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Experimental and Numerical Study on Copper and Aluminum Bus Duct System for the Prediction of Temperature Variation

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Abstract: This paper presents an experimental, mathematical and FEA thermal model of the heat transfer processes in an industrial bus duct system. The fundamental thermal problems like radiation and convection in copper bus bars, supporting parts and cooling air were coupled with the electromagnetic field to define the power losses. The mathematical model was based on the validated model of the bus duct system. The mathematical model results were compared with the experimental data and FEA thermal model for bus duct system. Then the algorithm has been developed to predict the temperature rise in the bus bars and also to compare the sizes of bus bar materials like copper and aluminum using MATLAB. It has been found that forced convection – perpendicular air flow reduces the power loss due to heat generation is also reduced in the bus bar conductors. Then the studies for basic configuration were considered. In the considered problem, the influence of the bus bar surface emissivity modification, applications of forced convection in bus duct system and temperature reduction within the bus duct system was analyzed. It is concluded that bus bar dimensions are compared for the copper and aluminum materials to predict the suitable equivalent dimensions for the same ampacity level and within the allowable temperature rise to reduce the panel cost.
Keywords: Air insulated bus bar, Heat transfer, Temperature rise, Current carrying capacity, Mathematical model development, Forced convection.

I. INTRODUCTION

Bus bar is one of the most primary elements of power system connecting variety of elements like generators, transmission lines and loads. Bus bars have been used in switchgears, control gear assemblies, and for power distribution in buildings [2]. Therefore bus bar have to meet standards regarding their electrical, mechanical and thermal performance. The fulfillment of thermal standards is available only with sufficient amount of heat dissipation capabilities. Thus, the cooling is important to assure the maximum performance and reliability. The thermal behavior of bus bar is estimated based on the temperature rise at certain points during the laboratory tests [1]. It is noted that the measurement tests are expensive, time consuming and also it provides only the partial information on the temperature field. The design requires few iteration before the final product has been delivered to the customer. To increase the quality of new design, the correlations regarding the temperature rise can be prepared as numerical model [4, 6]. The numerical calculation gives an opportunities for optimization in design, longer life and also increases in performance. Computational Fluid Dynamics (CFD) is helpful for understanding the flow physics within the bus duct and provides guidelines for the heat dissipation system design [3].

The methods used to remove the heat from the bus duct are classified as: active thermoelectric cooling, semi active methods and fully passive method [7]. The current trend in design towards fully passive methods without moving any parts. In some specific applications manufacturers considers active system also. The advantages in passive methods are their design simplicity, low operating costs, less maintenance and high reliability [5]. The heat transfer takes place in three basic modes; conduction, convection and radiation. Conduction depends on properties of the materials, the rise in heat transfer within the bus bar is limited by project constraints regarding the use of bus bar material. The most popular bus bar materials are aluminum and copper [8]. Copper is the frequently used material for the conduction paths because of its good electrical and thermal conductivity. Aluminum is rarely used because of its poor electrical and thermal properties [12, 14]. The electrical conductivity of aluminum is only 56% of the copper. The density of aluminum is lower than the copper, so aluminum is preferred for special applications where weight is the major application criteria. The most important heat dissipation modes in bus duct are natural convection and radiation. Convection heat transfer mode can be classified in to natural and forced mechanism. Natural convection is driven by buoyancy force and thus offers high protection and reliability in case of malfunctions of active cooling methods. For forced convection, the heat dissipation amount is higher than the natural convection. The last mode of heat transfer is radiation [21, 23]. 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 [10]. R phase is situated in the outer layer, Y phase bus bar is kept in between R and B bus bars [9]. 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 [22]. Therefore, current flow through the Y phase bus bar is greater than the R phase bus bar and B phase bus bar. The main goal in bus bar development is to increase the ampacity of the components and to reduce the material requirements. As a result of the current flow in bus bars, power losses occur, which always turn into heat [11]. Hence, cooling is important to guarantee the maximum performance and reliability.

II. BUS BAR ARRANGEMENT IN THE POWER HOUSE

The experiments have been conducted from the electric power facility of Sangeeth Textiles Mill, Coimbatore, which having a capacity of 2500A rating and 1500 KVA transformer substation [15]. In the transformer, the voltage is stepped down to 440V for distribution to points of consumption [13]. These arrangements are done in an enclosed chamber made of steel with minimum amount of ventilation with natural convection heat dissipation. The bus bar is made of copper. Figure 1 shows feeder and distributor arrangement.

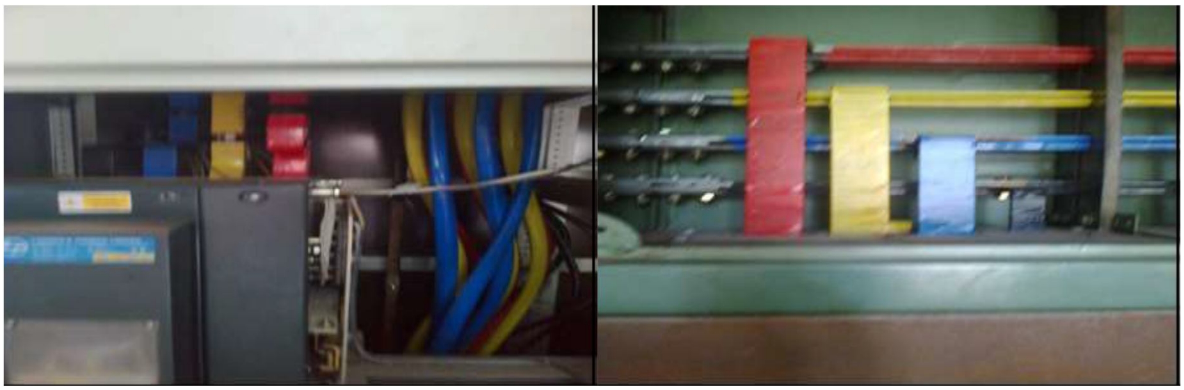

Figure 1 Feeder and distribution arrangement

Figure 2 Thermocouples and temperature indicator

Figure 2 shows thermocouples and temperature indicator. Thermocouple is used to measure the temperature in the bus bar. The electricity is transmitted through the main bus bar and distributed to different sections of the mill as per for the load requirement [17]. The current in the main bus bar depends on the number of sections operated [16]. Current fluctuation occurs in the main bus bar when some sections are inoperative. Bus bar with a rectangular cross-section is being used in the panel board. The sizes of the main bus bars are 100 × 6 mm with 3 sub bus bar per main bus bar in each runs and with a single run of 100 × 6 mm for the neutral. It passes horizontally along the length of the panel board. Experiments are conducted under conditions of natural convection and under conditions of forced convection by keeping the air flow parallel and perpendicular to the bus bar. Experiments are conducted for different velocities.

Figure 3 Experimental arrangement and Bus bar with 3 conductors per phase

Temperature variation predicted in the modeling of bus bar is validated by experimental observation. Thermal time constant has been predicted to find the steady state temperature of the bus duct system using analytical expression [18, 20]. Many factors are involved for choice of selecting appropriate temperature measurement instrument for the given application. Here, calibrated thermocouples are to be used for measuring the temperature in R, Y, B phases. The thermocouples are connected to the four channel temperature indicator as shown in figure2. The selected K-Type thermocouple can be used to measure temperature up to 1200°C and are also recommended in high moisture, dust, fog, smoke, liquid, high pressure, and corrosive environments [19]. Figure 3 shows experimental arrangement and bus bar with 3 conductors per phase in the power house of Sangeeth Textiles.

III. THERMAL MODEL OF BUS BAR

The energy balance equation for bus bar is written as

$$\rho c_p V \frac{dT}{dt} = I^2 R(t) - hA_s(T - T_\infty) - \varepsilon\sigma A_s(T^4 - T_\infty^4) \quad (1)$$

Equation (1) is simplified as,

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

Equation (2) is similar to the differential equation

$$\frac{dT}{dt} + a(T) = C \quad (3)$$

Where

$$a = \frac{hA_s\, \varepsilon\sigma A_s(T+T_\infty)(T^2+T_\infty^2)}{\rho C_p V}\,; C = \frac{I^2R(t)}{\rho C_p V} + \frac{hA_s\, \varepsilon\sigma A_s(T+T_\infty)(T^2+T_\infty^2)}{\rho C_p V}(T_\infty)$$

Solution for the above differential equation is,

$$T_{i+1} = \frac{C}{a}(1 - e^{-at}) + T_i(e^{-at}) \quad (4)$$

Thermal time constant is the function of geometrical, physical and thermal properties of the bus bar material.

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

The Thermal time constant equation is,

$$\tau = \frac{\rho C_p(\frac{V}{A_S})}{h + \varepsilon\sigma(T^2 - T_\infty^2)(T - T_\infty)} \quad (5)$$

Convectional coefficient (h) for the free convectional heat dissipation for vertical plate is calculated from the following Nusselt number correlation:

$$Nu_x = 0.508\, Pr^{0.5}(0.952 + Pr)^{-0.25} Gr_x^{0.25} \quad (6)$$

Similarly for the forced convection cooling with air flow perpendicular to the bus bar, the correlations used is:

$$Nu_x = 0.205 Re_x^{0.731} Pr^{\frac{1}{3}} \quad (7)$$

With air flow Parallel to the bus bar, the correlations used is:

$$Nu_x = 0.664 Re_x^{\frac{1}{2}} Pr^{\frac{1}{3}} \quad (8)$$

IV. ANALYTICAL ALGORITHM

The algorithm developed carried out in the research work is being given in fig4.The experimental work was conducted in a textile mill and a suitable thermal model is developed to determine the temperature of the bus bar under natural and forced convection mode. The program has been written in MATLAB for the algebraic equation developed from thermal model.

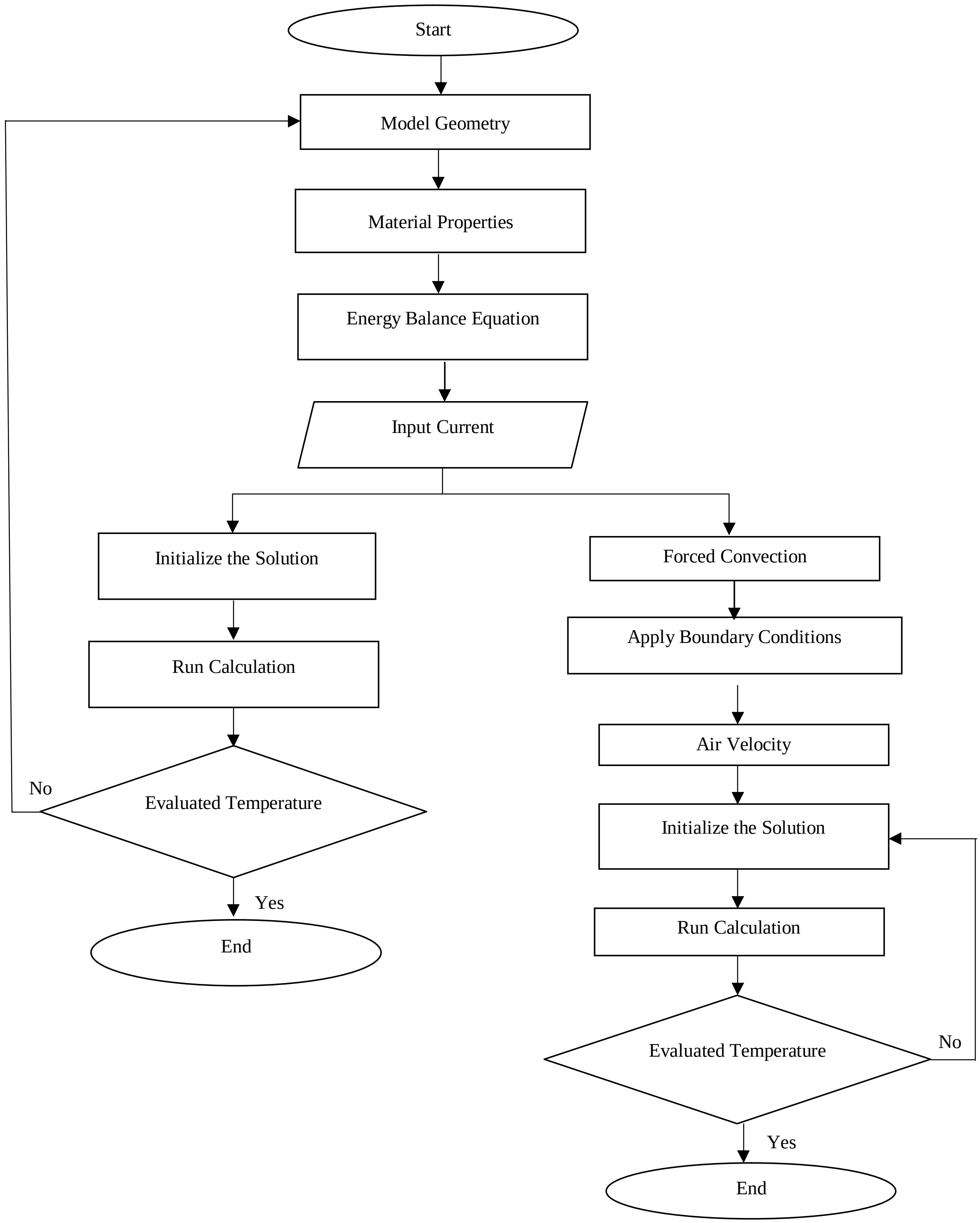

Figure 4 Algorithm for calculation of heat transfer coefficients due to natural and forced convection from bus bar systems

Time constant (τ)	Temperature variation under natural convection in copper bus bar(°C)	Temperature variation under forced convection in copper bus bar(°C)	
		Air flow parallel to bus bar axis	Air flow perpendicular to bus bar axis
τ	60.77	38.46	35.22
2τ	71.35	40.83	36.40
3τ	75.25	41.71	36.84
4τ	76.68	42.03	37.00
5τ	77.21	42.15	37.06
6τ	77.40	42.19	37.08
7τ	77.47	42.21	37.09

Table 1 Temperature variations of copper bus bar with the time constant under conditions of natural and forced convection

Time constant (τ)	Temperature variation under natural convection in aluminum bus bar(°C)	Temperature variation under forced convection in aluminum bus bar(°C)	
		Air flow parallel to bus bar axis	Air flow perpendicular to bus bar axis
τ	77.04	42.50	37.26
2τ	93.62	46.36	39.20
3τ	99.71	47.79	39.91
4τ	101.96	48.31	40.18
5τ	102.78	48.50	40.27
6τ	103.09	48.57	40.31
7τ	103.20	48.60	40.32

Table 2 Temperature variations of aluminum bus bar with the time constant under conditions of natural and forced convection

V. RESULTS AND DISCUSSION

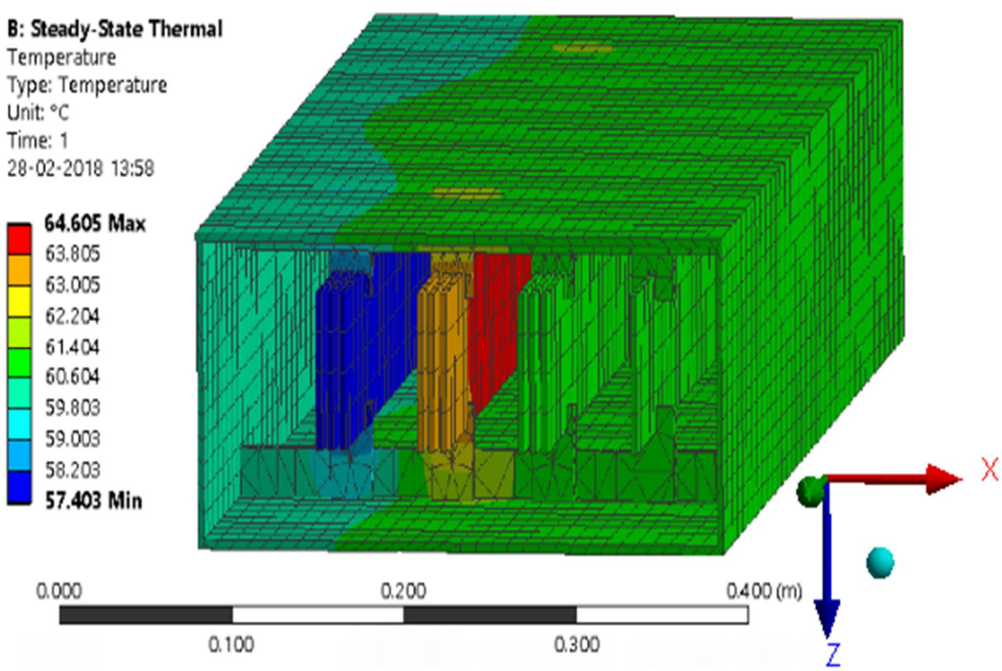

Figure 5 Steady state thermal analysis for copper bus bar under natural convection

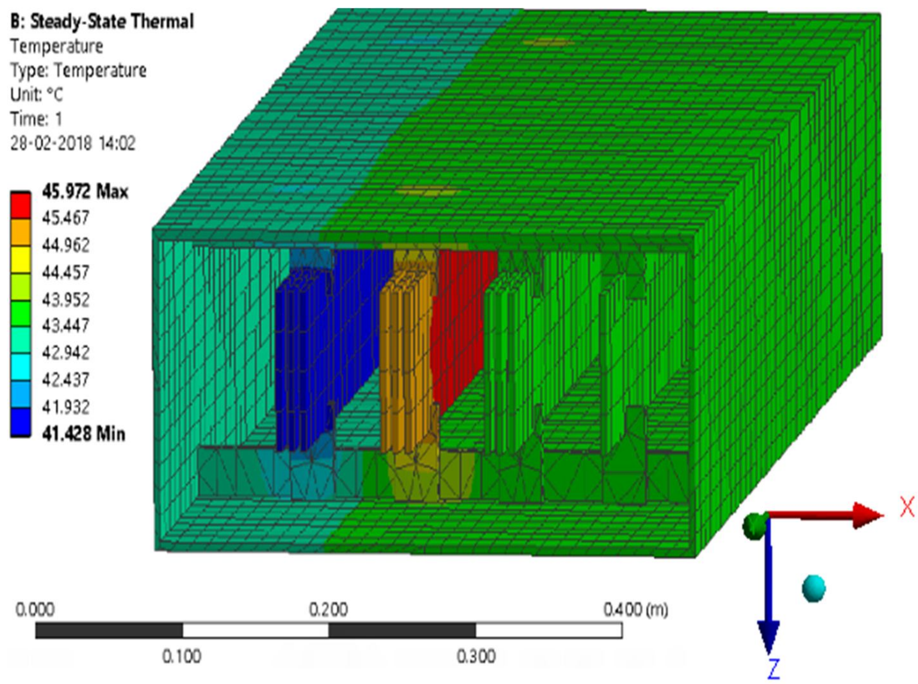

Figure 6 Steady state thermal analysis for copper bus bar under forced convection – Parallel air flow

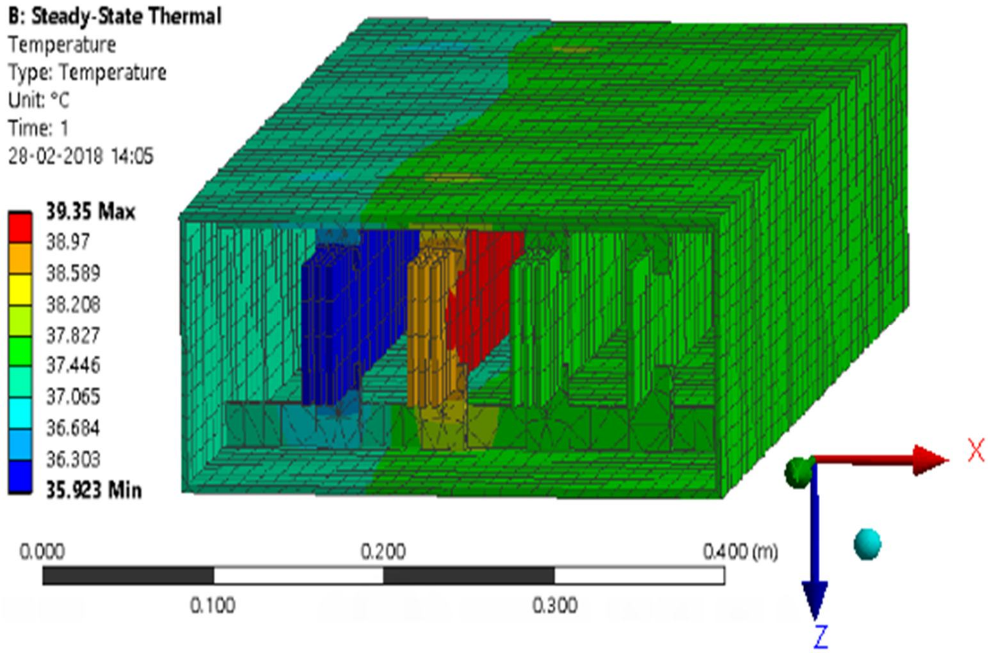

Figure 7 Steady state thermal analysis for copper bus bar under forced convection – Perpendicular air flow

Figure 5, 6 and 7 shows steady state thermal analysis for copper bus bar under natural convection, forced convection – parallel air flow and forced convection – perpendicular air flow. In these steady state thermal analysis the temperature attained in the copper bus bar under natural convection mode is 64°C and 57°C as maximum and minimum values. The maximum temperature is attained in the Y phase due to high current flows through the bus bar. The minimum temperature is attained in the R phase due to low current flows through the bus bar. To reduce the temperature rise in the bus bar, the forced convection mode is adapted. In the forced convection method, during parallel air flow the temperature is reduced to maximum temperature of 45°C in Y phase copper bus bar and minimum temperature of 41°C in R phase copper bus bar. Then during perpendicular air flow, the temperature is reduced to maximum temperature of 39°C in Y phase copper bus bar and minimum temperature of 35°C in R phase copper bus bar. The current carrying capacity of bus bar with aluminum material is lower than the copper material. Due to low cost, aluminum has been chosen for this research work as alternate to copper.

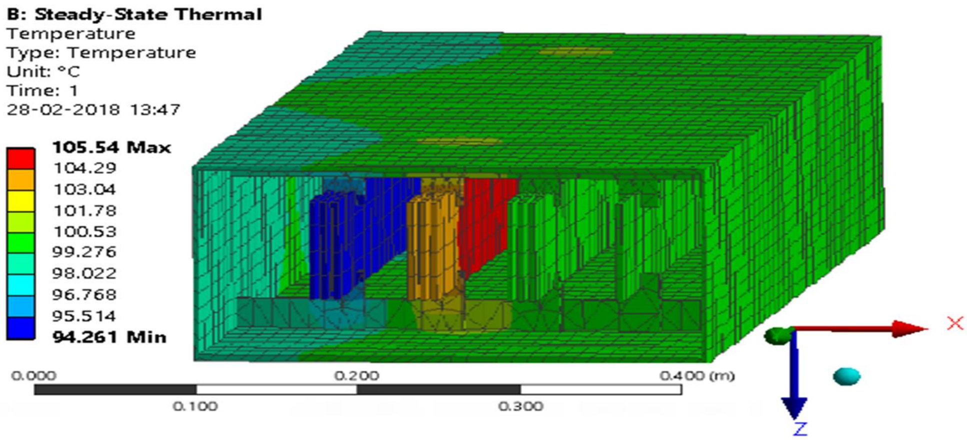

Figure 8 Steady state thermal analysis for Aluminum bus bar under natural convection

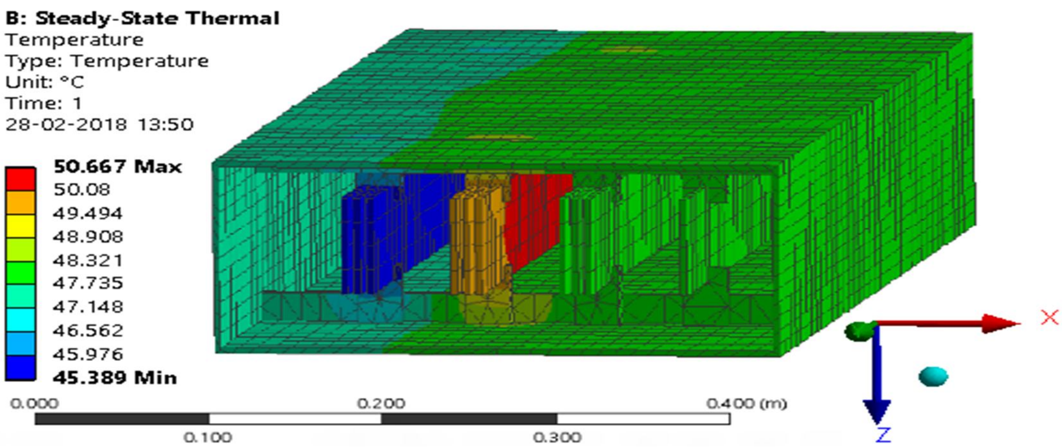

Figure 9 Steady state thermal analysis for Aluminum bus bar under forced convection – Parallel air flow

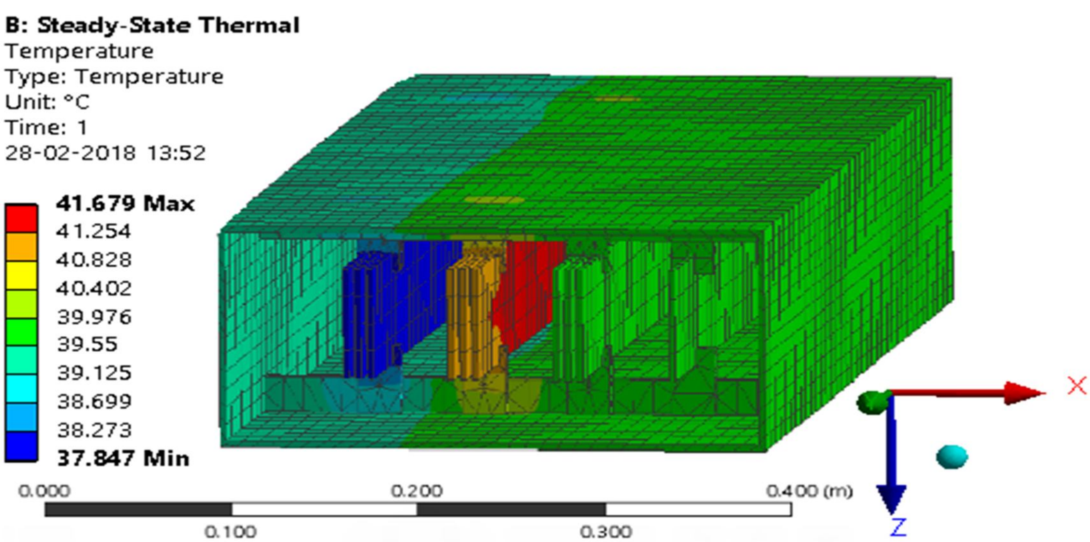

Figure 10 Steady state thermal analysis for Aluminum bus bar under forced convection – Perpendicular air flow

Figure 8, 9 and 10 shows steady state thermal analysis for aluminum bus bar under natural convection, forced convection – parallel air flow and forced convection – perpendicular air flow. In these steady state thermal analysis the temperature attained in the aluminum bus bar under natural convection mode is 105°C and 94°C as maximum and minimum values. The maximum temperature is attained in the Y phase due to high current flows through the bus bar. The minimum temperature is attained in the R phase due to low current flows through the bus bar. To reduce the temperature rise in the bus bar, the forced convection mode is adapted. In the forced convection method, during parallel air flow the temperature is reduced to maximum temperature of 50°C in Y phase aluminum bus bar and minimum temperature of 45°C in R phase aluminum bus bar. Then during perpendicular air flow, the temperature is reduced to maximum temperature of 41°C in Y phase aluminum bus bar and minimum temperature of 37°C in R phase aluminum bus bar.

When comparing aluminum bus bar to the copper bus bar the temperature rise in very high in aluminum bus bar under natural convection mode. The difference in the temperature are 40°C in Y phase bus bar under natural convection. During forced convection – parallel air flow, the temperature difference between the aluminum and copper bus bar is 5°C increased in aluminum bus bar. Then during perpendicular air flow, the temperature difference between the aluminum and copper bus bar is 2°C increased in aluminum bus bar. Then it shows that forced convection – perpendicular air flow having a maximum amount of heat dissipation in both copper and aluminum bus bar.

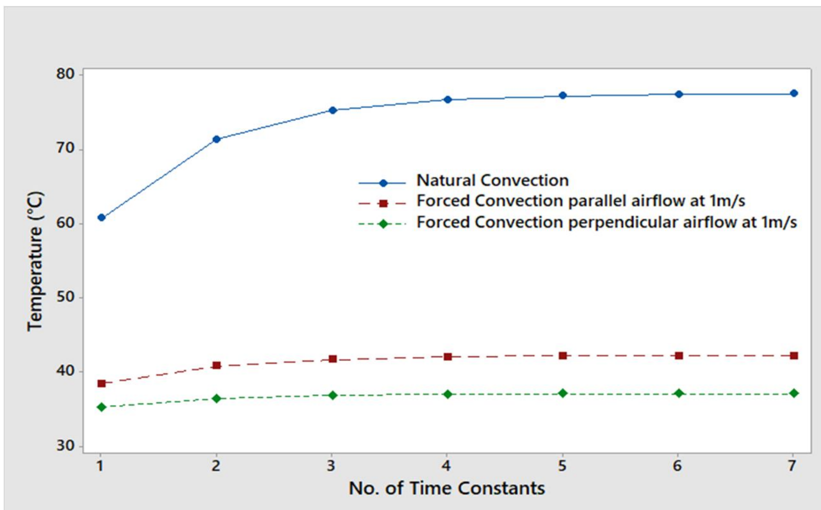

Figure 11 Temperature variation for copper bus bar under natural and forced convection

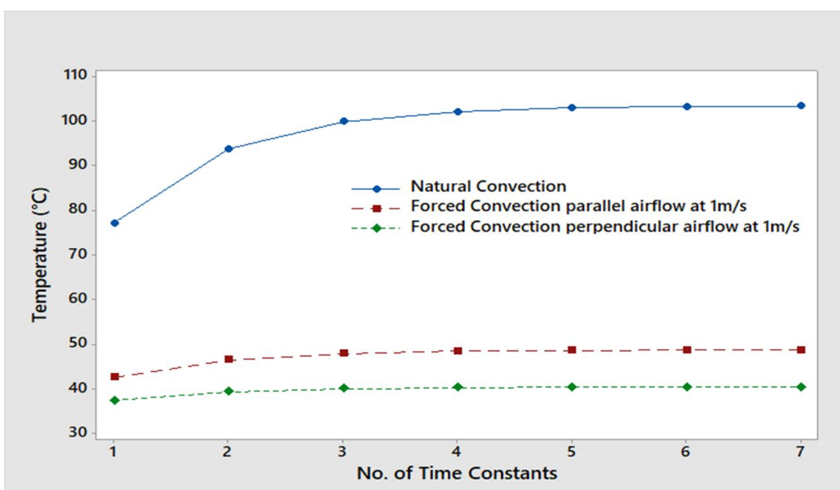

Figure 12 Temperature variation for aluminum bus bar under natural and forced convection

Figure 11 shows a temperature variation with time constant for copper bus bar under natural and forced convection. With natural convection, the temperature of the copper bus bar increases steeply (60°C) due to high current flow. Then the temperature increases and reaches steady state of (77°C) at 4τ. During forced convection – parallel air flow, the temperature increases from initial condition (38°C) and attains the steady state condition (42°C) at same 4τ. For the forced convection – parallel air flow mode of heat transfer from the bus bar, the temperature rise has been reduced 35°C compared with natural convection mode. During forced convection – perpendicular air flow, the temperature increases from initial condition (35°C) and attains the steady state condition (37°C) at same 4τ. For the forced convection – perpendicular air flow mode of heat transfer from the bus bar, the temperature rise has been reduced 40°C compared with natural convection mode. When compared to parallel and perpendicular air flow in copper bus bar, the temperature rise due to perpendicular air flow is reduced 5°C. Figure 12 shows a temperature variation with time constant for aluminum bus bar under natural and forced convection. With natural convection, the temperature of the aluminum bus bar increases steeply (77°C) due to high current flow. Then the temperature increases and reaches steady state of (103°C) at 4τ. During forced convection – parallel air flow, the temperature increases from initial condition (42°C) and attains the steady state condition (48°C) at same 4τ. For the forced convection – parallel air flow mode of heat transfer from the bus bar, the temperature rise has been reduced 55°C compared with natural convection mode. During forced convection – perpendicular air flow, the temperature increases from initial condition (37°C) and attains the steady state condition (40°C) at same 4τ. For the forced convection – perpendicular air flow mode of heat transfer from the bus bar, the temperature rise has been reduced 63°C compared with natural convection mode. When compared to parallel and perpendicular air flow in aluminum bus bar, the temperature rise due to perpendicular air flow is reduced 8°C. Therefore perpendicular air flow is preferred for maximum heat dissipation.

Bus bar degradation mechanisms such as, corrosion and oxidation typically occurs around 85°C. For aluminum bus bar of standard size (100 mm width) with natural convection mode, the temperature rise approaches 100°C which is closer to the damage condition of the bus bar. Therefore, forced convection heat dissipation with the airflow perpendicular to the bus bar arrangement is preferable when aluminum replaces the copper bus bar.

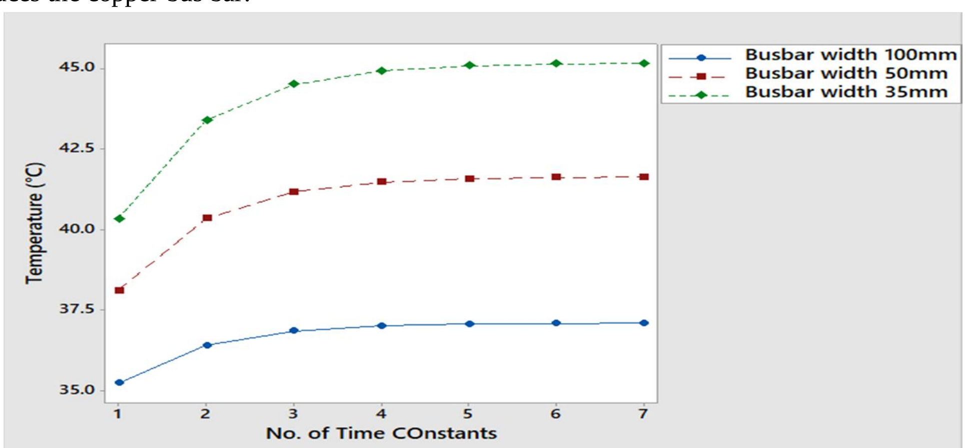

Figure 13 Temperature variation with time constant for various standard sizes of copper bus bar

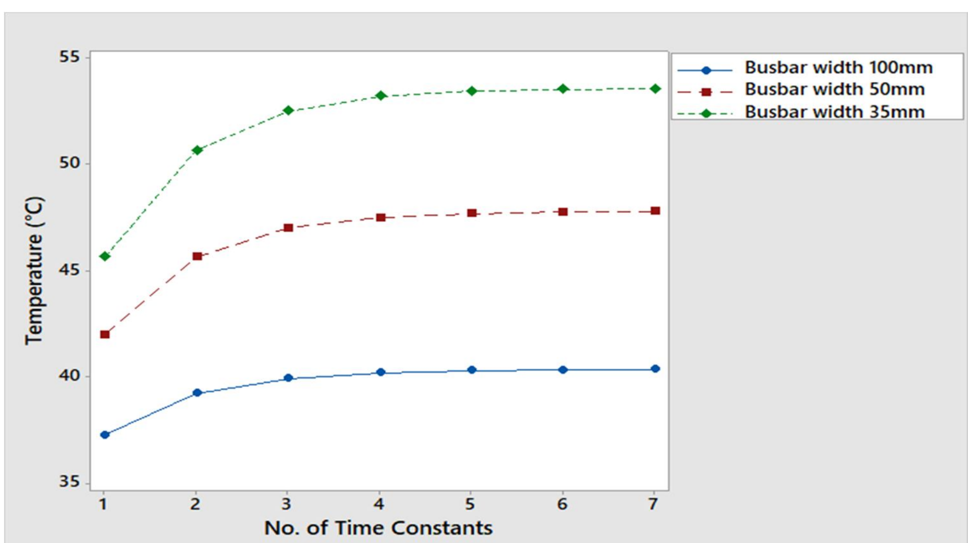

Figure 14 Temperature variation with time constant for various standard sizes of aluminum bus bar

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In the aspect of optimizing the size of the bus bar, the algebraic equation developed from thermal model is solved using MATLAB by considering different standard sizes of 35 mm, 50 mm and 100 mm bus bars of copper and aluminum materials under the forced convection arrangement. Temperature variation of bus bar with the time constant for different sizes of bus bar for the air flow in the perpendicular direction to bus bar are shown in the fig 13 and 14 for copper and aluminum bus bars respectively.In figure 13 copper bus bar for 100mm width, steady state temperature is attained at 37°C. If the width is reduced to 50mm the steady state temperature increases by 10%. Further, if the width of the bus bar is stepped down to the next standard size (35mm) the steady state temperature increases by 18%. Whereas in figure 14 aluminum bus bar for 100mm width, steady state attains at 40°C. If the width is reduced to 50mm the steady state temperature is increased by17%. Moreover, if the width of the bus bar is stepped down next standard size (35mm) the steady state temperature is increased by 32%.Then the steady state temperature for forced convection - perpendicular airflow of aluminum bus bar of 35mm width is reached to 53°C which is below that for a standard size copper bus bar of 100mm width by natural convection (77°C). Therefore aluminum bus bar can also be selected suitably for effective cost reduction. So it is understood that aluminum bus bar with reduced sizes can be used in place of copper under the forced convection mode.

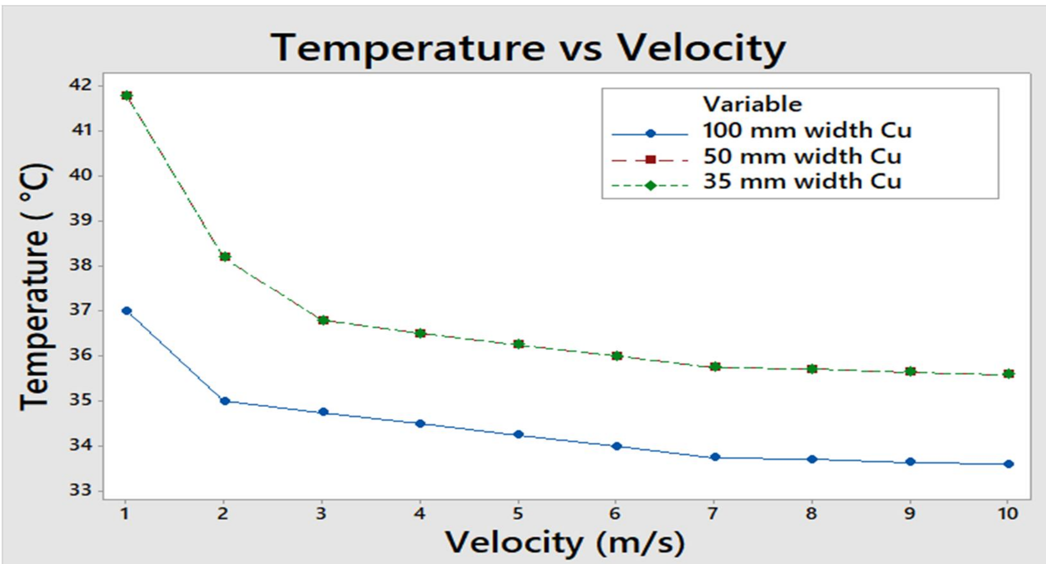

Figure 15 Comparisons of different standard width temperature of Y Phase bus bar with Velocity under forced convection – perpendicular air flow to the copper bus bar

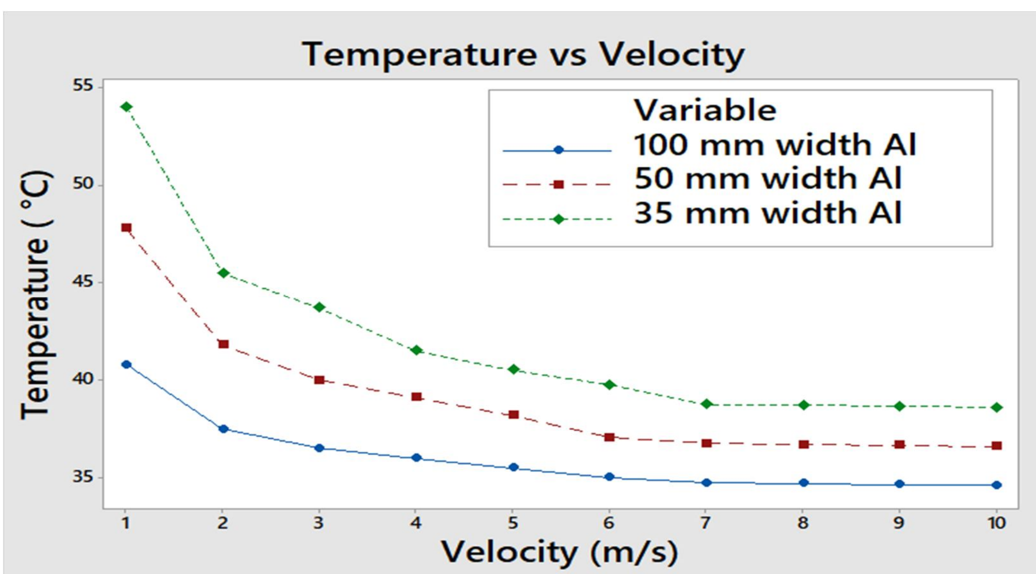

Figure 16 Comparisons of different standard width temperature of Y Phase bus bar with Velocity under forced convection – perpendicular air flow to the aluminum bus bar

Figure 15 shows the Comparisons of different standard width numerical temperature rise of Y Phase bus bar with velocity from 1 to 10 m/s under forced convection with air flowing perpendicular to the copper bus bar. Figure 16 shows the Comparisons of different standard width numerical temperature rise of Y Phase bus bar with velocity from 1 to 10 m/s under forced convection with air flowing perpendicular to the aluminum bus bar In the aspect of optimizing the size of the steady state temperature of the bus bar, the algebraic equation developed from thermal model is solved from using MATLAB by considering different standard width sizes of 35 mm, 50 mm and 100 mm by keeping thickness as constant of 6mm for copper and aluminum bus bar materials under the forced convection mode. It is observed from the figure 15, the heat transfer rate is almost same for35 mm and 50mm width when compared to 100 mm width of the copper bus bar. The temperature is decreasing continuously up to the velocity of 7 m/s, but after 7 m/s the temperature reduces gradually for the copper and aluminum bus bar. The optimized width of 35 mm for copper and aluminum bus bar has the maximum temperature of 42°C and 54°C respectively, which in turn reduces the power loss to 45% as compared to natural convection.

VI. CONCLUSION

An experimental observation of temperature variation for standard size copper bus bar is validated with theoretical analysis using MATLAB. An algorithm has been developed to perform analysis to determine the temperature variations in the bus bar of different materials of copper and aluminum with different standard size using MATLAB. Then, with forced convection cooling arrangement, the temperature variation of copper bus bar is observed and it is found that the temperature variation is well under the safety range. Hence a theoretical analysis is carried out with different size of copper and aluminum bus bar with different air velocities to predict the temperature rise which is also under the safety range. It is suggested that by reducing the size of bus bar, cost of panel can be saved. During the course of validation of the analytical algorithm, it is confirmed that due to forced convection - perpendicular airflow heat dissipation, time constant for attaining steady state condition is improved. Aluminum bus bar with reduced width size having the minimum temperature under forced convection – perpendicular air flow when compared to the copper bus bar of normal width size under natural convection. So it is understood that aluminum bus bar with reduced sizes can be used in place of copper under the forced convection mode. Therefore, forced convection heat dissipation with the airflow perpendicular to the bus bar arrangement is preferable when aluminum replaces the copper bus bar. Hence, proximity and skin effect are much controlled which leads to the reduction of power consumption in the load.

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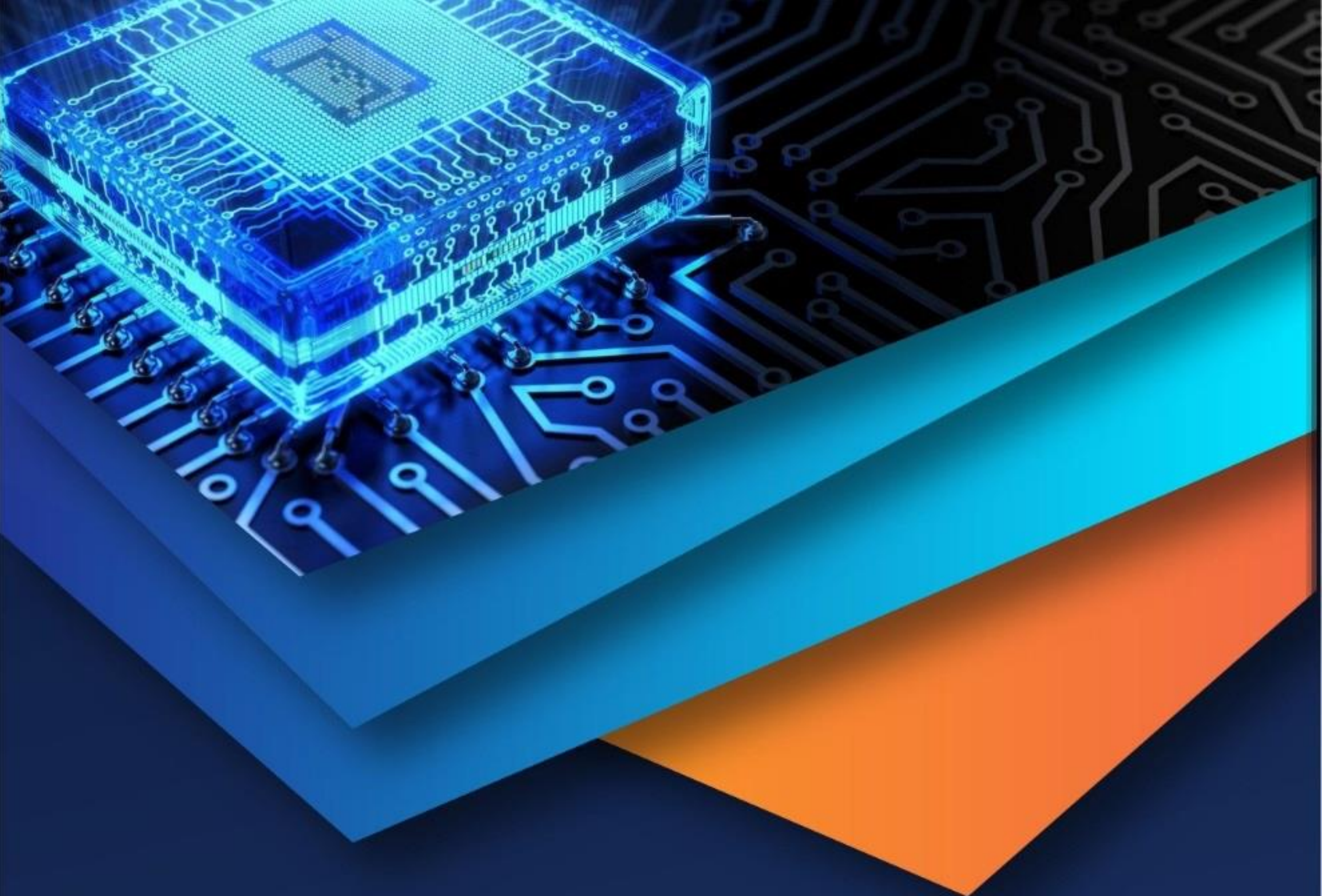

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