, a detailed study has been conducted to find the temperature rise in the bus bar under the natural convection and forced convectional arrangement with different directional air flow. Experimental observations are validated by developing mathematical modeling for natural convectional and forced convectional model of heat dissipation. From this study, it is understood that due to the forced convectional heat dissipation the temperature rise will be reduced by about 45 % when air blows perpendicular to bus bar whereas, it is reduced by about 35 % when air blows parallel to bus bar. Due to forced convectional heat dissipation, response time (time constant) for attaining steady state condition is improved. Hence, the proximity and skin effect is very much controlled which leads to reduction of power consumption in the load.

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