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Optimization of the Cooling Parameters of a 250 kW PMSM by Taguchi Method

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Abstract

Nowadays, Permanent Magnet Synchronous Motors (PMSM) are researched for the development of electric motors to work more efficiently with electric vehicles. PMSMs can be classified according to their mechanical and electrical topologies. PMSM can be shown as the most efficient motor among all motor types, with their unique structures to provide high torque values at high rpm values. It has higher efficiency values by showing higher performance at lower motor volumes compared to motor types with the same power.

The biggest problem of electric motors is the serious decrease in efficiency out of the ideal operating temperature. In response to variable ambient temperature or sudden torque and power demands, a sudden temperature increase occurs. In this study, a nine-phase, 250 kW PMSM was considered, and both the magnetic and thermal models of this motor with heat losses are studied. It is aimed to improve the motor efficiency, which is cooled with refrigerant through the fixed parallel channels on the stator, by changing the critical variables determined on the cooling jacket.

As a result of this study, the life span of the mechanical parts that make up the motor and the efficiency of the motor will increase when the motor works at the ideal operating temperature.

Key words

PMSM, Thermal Model, Magnetic Model, Efficiency, 3D Parametric Design, Cooling Methodology

1. INTRODUCTION

Nowadays, Permanent Magnet Synchronous Motors (PMSM) are researched for the development of electric motors to work more efficiently with electric vehicles. PMSMs can be classified according to their mechanical and electrical topologies. PMSM can be shown as the most efficient motor among all motor types, with their unique structures to provide high torque values at high rpm values. It has higher efficiency values by showing higher performance at lower motor volumes compared to motor types with the same power.

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As a result of this study, the life span of the mechanical parts that make up the motor and the efficiency of the motor will increase when the motor works at the ideal operating temperature.

2. LITERATURE REVIEW

Literature reviews showed that cooling systems are depending on the motor's power as summarized in Figure 1. Air is generally used for cooling under 40kW power, on the other hand, water-cooled systems are frequently used for motors over 40kW power range. In this study, the unique features that distinguish these works are the 9-phases, outer rotor topology, and 250kW maximum power.

There are many studies can be found from the literature survey which is focusing on the cooling strategy of the motors not only limited with air or water coolant but also related with the system design and the thermal system improvement of the vehicles. In the study of Sun et al. [18], concluded that the design considerably reduces the cost of the coolant structure when the temperature performance of the motor increases in the tested and simulated model the motor tested to obtain outlet temperature with different flow ratios at 5000 rpm, 101 Nm, and water temperature 55ºC. And then the better combinations were obtained when the constant was changed. The thermal model in the study of Satrústegui et al. [21] was used in to obtain variables for the main parameters that define the water jacket and the shaft. Firstly, the topology of the water jacket was analyzed to create a thermal model, and it was compared that the other topologies are spiral, U-shaped (single channel), U-shaped (bifurcated), and axial. As a result, the study importantly reduced the temperatures of some motor parts. In the study of Putra and Ariantara [2], the heat pipes are L-shaped and placed on the surface of the motor housing. In this way, installation and maintenance are effortlessly obtained by the new topology. The focus of this study is to provide better performance of the electric motor thermal management system by heat pipes. In the paper of Staton et al. [3], the effect of different cooling arrangements was studied in order to find out the impact of the frame openings and the rotor end-ring wafters on the end-winding cooling. The measured temperature increase is used to estimate the heat transfer between end-windings and external frame, by the help of the considered cooling arrangements. Results of these prototypes are compared with calculated results via thermal networks.

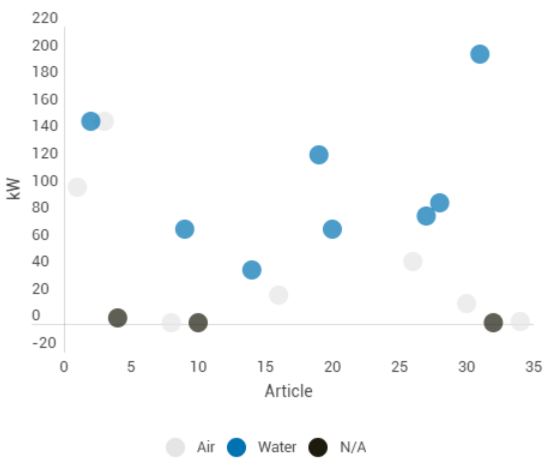

Figure 1. Motors Power rating according to refrigerant types in Literature review [1-35].

As given in above, the studies in the literature is limited which are focusing on the cooling design of the motor. In this study, in order to improve the performance of the cooling structure of the PMSM, the heat transfer of the Cooling Jacket (CJ) is analyzed with many variables such as the mass flow rate of the coolant, the pipe diameter of the coolant pipe, the number of turns of this pipe, the type of the refrigerant, and the change of the torque. The optimization of these variables are performed and the average winding temperature is analyzed in this study. By optimization of the mass flow rate of the coolant, the pipe diameter of the coolant pipe, the number of turns of this pipe, the type of the refrigerant, and the change of the torque, the best cooling design is obtained.

3. THE COOLING JACKET DESIGN

Fig. 2 presents the view of the cooling jacket with the single flow pipeline. The cooling jacket is placed stator inner surface which is close to the winding. The refrigerant fluid which is at 45 °C (for cooling) is flowing inside of the single flow pipe for cooling. The cooling jacket exchanger is cooled via a single pipe. During the cooling process, the refrigerant fluid starts to flow from the cooling jacket pipes.

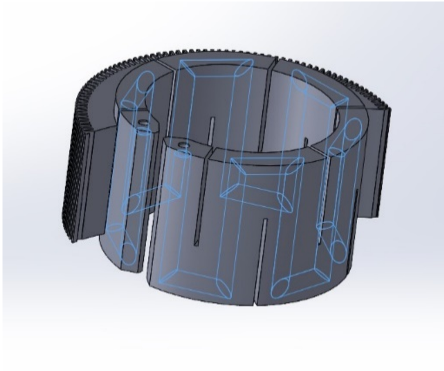

Figure 2. Motor Cooling Jacket Cross Section and the One Single Pipe Line.

As illustrated in Figure 3, the motor cross-section is shown where the shaft temperature is constant. The green-colored side is the cooling jacket, the hottest spot seen is the winding parts colored in red which is the hottest region. The light blue represents the rotor temperature, and the dark blue color shows the motor casing temperature which is located outer side of the motor. The maximum and the minimum temperatures for the current design of the motor are found 98 and 75 °C, respectively. In this analysis, the outlet temperature of the refrigerant fluid of the motor at constant 900 rpm is plotted and shown in Figure 4. The outlet temperature of the refrigerant, which the inlet temperature is assumed to be constant at 45 °C, was measured as 54.9°C at 900 secs later at constant 900 rpm motor speed. The result which is found by numerical modelling has been validated by the experimental data with a %4 margin of error.

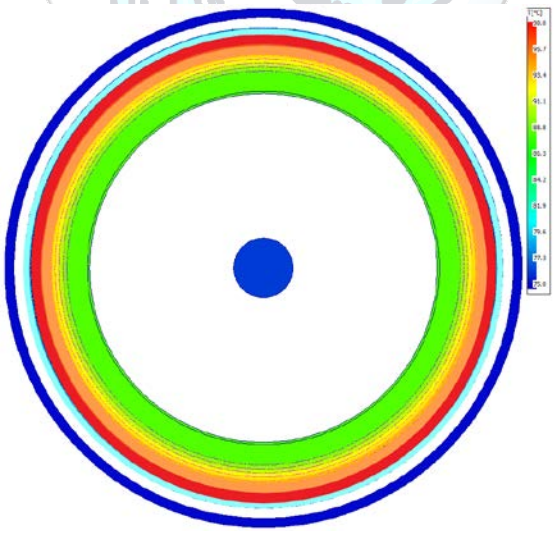

Figure 3. Thermal distribution of the Motor for the first time.

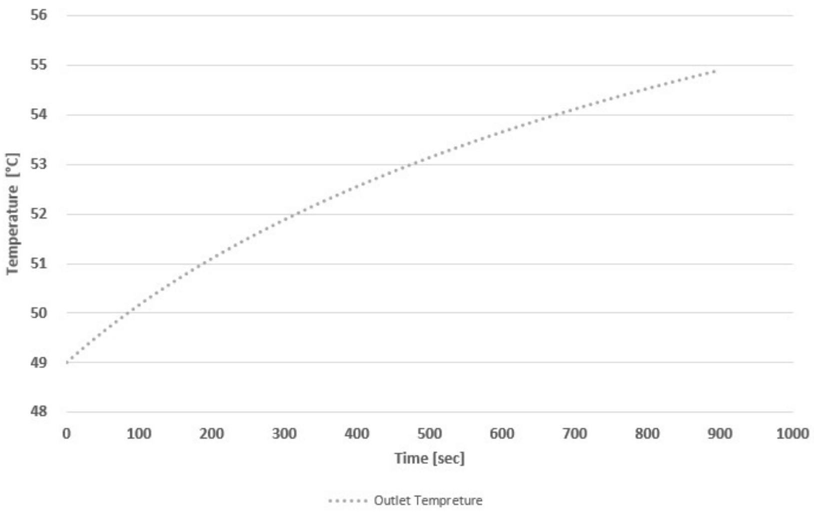

Figure 4. The Temperature of the Outlet Refrigerant Fluid at between 0 sec to 900 sec.

The current motor has cooling jacket coolant with a mass flow rate of 20 L/min, the pipe diameters of the coolant pipe of 25.4 mm with 12 number of turns in the stator region. The type of the refrigerant of this coolant is EGW 60/40. There are four main geometrical parameters are taken into account to develop the cooling jacket design such as; Mass flow rate (A), Pipe diameter (B), Number of turns (C), Type of the coolant fluid (D), and the Motor torque (E).

The parameters and the change of their values are summarized in Table 1. Mass flow rate (A), Pipe diameter (B) and the Number of turn of the cooling pipe (C), the Motor torque (E) parameters are changed in values. On the other hand, for the parameter which refers the Types of coolant fluid (D) are taken as; EGW60/40, PGW60/40, EGW50/50, and Therm. The specified diameter sizes are referenced from the commonly used brass pipes. Referenced dimensions have corresponded from inch to mm. The parameters are chosen for developing the cooling strategy of the motor by only changing the design parameters of the cooling pipe of the PMSM.

To optimize the cooling strategy for best cooling design, the Taguchi Methodology is performed in this study. Taguchi L16 orthogonal array is implemented L16 (45) for different 5 factors (A-E) each has 4 different values (levels). 45 runs should be performed to analyze the results. Thanks to Taguchi method the number of runs reduces to 16 to optimize the cooling strategy of the motor. Factors determined as stated above variables are analyzed by using the Taguchi Method as shown in Table 1. As illustrated in Table 2, Taguchi created 16 runs with these levels and factors. After that, these 16 runs were analyzed by using Motor CAD. As a result of these runs, the CJ outlet and average winding temperatures were calculated and the results are given in Table 2.

Table 1. Factors &Levels in Taguchi Method.

Factor Information

Factor	Type	Levels	Values
Mass Flow Rate	Fixed	4	20; 30; 40; 50
Pipe Dia	Fixed	4	17,7; 19,0; 25,4; 31,7
Number of Turns	Fixed	4	12; 16; 20; 24
Type of Fluid	Fixed	4	EGW60/40; PGW60/40; EGW50/50; THER
Torque	Fixed	4	500; 1000; 1500; 2000

Table 2. Taguchi Iterations and Results.

Iterations	Mass Flow Rate [L/min]	Pipe Dia[mm]	Number of Turns	Type of Fluid	Torque[Nm]	Shaft Speed [rpm]	CJ INLET TEMP[°C]	CJ OUTLET TEMP[°C]	WINDING TEMP (AVG) [°C]
1.	20	17.7	12	EGW60/40	500	3422	49	57.89	122.71
2.	20	19	16	PGW60/40	1000	2359	49	57.31	104.10
3.	20	25.4	20	EGW50/50	1500	1554	49	55.64	88.12
4.	20	31.7	24	THER	2000	1106	49	50.40	97.85
5.	30	17.7	16	EGW50/50	2000	1106	49	57.45	80.79
6.	30	19	12	THER	1500	1554	49	56.75	104.42
7.	30	25.4	24	EGW60/40	1000	2359	49	54.55	96.28
8.	30	31.7	20	PGW60/40	500	3422	49	54.07	120.51
9.	40	17.7	20	THER	1000	2359	49	57.75	103.74
10.	40	19	24	EGW50/50	500	3422	49	54.31	114.01
11.	40	25.4	12	PGW60/40	2000	1106	49	53.24	91.07
12.	40	31.7	16	EGW60/40	1500	1554	49	53.84	86.14
13.	50	17.7	24	PGW60/40	1500	1554	49	54.01	82.36
14.	50	19	20	EGW60/40	2000	1106	49	54.86	77.22
15.	50	25.4	16	THER	500	3422	49	55.39	122.61
16.	50	31.7	12	EGW50/50	1000	2359	49	53.01	96.89

In order to obtain the best results, the lowest winding temperature is required for the cooling jacket. Therefore, the smaller the better method in Taguchi method is used for the Average Winding Temperature. The Taguchi analysis created the plot in Figure 5. The effects of five design parameters on the cooling jacket are plotted in Figure 5. As seen for this figure, the smallest values of each factors should be taken for the lowest average winding temperature. And also, these points corresponding values are shown in Table 3. As seen these values on the chart to obtain the best thermal design for Cooling Jacket as mass flow rate (A); 50 l/min, the pipe diameter (B); 17.7mm, the number of turns (C); 20, the type of fluid (D); EGW 50/50, and the torque (E); 2000 Nm give the lowest winding temperature. Thus, A4B1C3D3E4 can be defined as the best cooling design for a cooling jacket.

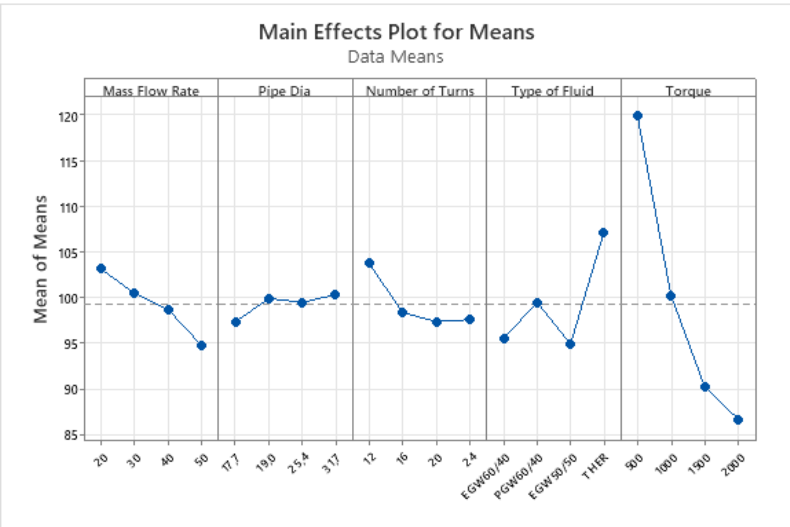

Figure 5. The Plot of the Main Effect per Levels for Means.

Table 3. Results of the Means.

Response Table for Means

Level	Mass Flow Rate	Pipe Dia	Number of Turns	Type of Fluid	Torque
1	103,19	97,40	103,78	95,59	119,96
2	100,50	99,94	98,41	99,51	100,25
3	98,74	99,52	97,40	94,95	90,26
4	94,77	100,35	97,62	107,16	86,73
Delta	8,42	2,94	6,38	12,20	33,23
Rank	3	5	4	2	1

4. RESULTS AND DISCUSSION

This study aims to optimize the cooling jacket design for the best cooling performance of a PMSM. In order to obtain the intended results, the 3D cooling jacket design is considered for this study. The L16 orthogonal array values are calculated for predicting the best configuration. Iterations of the cooling jacket have an effect on average winding temperature and the found results of the cooling jacket and average winding temperature iteration results are given in Table 2. These results is used for the best design. The optimization of the best configuration values was obtained as; Mass flow rate (A): 50 L/min, Pipe diameter (B):17.7 mm, Number of turns (C): 20, Type of the coolant fluid (D): EGW50/50 , and the Motor torque (E): 2000 Nm which is 1106 rpm.

As mentioned above, A4B1C3D3E4 design is the best cooling design for a cooling jacket. On the other hand, the worst case is found as A1B4C1D4E1 where the Mass flow rate (A1) is 20 l/min, the Pipe diameter is 31.7mm (B4), the number of turns is 12 (C1), type of fluid is Therm (D4), and torque value is 500 Nm (E1).

As illustrated in Figure 6. the thermal distributions of the motor cross-section are given for the current (A1B3C1D1E4), worst (A1B4C1D4E1), and best (A4B1C3D3E4) models, respectively.

The current model of the motor shown in Figure 6. has high and cold spot temperatures of 98°C and 75°C. The best model in Figure 6. has a hot spot temperature of 79°C while the cold spot temperature is 58 °C. The worst model of the motor has 159°C and 76°C as max and min temperatures. The cold spot temperature decreased to 54 °C from 75°C. The hot spot temperature decreased to 79 °C from 98 °C when compared to best and current models.

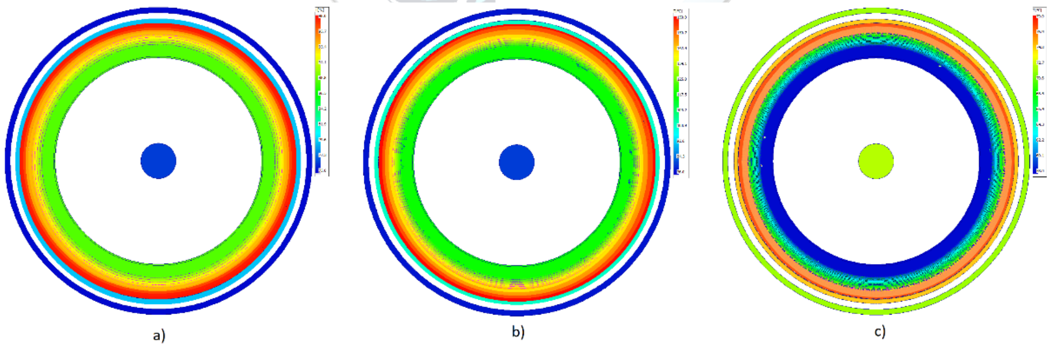

Figure 6. Thermal distribution of the a) Current, b) Worst and c) Best design, respectively.

The created thermal models of the motor were compared according to the temperature of the cooling jacket and winding average temperature changes respectively shown in Figure 7 and Figure 8.

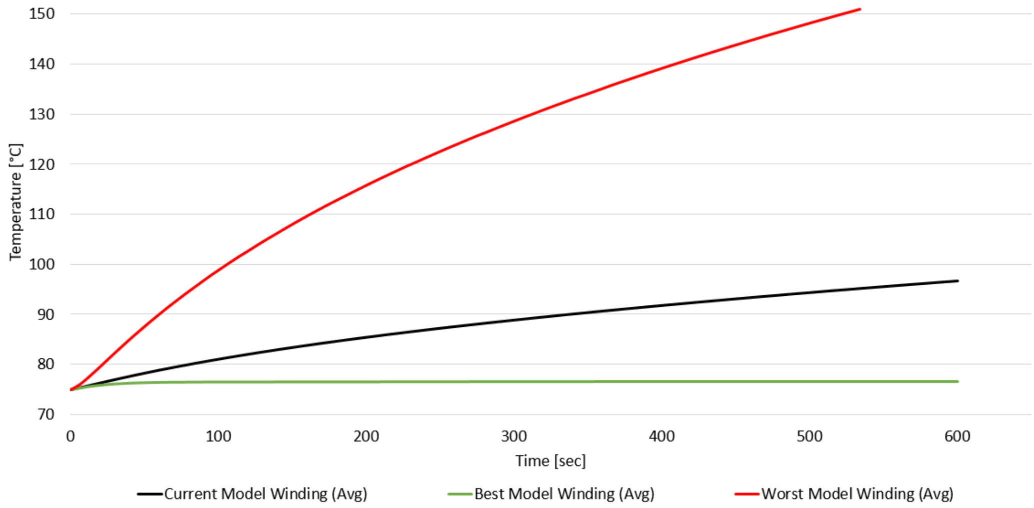

Figure 7. Compared between Current, Best and Worst Model temperature of Winding(Avg).

The cooling jacket temperatures reached about the same degree at the end. In this case, the earlier stages are more important because the cooling jacket temperature should be increased easily at the beginning. This indicates that it absorbs heat faster. The best model reaches 55 °C rapidly after then the temperature curve stabilizes at 55.9 °C. Because of that, 55 °C is chosen as the reference temperature. The best model reaches 55 °C at 138sec while the current model and worst model temperatures are respectively 50.94 °C and 82.86 °C. The best performance increases 7.97% compared to housing jacket outlet temperature at 138 sec.

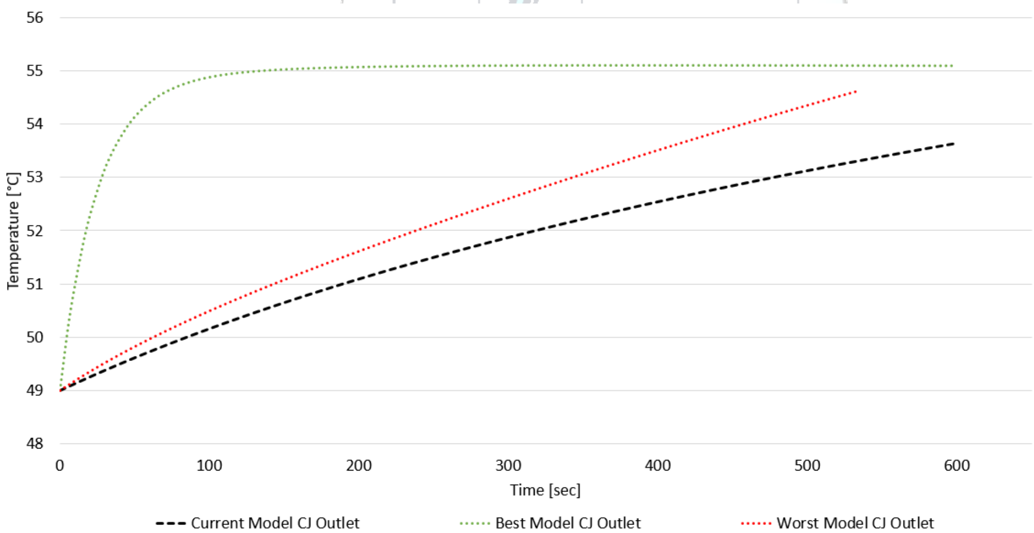

Figure 8. Compared between Current, Best and Worst Model temperature of CJ Outlet.

The best performance increases by 19.39% compared to the winding temperature for the cooling jacket. This improvement results can be seen easily as shown in Figure 6 and Figure 7.

5. CONCLUSIONS

This study aims to improve the thermal efficiency of a 250 kW permanent magnet synchronous motor over the determined parameters. These parameters are the basic design parameters that make up the cooling jacket. The studied parameters are mass flow rate, pipe diameter, number of turns, fluid types, and torque value. The variables of the parameters are defined as levels, and the best thermal model will create over common usage values.

In order to compare iterations between each other, it is necessary to form combinations of all levels and factors in themselves. In this way, the best result can be achieved. Since there are four levels of each of the five factors, 1024 iterations must be made. The Taguchi method is an L16 orthogonal array that defines the iterations. Thus the iteration numbers decrease to 42(16) from 45(1024) iterations.

The iterations were analyzed on Ansys and obtained the average winding and cooling jacket temperature results written on the Taguchi analysis table. The Taguchi is based on the minimum average winding temperature in this study. The Taguchi analysis was used as a “smaller is better method” to decrease hot spot temperature on the motor. The hot spot points appear in the motor winding, and the temperature distribution is not equal throughout the winding. Because of that, the data is approved on average. Thus, the best and worst model is acquired by the Taguchi method.

The best thermal model is obtained with these parameters; mass flow rate: 50 l/min, pipe diameter: 17.7 mm, number of turns: 20, type of fluid: EGW 50/50, torque: 2000 Nm. Analysis was performed in Ansys using the best values obtained. As a result of this analysis, changes in the output temperature of the coolant were observed. It reached 55 degrees in 138 seconds. For this reason, the efficiency calculation was made by evaluating the temperature values in 138 seconds. In this stage, the refrigerant efficiency was increased by 7.97%. This way, the PMSMs hot spot temperature decreased to 79°C from 98°C. Due to the improved model, thermal efficiency increased 19.39% with changes only to the cooling jacket.

REFERENCES

[1]. Chiwon Kim, Kwan-Soo Lee , Se-Jin Yook, Effect of air-gap fans on cooling of windings in a large-capacity, high-speed induction motor, ELSEVIER, Applied Thermal Engineering 100 (2016) 658–667.
[2]. Nandy Putra, Bambang Ariantara, Electric motor thermal management system using L-shaped flat heat pipes, ELSEIVER, Applied Thermal Engineering 126, 1156–1163, 2017.
[3]. D. Staton, Mircea Popescu, D. Hawkins, Aldo Boglietti, Influence of different end region cooling arrangements on end-winding heat transfer coefficients in electrical machines, IEEE Xplore, October 2010.
[4]. Staton, D. & Popescu, Mircea & Hawkins, D. & Boglietti, Aldo & Cavagnino, Andrea, Influence of different end region cooling arrangements on end-winding heat transfer coefficients in electrical machines, IEEE Energy Conversion Congress and Exposition, ECCE 2010 - Proceedings. 1298 – 1305, 2010.
[5]. Xia, Zhengpeng & Zhou, Chenquan & Shen, Dan & Ni, Hongjun & Yuan, Yinnan & Ping, Liao. (2014). Study on the Cooling System of Super-Capacitors for Hybrid Electric Vehicle. Applied Mechanics and Materials, 492, 37-42.
[6]. Meenen, Jordan, MIT Electric Vehicle Team Porsche Designing a Cooling System for the AC24 Electric Motor, 2010.
[7]. Demetriades, Georgios & Zelaya De La Parra, Hector & Andersson, Erik & Olsson, Hakan, A Real-Time Thermal Model of a Permanent-Magnet Synchronous Motor, Power Electronics, IEEE Transactions on. 25. 463 - 474.
[8]. Ying Xie, Yunyang Wang, 3D temperature field analysis of the induction motors with broken bar fault, ELSEVIER, Applied Thermal Engineering 66, 25-34, 2014.
[9]. Mokukcu, Mert, Electric Vehicle Powertrain Design and Implementation, 2014.
[10]. Fatih Alpaslan KAZAN, Osman BİLGİN, Simulation of PMSM Operating at Different Speeds and Optimization of PI Controller Parameters, MAKÜ-Uyg. Bil. Derg., 4(1), 86-105, 2020.
[11]. Demetriades, G.D., Zelaya, H., Andersson, E., & Olsson, H., A Real-Time Thermal Model of a Permanent Magnet Synchronous Motor Based on geometrical measures, IEEE Power Electronics Specialists Conference, 3061-3067, 2008.
[12]. Li, Guang-Jin & Ojeda, Javier & Hoang, Emmanuel & Gabsi, Mohamed, Thermal-Electromagnetic Analysis of a Fault-Tolerant Dual Star Flux-Switching Permanent Magnet Motor for Critical Applications, Electric Power Applications, IET. 5. 503 – 513, 2011.
[13]. Chaieb, Mohamed & Naourez, Benhadj & Kammoun, J.K. & Neji, Rafik, Thermal modeling of permanent magnet motor with finite element method. 594-598, 2015.
[14]. R. Cermak and R. Pechanek, Thermal Study of Permanent Magnet Direct Drive Wheel Motor, 2018 18th International Conference on Mechatronics - Mechatronika (ME), 2018, pp. 1-6.
[15]. A. Kačenka, A. -C. Pop, I. Vintiloiu and D. Fodorean, Lumped Parameter Thermal Modeling of Permanent Magnet Synchronous Motor, 2019 Electric Vehicles International Conference (EV), 2019, pp. 1-6.
[16]. Kefalas, Themistoklis & Kladas, A.. (2014). Thermal Investigation of Permanent-Magnet Synchronous Motor for Aerospace Applications. Industrial Electronics, IEEE Transactions on. 61. 4404-4411.
[17]. Malumbres, Jose & Satrústegui, Marco & Elosegui, Ibon & Ramos, Juan & Martinez-Iturralde, Miguel, Analysis of relevant aspects of thermal and hydraulic modeling of electric machines, Application in an Open Self Ventilated machine. Applied Thermal Engineering, 2014.
[18]. Yalong Sun, Shiwei Zhang, Wei Yuan, Yong Tanga, Jingrong Li, Kairui Tang, Applicability study of the potting material based thermal management strategy for permanent magnet synchronous motors, ELSEIVER, Applied Thermal Engineering 149, 2019, 1370–1378.
[19]. Johnston, David & Kumar, Nitish & Joshi, Yogendra & Kumar, Satish & Tikadar, Amitav, Comparison of Electro-Thermal Performance of Advanced Cooling Techniques for Electric Vehicle Motors, Applied Thermal Engineering, 2020.
[20]. O. Ustun et al., "Design and manufacture of electric powertrain and its cooling system for ITU EV project," International Conference on Electrical Machines (ICEM), 2014, pp. 730-735.
[21]. Satrústegui, Marco & Martinez-Iturralde, Miguel & Ramos, Juan & Gonzalez, Patxi & Astarbe, Gorka & Elosegui, Ibon, Design criteria for water cooled systems of induction machines. Applied Thermal Engineering, 2016.
[22]. T. D. Kefalas and A. G. Kladas, "Finite element transient thermal analysis of PMSM for aerospace applications," 2012 XXth International Conference on Electrical Machines, 2012, pp. 2566-2572.
[23]. Yaşar MUTLU,(2011), ELEKTRİKLİ ARAÇ MOTORUNUN SOĞUTMA SİSTEM TASARIMI.
[24]. A. Apte, R. Walambe, V. Joshi, K. Rathod and J. Kolhe, "Simulation of a permanent magnet synchronous motor using Matlab-Simulink," 2014 Annual IEEE India Conference (INDICON), 2014, pp. 1-5.
[25]. Jebahi, Radhia & Aloui, Helmi & Ayadi, Moez, One-dimensional Lumped-Circuit for Transient Thermal Study of an Induction Electric Motor. International Journal of Electrical and Computer Engineering (IJECE), 2017.

[26]. Ponomarev, Pavel & Polikarpova, M. & Pyrhönen, J., Thermal modeling of directly-oil-cooled permanent magnet synchronous machine, Proceedings – 2012, 20th International Conference on Electrical Machines, 2012.
[27]. Aziz, Rebaz & Atkinson, G. & Salimin, Suriana, Thermal Modelling for Permanent Magnet Synchronous Machine (PMSM), International Journal of Power Electronics and Drive Systems (IJPEDS), 2017.
[28]. Rehman, Z.; Seong, K., Three-D Numerical Thermal Analysis of Electric Motor with Cooling Jacket. Energies,11(1), 92, 2018.
[29]. Fan, Jinxin & Zhang, Chengning & Wang, Zhifu & Dong, Yugang & Nino, C.E. & Rehman, Abdul & Strangas, Elias, Thermal Analysis of Permanent Magnet Motor for the Electric Vehicle Application Considering Driving Duty Cycle, Magnetics, IEEE Transactions on. 46. 2493 – 2496, 2010.
[30]. Fang, Guoyun & Yuan, Wei & Yan, Zhiguo & Sun, Yalong & Tang, Y., Thermal management integrated with three-dimensional heat pipes for air-cooled permanent magnet synchronous motor, Applied Thermal Engineering, 2019.
[31]. Cavazzuti, Marco & Gaspari, Gloria & Pasquale, Stefano & Stalio, Enrico, Thermal management of a Formula E electric motor: Analysis and optimization, Applied Thermal Engineering, 2019.
[32]. Zhang, Hengliang & Giangrande, Paolo & Sala, Giacomo & Xu, Zeyuan & Hua, Wei & Madonna, Vincenzo & Gerada, David & Gerada, Chris, Thermal Model Approach to Multisector Three-Phase Electrical Machines, IEEE Transactions on Industrial Electronics, 2020.
[33]. Tauseef, Giasuddin & Chao, Shuo, Thermal Analysis of PMSM Stator using ANSYS, 2014.
[34]. Wang, Shengnan & Li, Yunhua & Li, Yun-Ze & Wang, Ji-Xiang & Xiao, Xi & Guo, Wei,Transient cooling effect analyses for a permanent-magnet synchronous motor with phase-change-material packaging, Applied Thermal Engineering, 2016.