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Design of Cooling System for Permanent Magnet Synchronous Motor ina Formula Student Electric Vehicle

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Abstract - *The efficiency of the electric powertrain is approximated to 90% which is significantly higher when compared to the vehicles propelled using the internal combustion engines. The loss of energy in the electric motors is due to factors like eddy currents, winding resistance, friction and unbalanced change in load leading to sudden drawing of excess current. In order to dissipate the heat developed by the electric motor, conventional heat transfer system is being developed where water is used as a coolant and circuited around the fluid jacket near the motor windings for convection of heat. The water is then passed through a heat exchanger with the help of the pump and then recirculated through the water jacket. The Normal Transfer Units method is used for heat transfer calculation .*

Key Words**: Cooling System, PMSM, Electric Vehicles, Normal Transfer Units.**

1. INTRODUCTION

With significant development in cell chemistry of the Li-ion cells, the electric vehicles have significantly increased the demand for short distance travels or city commutes. During to the stop and go traffic conditions, the electric vehicles provide excellent starting torque. But the same situation has an adverse effect on the electric motor due unbalanced current loads. Hence, it is necessary for the electric motors to have a cooling system to maintain its lifecycle. The electric motors have different grades of insulations such as F type or D type which is commonly observed in PMSM motors. These insulations are rated for temperature of approximately 120°C and a life period of 20 years. But the Arrhenius Law states that, increase in temperature of 20°C above the rated one reduces the insulation life by half. Therefore, if the motor becomes too hot, the windings will prematurely fail. Another reason for need of cooling system is the motor efficiency. Copper has a positive temperature coefficient of resistance, as a result increase in temperature of motor leads to higher winding resistance and lower efficiency. Increase in temperature of motor windings by 10°C will increase the winding losses by 4%. The last reason for need of cooling system is reduction permeability of magnetic steel due increase in temperature. It eventually leads to reduction in available torque as the magnetic field is weakening.

Depending on need of heat dissipation and fluids available heat transfer, there are two types of cooling systems commonly used for automobiles, namely – Air Cooled and Water Cooled. Air cooled motors are the simplest method of cooling the components of the motor . In simple words the air is pulled through small openings in the casing of the motor . Due to the rotating parts it passes through the entire structure and is then expelled out . For increasing the efficiency of this system a fan can be installed on the shaft of the motor . The Cooling fan helps in pulling the air forcefully through the motor . As a result , it increases the flow rate of the air and hence increases the overall heat transfer of the system . Installing the fan also assures that there is continuous flow of air through the cooling circuit . The advantages of an air cooled motor is that it is a low cost system , no need of any external power source , high reliability and good cooling at the ends of thewinding . The major drawback is that this system is highly influenced by the external factor like the ambient temperature , dirty air , etc. We have no control over the cooling and there is almost no airflow when the vehicle is stationary. For high power density motors , water cooling is generally employed as the air cooling method is not sufficient . The two main topologies are water jackets in the housing of the machines or ducts inside the machines . This method is also called as indirect method of the cooling as the cooling medium is not directly in contact with the components . Water is used as primary used as the cooling the medium as the overall heat transfer coefficient of water is very high .. A water pump is needed to flow the water through the water jackets and further pass it through the heat exchanger. The major advantage it provides is uniform cooling of the motor windings.

2. Literature Survey

The design and development along with the latest trends are being studied[1]. It also gives a brief description about different types of radiators along with a comparative analysis for use in various conditions. The research paper is used to understand the effect of velocity of fluids on the heat transfer system[2]. The study of change mass flow rate of air and the velocity of air as it passes through the radiator is also studied[3]. Different parameters the fluid and their influence on the design of cooling system have also been studied[4] .

Normal Transfer Units method is chosen for calculating the required size of the heat exchanger as the available information of design parameters is insufficient. Along with that, the equations have high accuracy while studying a counter currentflow heat exchanger [5-8].

3. Methodology

3.1 Selection of Heat Exchanger

Based on the available options, a single pass radiator is selected. The single pass radiator is commonly used in automobiles, making its availability comparatively easy. The inlet and outlet of the radiator are on opposite sides, thus routing of the cooling lines is simplified. It also requires a pump of lower capacity when compared to thatfor double pass radiators.

The radiator selected is a high density one with fin density of 40/inch^2 where the area of a single fin is approximated as 590mm^2.

We consider the length and breadth of radiator as 300mm and 140mm respectively with 20 tubes for coolant to flow with a cross section of 16.2mm^2 and perimeter of 56mm, thus giving total area available for heat transfer as 1416480mm^2.

3.2 Heat Transfer Coefficient of Hot Fluid

The Hot fluid is the one that passes through the coolant jacket around the motor windings. The main purpose of this is to absorb maximum heat from the motor windings, allowing the windings to be at rated temperature as per the insulation motor. The selected PMSM motor has an F-Type insulation, which means that the motor is safe to work up to a maximum temperature of 120^{o}C. But for considering the safety barrier, the maximum temperature is considered as 90^{o}C to prevent damage to the winding in case of harsh environmental conditions.

The Hot fluid considered here for the calculation is distilled water. The Coefficient of Heat Transfer for distilled water is calculated as follow:
Cross Section of Radiator Tube = A = 16.2mm^2 , Perimeter ofTube = P= 56mm , Number of Tubes = N = 20
Hence, Hydraulic Diameter (D_h) = (4 * A) / P = 1.157 mm

Velocity of Fluid (V) = Mass flow Rate of Pump / (Density of Water * Cross Section of Tube * Number of Tubes)

$$= 0.224 / (977.78 * 16.2 * 21 * 10^{-6})$$

$$= 0.673 \text{ m/s}$$

Reynold's Number (Re) = (Density of Water * Velocity of Fluid * Hydraulic Diameter) / Kinematic Viscosity

$$= (977.78 * 0.673 * 1.157 * 10^{-3}) / (0.404 * 10^{-3})$$

$$= 1884.78$$

As the fluid is laminar flow, the Nusselt number is calculatedas follow:
Nusselt number (Nu) = 0.023 * (Re)$^{0.8}$ * (Prandtl number)$^{0.4}$

$$= 0.023 * 417.07 * 1.454$$
$$= 13.947$$

Heat Transfer Coefficient (Ht_h) = (Nu * Thermal Conductivity of Fluid) / (D_h)

$$= 7992.48 \text{ W/m}^2\text{K}$$

3.3 Heat Transfer Coefficient of Cold Fluid

The Cold fluid is the air that passes across the radiator. Theheat transfer coefficient for the air can be calculated in a similar way to the calculation of heat transfer coefficient of hot fluid as above. The air is considered to be flowing at an average velocity(V) of 14m/s.

From the available data, Area of Fins (A) = 1.92mm^2 and Perimeter (P) = 25.88mm

Hydraulic Diameter (D_h)= (4 * A) / P = 2.022 mm

Reynold's Number (Re) = (Density of Air * Velocity of Fluid
* Hydraulic Diameter) / Kinematic Viscosity

= (1.164 * 14 * 2.022 * 10^{-3}) / (1.872 * 10^{-5})

= 1884.78

As the fluid is laminar flow, the Nusselt number is calculatedas follow:
Nusselt number (Nu) = 0.664 * (Re $)^{0.5}$ * (Prandtl number $)^{0.33}$

= 0.664 * 41.95 * 0.89
= 24.79

Heat Transfer Coefficient (Ht_c) = (Nu * Thermal Conductivity of Fluid) / (D_h)

= 316.35 W/m²K

3.4 Overall Heat Transfer Coefficient

The overall heat transfer coefficient for a single pass radiator is calculated as the geometric mean of the individual heat transfer coefficients of Cold and Hot fluid. Hence, Overall Transfer Coefficient (H) = (Ht_c + Ht_h) / (Ht_c * Ht_h)

= 304.31 W/m2^K

3.5 Normal Transfer Units

For calculation of the normal transfer units, we require the individual heat capacity of the hot and cold fluid respectively and then the heat capacity ratio. Along with that, we also require the efficiency of the heat transfer system.

The calculation of heat capacity is as follow:

Heat Capacity of hot Fluid (Ch) = Cp of Water * mass flowrate

= 4213 J/KgK * 0.224 Kg/s

= 943.71 J/Ks = Cmax

Heat Capacity of cold Fluid (Cc) = Cp of air * mass flow rate

= 1007 J/KgK * 0.271 Kg/s

= 276.3 J/Ks = Cmin

Heat Capacity ratio (C) = Cmin / Cmax = 0.293

Normal Transfer Units (NTU) ={ Log [Heat Capacity Ratio
* Log(1-Efficiency of System) +1] } / Heat Capacity ratio

= { Log [C + Log(1-E) +1] } / C

= 0.76

3.6 Sizing of Heat Exchanger

Based on the Normal Transfer Units, heat capacity of the fluids and the overall heat transfer coefficient that have been calculated, the area required for the heat exchanger is calculated as :
Area required (Areq) = (Normal Transfer Units * Cmin)
/ Overall Heat transfer Coefficient

= (NTU * Cmin) / U
= (0.79 * 276.3) / 304.31
= 717285 mm^2

From the given data, the Factor of Safety = Area Available for Cooling / Area Required for Cooling

= 1416480 / 717285

= 1.97

4. Conclusion

The cooling system has an approximate Factor of Safety of 2 as discussed above which is desired especially when dealing with critical components of any automobile. The real world performance of the designed system is expected to deviate from the above calculations due to transient ambient conditions. In order to serve the purpose of developing a cooling method for electric motors, the Normal Transfer Units method is selected as the temperatures required during the calculations for Log Mean Temperature Difference method are not available. The fin density plays an extremely important factor in selection of radiator, as higher rate of heat dissipation can be easily achieved due to increase surface area available for convective heat transfer. Future scope of the research lies in simulation of above conditions using the available CFD tools.

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