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RESEARCH ARTICLE

Thermal Optimization of a Radial Flux Permanent Magnet Synchronous Motor With Axial Division

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ABSTRACT

This paper proposes a method for thermal optimization for the radial flux permanent magnet synchronous motor (PMSM) used in light electric vehicles. Thermal effects cause many negative impacts, especially losses in electrical machines. These effects cause the permanent magnets to deteriorate and the motor to become inoperable in PMSMs. Therefore, it is important to optimize the operating internal temperatures of PMSM. In this study, it is suggested that the permanent magnets of the PMSM should be made in pieces in the axial direction in order to reduce the operating temperature value. The simulated design is a radial flux PMSM used in light electric vehicles with a power of 3.2 kW, 150 V, and 1000 rpm. ANSYS Electronics Desktop, a finite element method-based software, was used for electromagnetic field analysis, and ANSYS Motor-Cad software was used for thermal simulation. The simulation results show that the axial division of the permanent magnets reduces the PMSM internal temperature value.

Index Terms—Axial division of magnets, losses, permanent magnet synchronous motor, thermal analysis

I. INTRODUCTION

Permanent magnet synchronous motor (PMSM) has been used frequently in industrial applications and electric vehicles in recent years. At the same time, PMSMs are still in the process of development today. The PMSM is an electric motor which is light, small in size, highly efficient, long-lasting, has functional mobility, and can operate in the desired speed range [1]. These motors can reach the reference speed value in the shortest time during speed changes. In addition, the low torque fluctuation and noise have caused the usage areas to become widespread recently [2].

Today, many development studies are carried out on permanent magnets and ferromagnetic materials. These materials form the basis of PMSM structures. Researchers create different PMSM designs with the help of these developed materials. It has been presented in the literature by many researchers that the use of different variations of the design parameters of PMSM changes the efficiency, power, torque, and cost of the motor [1–4].

Electromagnetic simulation results are important to improve the performance of electric motors. Electromagnetic analysis results provide information about electric motor parameters. However, these results are not significant for realistic applications. In addition to these results, thermal simulation results are also needed in PMSMs. Since the temperature of electric motors is inversely proportional to the magnetic flux, it directly affects the efficiency of the motor [5, 6]. Therefore, it is important to examine the time-dependent temperature change with thermal simulations in order for PMSM prototypes to achieve the desired results. The purpose of thermal analysis for electric motors is heat dissipation. Thus, the heat dissipation can be calculated and the regions determined as the heat source can be determined [7, 8].

The PMSM is exposed to high thermal stresses during operation. Therefore, thermal simulation should be done before PMSM prototype production in order to reach the correct designs. The result of the analysis should be interpreted and the thermal effects should be calculated. Thermal effects can be minimized by both mechanical design changes and the selection of appropriate ferromagnetic materials [8]. Controlling the overheating of the PMSM with appropriate feeding techniques is another thermal optimization method. Thermal effects cause the motor to heat up and reduce the efficiency of the motor and reduce its life [9] and even cause the motor to malfunction and become inoperable.

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Thermal effects in PMSM also affect the loss of magnetic properties of permanent magnets. Reaching the maximum operating temperature of the permanent magnets, which is called the Curie temperature, causes the loss of their magnetic properties [8]. Thus, permanent magnet manufacturers offer these temperature values to users for each magnet. The temperature values on the magnets in the design can be determined with thermal simulation. Designers can choose the appropriate permanent magnet with this determined temperature value. Curie temperatures of magnets are important when choosing.

There are other factors besides the design factors that affect PMSM heating. The switching frequency of the motor and the related current has an effect. When the switching frequency of the power converter increases, the internal temperature of the motor rises due to the increase in losses [10]. It is also known that flux density affects temperature based on the analysis performed under various operating conditions [11].

There are different studies in the literature regarding the reduction of all these mentioned thermal increases. In these studies, mostly the method of variation of mechanical design parameters is used. In addition to mechanical designs, electric motor internal temperature values can be reduced with different cooling liquids and external cooling. However, these external methods are not preferred because they affect the manufacturing cost and require additional mechanical design and equipment. One of these methods is to prevent sudden heating of the motor by filling different types of stator slots with paraffin, which are specially created for the PMSM. As a result of various research, it has been revealed that winding temperatures can be increased or decreased by around 2°C by changing the thresholds of the motor current and the speed of the motor in relation to the reduction of the PMSM internal temperature [12].

Thermal optimization is very important for the motor's operating life for a high torque density PMSM. Thermal analysis of PMSM with heat pipe without changing the mechanical design is a method preferred by researchers. It is a method based on the transfer of motor winding temperatures with a heat pipe. It has been shown that winding temperatures can be reduced with this method. In addition, it was concluded that the operating time is longer than natural cooling [13].

The PMSM has been preferred in electric and light electric vehicles due to their superior properties in recent years. Many cities, which have targeted a sustainable environment and urban planning, encourage the use of electric and light electric vehicles. Torque ripple and thermal effects are important in brushless direct current motor [14] and PMSM. In this study, thermal simulation and thermal optimization of a radial flux PMSM with 3.2 kW power, 150 V voltage, and 1000 rpm rated speed for use in a mini electric garbage collection truck are aimed. The most common methods in the literature for thermal optimization are changing the geometries of the PMSM or external cooling. A method was used without changing the geometry of the PMSM and not requiring an additional cost increase with the study. Thermal optimization is achieved by dividing the magnets of the PMSM, which has permanent magnets in the radial direction, in the axial direction. It is aimed to thermally improve the radial flux PMSM with this method. The outstanding feature of this study is that the thermal optimization of radial flux PMSM magnets by axial segmentation has not been found in the literature.

Main Points

- Thermal optimization has been made for the Radial Intelligent Permanent Magnet Synchronous Motor (PMSM).
- Axial partitioning of radial flux motor is implemented.
- The internal temperature of PMSM has been reduced with split magnets.

It is not very meaningful to make thermal simulations only to obtain the design parameters of electric motors. Therefore, it is more appropriate to extract the dynamic models of the designs and perform electromagnetic analyses before thermal analysis. Magnetic components were sized by analyzing them with the RMxprt package under ANSYS Electronics Desktop software. Electromagnetic analyses were performed with the Maxwell package of the same software. Afterward, thermal simulations were performed with ANSYS Motor-CAD software.

The importance of thermal effects in electric motors and the explanation of these effects are explained in the second part of the study. Electromagnetic field analyses of PMSM, which is preferred in radial flux in-wheel mini waste management garbage trucks, are shown in the third section. The thermal simulation is given in the fourth section. The optimization study is shown in the fifth section.

II. THERMAL EFFECT

The PMSMs heat up due to current and losses when exposed to the voltage required for operation. There is a difference between the ambient temperature of the motor and the temperature at the loading condition. This difference is described as the thermal effect in motors. The motor's ability to remove heat is directly proportional to its operating time at high power levels. Electric motors must transfer their internal heat by conduction or radiation. The performance, efficiency, and cost of the motor are positively affected by the development of the motor's ability to remove heat [14].

Overheating of the motor leads to malfunctions and burns in the motor. Overheating can have many causes. These are incorrect motor size, changes in load, extreme misalignment, hot ambient conditions, and phase-induced vibration and phase losses [15]. The heat generated by the effect of increasing temperature causes thermal stresses in the motor under load. If these stresses cannot be prevented, they may cause problems such as cage structure breakage in the motor body [16].

The uneven heating of the PMSM can disrupt the insulation of the motor. The deterioration of the insulation is usually caused by the motor windings. These windings become short-circuited without insulation. Thus, the motor winding wires are scorched and burned. At the same time, it causes demagnetization of the magnet and damages the mechanical elements [17]. Thermal increases due to overheating of the windings also affect permanent magnets. Each permanent magnet has an operating temperature range. They deteriorate after a certain temperature. This limit temperature value is called the Curie temperature. Permanent magnets that reach the Curie temperature lose their magnetic properties. Therefore, it is important to know the motor operating temperature before production.

Heat sources cause heating in PMSM. Internal thermal sources of PMSM are copper, iron, and mechanical losses. Copper loss is the most important among these thermal sources. Copper losses result from heat dissipation due to ohmic resistance. The loss caused by copper losses constitutes approximately 96% of all losses [18]. The calculation of copper losses is shown in (1) [19].

$$P_{cu} = I^2 \times R\left[W\right] \tag{1}$$

where R represents the internal resistance of the stator and I represents the motor current. The stator internal resistance is directly proportional to the temperature. Also, it is a large heat source [20]. Iron losses are divided into two types as Eddy current losses and Hysteresis losses. Eddy current loss is part of ferromagnetic losses caused by electromagnetic induction [19]. The expression of these losses is shown in (2).

$$P_{eddy} = K_g.f^2.B_m{}^2\left[W/kg\right] \tag{2}$$

where K_g is the Eddy current loss coefficient of the material, f is the frequency of magnetic flux change, and B_m is the maximum intensity of the magnetic field.

Hysteresis losses are caused by the magnetization of the core as a result of the charging current. Its calculation is as in (3) [20–22].

$$P_{his} = K_h.f.B_m{}^x\left[W/kg\right] \tag{3}$$

where K_h is the hysteresis loss coefficient of the material and x is the Steinmetz constant depending on the material.

Mechanical losses are losses due to friction. The impact of these losses is not very high. It is negligible in calculations compared to other losses. Stator internal resistance, material structures, frequency, and external effects can be used as calculation parameters affecting the temperature.

Electric motors can operate continuously at nominal power values. The rated power expression can be defined as the maximum shaft power with continuous operation. There may be short-term overloads on the motor shaft in some non-standard operating conditions. This situation, which is higher than the rated power value, has a disruptive effect on the electric motor. These effects are acceptable if the operating time is not long. Extending the operating time in case of overload can cause the motor windings to burn out due to heating, damage the winding insulators, and permanently lose the properties of the permanent magnets. The motor operating temperature value can also be kept under control with the control of the overload condition. The standard for thermal performance tests of electric motors is specified in IEC 600034-1. This standard covers various load cases and operating conditions. IEC 600034-1 is the international standard for the performance evaluations of rotary electrical machines.

The thermal analysis of the radial flux PMSM used in this article was performed with ANSYS Motor-CAD simulation software. ANSYS Motor-CAD software uses mesh networks similar to loop electrical circuit structures consisting of nodes. Thus, it reveals thermal problems and defines the thermal circuit model in a steady state. The software includes thermal resistors and heat sources connected between nodes of electric motor parts. In addition, this software also adds the thermal resistances of the object in the transient simulation model. Meanwhile, thermal capacitances are used to add the time-varying internal energy of the body to the calculations. The thermal resistances specified are calculated as conduction and diffusion as in (4) and (5) [20–22].

$$R_{cond} = \frac{l}{\lambda A} \tag{4}$$

$$R_{diff} = \frac{l}{\alpha A} \tag{5}$$

where l is the distance between the nodes, λ is the thermal conductivity coefficient, A is the cross-sectional area, and α is the heat diffusion coefficient. The thermal capacitances are as in (6) [20–22].

$$C = V\rho c \tag{6}$$

where V is the volume, ρ is the density, and c is the thermal capacity of the material [19].

III. SIMULATION OF RADIAL FLUX PMSM

A radial flux PMSM with a power of 3.2 kW, a voltage of 150 V, and a rated speed of 1000 rpm, used in the drive system of electric garbage collection vehicles, was determined. Garbage collection trucks that can work comfortably in narrow side streets in many districts of Istanbul, which have a sustainable and environmentally friendly urbanism, have turned into electric driven mini garbage collection trucks. These mini truck manufacturers, which are in the category of light electric vehicles, generally use PMSMs in the propulsion systems of these vehicles.

The PMSM, which is the subject of the study, is determined as radial flux and outer rotor. Outer rotor electric motors are known as in-wheel electric motors. In-wheel PMSM is used in applications that do not require high power. In addition, this type of motor is ideal for small vehicles as it saves space. It is economical because it uses the power on the motor shaft without a drivetrain. The optimum solution for mini waste management garbage trucks, which are light electric vehicles, is the outer rotor structure. The values given in Table I were taken as the initial design parameters of the study. These parameters have been determined in accordance with the electric mini waste management garbage trucks currently in use, and the dimensional dimensioning of the motor has been created in accordance with these vehicles. Based on the parameters in Table I, simulations were carried out with the RMxprt package in ANSYS Electronics Desktop software to extract the dynamic model of the motor.

TABLE I.
PMSM DESIGN PARAMETERS

Parameter	Value
Power (kW)	3.2
Voltage (V)	150
Rated speed (min^{-1})	1000
Stator inner diameter (mm)	190
Rotor outer diameter (mm)	273

PMSM, permanent magnet synchronous motor.

The most preferred materials in the literature are used as the rotor and stator materials of PMSM in the initial design. These materials, which are specified as the initial parameter, have received positive results from the researchers. Pre-simulation studies were carried out with these materials in order to reach the final design parameter. It was decided to use M19-26G as the stator material, Steel 1010 as the manufacturing steel for the rotor back iron, and NdFeB-38H as the permanent magnet as a result of the preliminary simulation study. The 24/18, 36/30, 36/26, and 24/20 models were analyzed in simulation studies to determine the appropriate slot/pole number. According to the results of the simulation study, it is concluded that the 24/20 slot/pole number has the most efficient and suitable motor output values. Mechanical design parameters affect the output data of electric motors. One of the most important mechanical design parameters in PMSM is the slot structure. Simulations were made with ANSYS Electronics Desktop with different slot structures and dimensions. As a result, an optimized design was obtained. A similar determination was made for the magnet embrace ratio and the winding structure. The magnet embrace ratio was determined as 0.8. Single-layer winding has been chosen because it gives much better results as the motor winding structure of PMSM.

The slot occupancy rate has been determined not to exceed 60% with the specified parameters. This value is important for the placement of the motor windings without salient from the slot area. In addition, the resistance, self, and mutual inductance of all phase windings are equal and constant, magnetic circuit saturation is neglected and the motor's internal operating temperature value is determined as 90°C.

The ANSYS Electronics Desktop software RMxprt package simulation results performed after the design parameters are determined are shown in Table II.

It is seen in Table II that the simulated radial flux PMSM can operate at the target speed and torque value with the determined power value. One of the most important concepts in electric vehicles is range. Today, many research topics are on increasing the range of electric vehicles. One of the ways to increase the range is to use a high-efficiency electric motor. It is understood that the targeted efficiency value is satisfied due to the experimental value.

TABLE II.
PMSM ANSYS RMXPRT SIMULATION RESULTS

Parameter	Value
Cogging torque (Nm)	0.6512
Average input current (A)	22.9259
Armature current density (A/mm^2)	5.46578
Total loss (W)	239.018
Output power (W)	3199.87
Input power (W)	3438.89
Efficiency (%)	93.0496
Rated speed (min^{-1})	1048.31
Rated torque (Nm)	29.1484

PMSM, permanent magnet synchronous motor.

Another parameter to be considered in electric motor designs is the armature current density. This value is expected to be between 4 and 6 A/mm^2. An electric motor with an armature current density of more than 6 A/mm^2 needs an external cooling system. In-wheel electric motors are not suitable for external systems due to space constraints. Therefore, the design of these types of motors should not require external cooling. As seen in Table II, PMSM armature current density value is 5.46578 A/mm^2. Accordingly, the proposed design is suitable for natural cooling.

The output torque change curve according to the speed change of the design simulated with the ANSYS Electronics Desktop RMxprt package is shown in Fig. 1. It is understood that the torque–speed curve of the PMSM is quite compatible with the targeted result. It has a torque of 29.1484 Nm at the target speed of 1000 rpm.

In order to be able to drive the mini waste garbage truck with PMSM, it must produce 3.2 kW of power at 1000 rpm. As a result of the simulation, it is seen that PMSM can produce this power at 1000 rpm. The change curve of the output power according to the motor speed is as in Fig. 2.

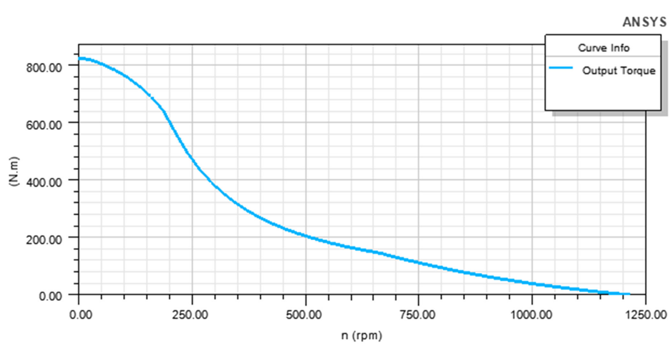

Fig. 1. Output torque–velocity graph as a result of simulation.

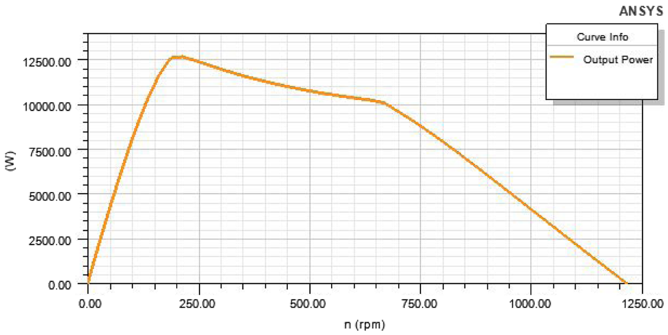

Fig. 2. Output power–velocity graph as a result of simulation.

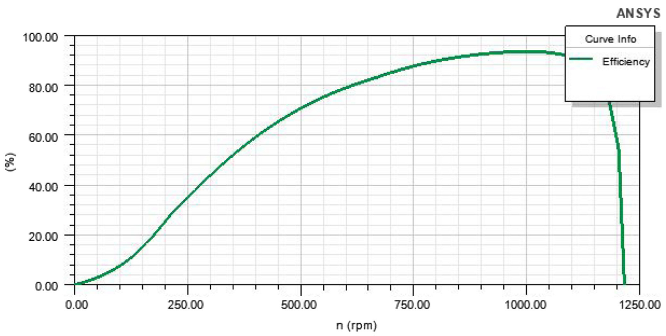

Fig. 3. Efficiency–velocity graph as a result of simulation.

The efficiency–speed change curve of PMSM is as in Fig. 3. It is seen that the design has an efficiency of 93.05% at 1000 rpm, which is the motor speed.

Analytical solution results are not sufficient to evaluate the electric motor design results. The results of electromagnetic field analysis should also be examined. After the analysis with ANSYS Electronics Desktop RMXprt package, electromagnetic field simulation was done with Maxwell package under ANSYS Electronics Desktop software. According to the results obtained from both Table I and Figs 1–3, it is understood that the optimized design has been obtained. In order to verify these values obtained, PMSM's electromagnetic field analysis results should also support this.

Two-dimensional and three-dimensional electromagnetic simulations of the motor were carried out with the ANSYS Electronics Desktop software Maxwell package after it was concluded that the optimized design values were reached. Fig. 4 shows the two- and three-dimensional magnetic flux density distribution of the PMSM.

As seen in Fig. 4, the magnetic flux density does not reach the limit values. The near-saturated sections whose flux density is around 2.2 T are shown on the edges of teeth only. Also, as shown in Fig. 4, the flux exhibits a smooth and homogenous distribution as expected.

IV. RADIAL FLUX PMSM THERMAL ANALYSIS

The simulation results before the prototype production of electric motors are guiding for manufacturing. Electric motor output values and electromagnetic field analysis results obtained by the finite element method are important for electric motor design. These data should be supported by thermal simulation to create a realistic approximation. The thermal effect is a very important parameter for electric motors. There is a dimension restriction on the in-wheel electric motor. Therefore, it is not possible to design an external cooling for the in-wheel PMSM. Since the outer body of the motor will be inside the tire, there cannot be a cooling design in the outer body. For these reasons, thermal simulation of radial flux PMSM design is important.

Thermal analysis results should be well understood. The distribution of thermal effects on the electric motor must be determined. Thus, the thermal values on the motor windings, permanent magnet, and stator are obtained. In this study, ANSYS Motor-CAD software was used for thermal simulation. ANSYS Motor-CAD creates a realistic approach as it models the operation of the electric motor. This software takes many data such as the geometric dimensions of the motor, electrical parameters, and magnetic field analysis results from the simulation file of the magnetic field analysis in order to perform thermal analysis. The collective parameter circuit model, which forms the basis of this software, is an analytical approach used to reveal the temperature effects of electric motors. Similar software that performs thermal analysis performs their analysis according to the stacks and their parameter circuit model. ANSYS Motor-CAD software calculates solutions with a thermal circuit model. The thermal model is like an electrical circuit. It contains the parts of the electric motor and their thermal parameters. The thermal circuit model determines the thermal effect by convection, conduction,

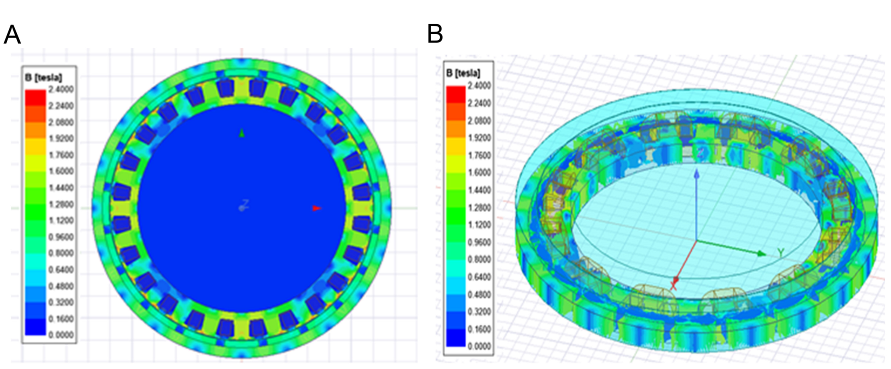

Fig. 4. Magnetic flux density distribution: (a) Two-dimensional; (b) Three-dimensional.

and radiation methods. The thermal values of these thermal spots interacting with each other are calculated by analytical methods. The thermal behavior of the stator and rotor is different from each other in the starting operation, continuous operation, and continuous overload situations in PMSM. Therefore, motor heating and cooling dynamics should be examined separately for the stator and rotor. Continuously operating rotor and stator thermal models should be combined. The thermal model for the stator and rotor is as in (7) and (8).

$$\Delta\Theta_R = \left[p_R\left(\frac{I}{I_N}\right)^2 \Delta\Theta_{NR}\right]\left[1-e^{-t/\tau_{1R}}\right]+\left[(1-p_R)\left(\frac{I}{I_N}\right)^2 \Delta\Theta_{NR}\right]\left[1-e^{-t/\tau_{2R}}\right] \quad (7)$$

$$\Delta\Theta_S = \left[p_S\left(\frac{I}{I_N}\right)^2 \Delta\Theta_{NS}\right]\left[1-e^{-t/\tau_{1S}}\right]+\left[(1-p_S)\left(\frac{I}{I_N}\right)^2 \Delta\Theta_{NS}\right]\left[1-e^{-t/\tau_{2S}}\right] \quad (8)$$

where $\Delta\Theta_R$ is the thermal increase in the rotor, $\Delta\Theta_S$ is the stator thermal increase, p_R and p_S are the weight factor for the short-time constant of the rotor and stator windings, I_N is the nominal current, I is the phase current, τ_{1R} and τ_{1S} is the instantaneous cooling-heating time constant of the rotor and stator windings, $\Delta\Theta_{NR}$ and $\Delta\Theta_{NS}$ give the thermal increase of the rotor and stator at nominal load and current state, time t, and τ_{2R} and τ_{2S} give the cooling-heating time constant in the rotor and stator body [21–25].

As a result of the thermal simulation made with ANSYS Motor-CAD, the overall thermal distribution on the PMSM is shown in Fig. 5.

The highest temperature region of the radial flux PMSM is 94.8°C in the stator windings as seen in Fig. 5. It is concluded that the lowest temperature region is the PMSM body with 65.1°C. According to the general thermal distribution, it is seen that the back iron temperature value is 65.1°C, the stator surface is 77.7°C, and the stator teeth are 77.9°C. The average temperature of the radial flux PMSM is 94°C.

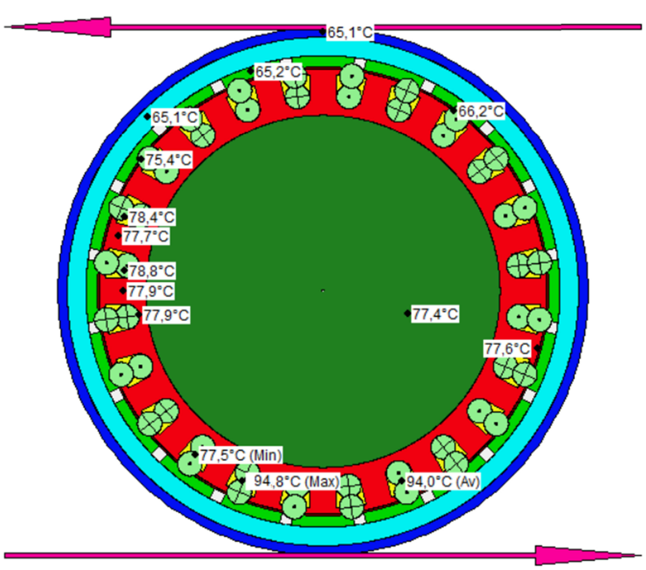

Fig. 5. General thermal dissipation of the PMSM. PMSM, permanent magnet synchronous motor.

TABLE III.
PMSM THERMAL ANALYSIS RESULT

Temperature Zone	Temperature (°C)
Housing	65.1
Magnet surface	65.2
Stator surface	77.9
Winding (average)	94.0
Back iron	65.1
Bearing	77.4
Shaft	77.4

PMSM, permanent magnet synchronous motor.

It can be seen that the temperature on the permanent magnet is 69.2°C. It is known that the maximum operating temperature of the NdFeB-38H permanent magnet used in this design is 80°C. According to the thermal analysis results, it is seen that the magnet has not reached the maximum operating temperature. NdFeB-38H magnet does not reach Curie temperature. The permanent magnet is in the ideal operating temperature range. One of the PSMS thermal simulation results is that the magnets will not deteriorate.

All thermal analysis data obtained by ANSYS Motor-CAD simulation are as in Table III.

The hottest area of the PMSM is around the motor windings. Although PMSM winding temperature is high, it is within acceptable limits. The stator and rotor steel materials selected for the prototype are materials that can operate within the temperature values specified in the thermal analysis results.

V. THERMAL OPTIMIZATION OF THE PMSM

Two methods are generally used for the thermal optimization of conventional PMSMs. One of these methods is the mechanical design. The mechanical design method is based on two structures. The first step is increasing the contact surface of the motor with air. The second step is to remove heat from the motor. For this reason, most electric motors have cooling fins. The second method is the external cooling mechanism. The aim of the external cooling method is to increase the frequency of contact with air. In this way, cooling is aimed to be achieved without changing the surface dimensions. Both methods affect the production cost of PMSM.

Radial flux PMSMs with in-wheel structures do not have many options for thermal optimization. These thermal optimization methods are not preferred because of dimensional limitations. A new method has been created for this situation of radial flux PMSM, which is missing in the literature with the study.

Eddy current losses have an effect on the output values and especially the thermal values of the radial structured PMSM. It is known that

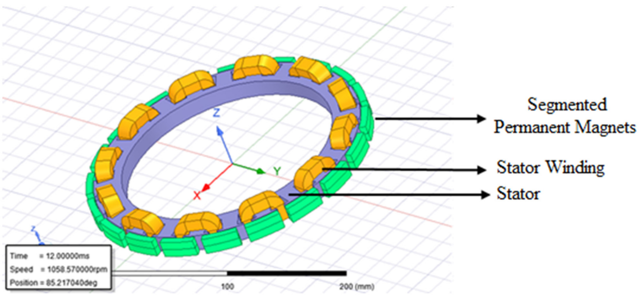

Fig. 6. Radial flux PMSM motor design with axial division. PMSM, permanent magnet synchronous motor.

with the decrease in eddy current paths, these losses will decrease. Thus, it is estimated that the heat distribution of the motor will improve. To reduce eddy current losses, the radial arrangement of magnets in the radial PMSM is divided into axial segmentation. This situation is seen in Fig. 6.

The new design, which is formed by dividing the permanent magnets forming the rotor into two parts in the axial direction, is given in Fig. 6. The new design is simulated with the parameters given in Table I. The result of the ANSYS Motor-CAD analysis of the PMSM in the axial segmented magnet structure is shown in Fig. 7.

The thermal distribution of PMSM has changed with the axially partitioned design. In particular, it changes in the magnet and its surroundings. The reduction in thermal effects on the magnet, motor windings, and their surroundings are given in Fig. 7. This decrease is approximately 1°C. The radial flux PMSM has been thermally optimized without dimensional changes and without any additional cost. The thermal change caused by dividing radially placed magnets in the axial direction is given in Fig. 8.

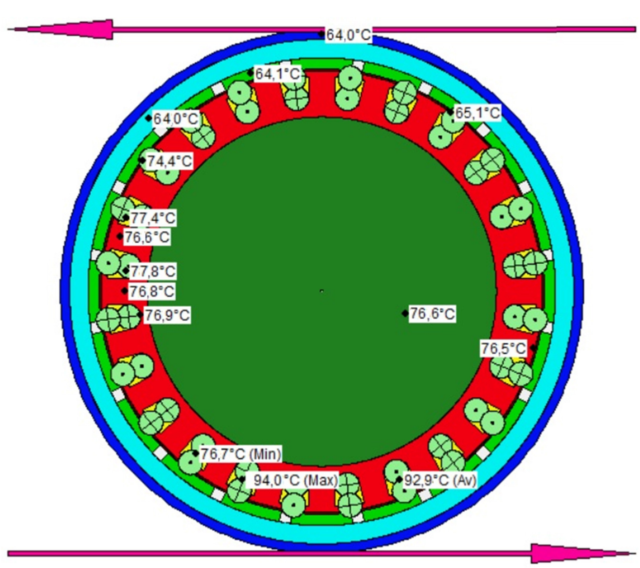

Fig. 7. General thermal dissipation of the segmented magnet PMSM. PMSM, permanent magnet synchronous motor.

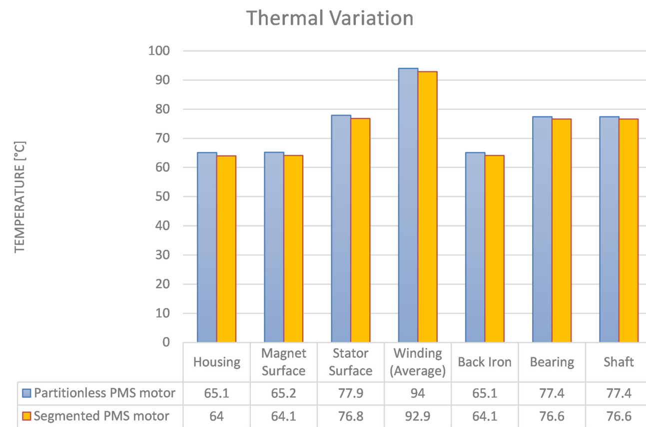

Fig. 8. General thermal variation of the segmented PMSM in the axial direction. PMSM, permanent magnet synchronous motor.

VI. CONCLUSION

The thermal effect is one of the important parameters affecting the in-wheel PMSM performance. There are mechanical solutions such as adding propellers and fins to the body for cooling inside the body in standard electric motors with internal rotors. However, external cooling structures cannot be used in the in-wheel PMSM due to mechanical limitations. Therefore, it is necessary to analyze the thermal effects well before manufacturing. Thermal effects cause many negative effects, especially losses in electrical machines. These effects cause the permanent magnets to fail and the PMSM to become inoperable. The longer life cycle of the motor and less failure depend on thermal effects.

ANSYS Motor-CAD is thermal simulation software frequently used by researchers. It is used to analyze the thermal distribution of electric motors. In this study, thermal optimization of radial flux in-wheel PMSM was performed for a mini waste management garbage truck. The PMSM is frequently used in electric vehicles and industrial applications. It is recommended to partition the radial permanent magnets in the axial direction for in-wheel PMSM thermal optimization. The temperature in permanent magnets decreases from 65.2°C to 64.1°C with the axial division. The average temperature value of the motor windings, which is the section with the highest thermal effect, decreased from 94°C to 92.9°C. A decrease of approximately 1°C was obtained in the motor's internal temperature with the axial partition. The thermal reduction was achieved without any change in PMSM output values such as power, speed, and torque production. The thermal reduction obtained without changing the mechanical design is important as the production cost. Thus, thermal improvement was made without changing the motor geometry, using additional equipment and without additional costs. It is thought that the results obtained by dividing the magnets in the axial direction will be beneficial to the design process of hybrid and light electric vehicles. It supports the applications and productions for mass production on radial flux in-wheel PMSMs. The production of PMSM is considered with these simulation data. The comparison of the performance test results of the prototype on the test bench with the simulation results will be shared with future studies.

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REFERENCES

1. D. Wang, X. Wang, M. K. Kim, and S. Y. Jung, "Integrated optimization of two design techniques for cogging torque reduction combined with analytical method by a simple gradient descent method," *IEEE Trans. Magn.*, vol. 48, no. 8, pp. 2265–2276, 2012. [CrossRef]
2. M. S. Rafaq, W. Midgley, and T. Steffen, "A review of the state of the art of torque ripple minimization techniques for permanent magnet synchronous motors," *IEEE Trans. Ind. Inform.*, 1–13, 2023. [CrossRef]
3. M. S. Rafaq, and J. W. Jung, "A comprehensive review of state-of-the-art parameter estimation techniques for permanent magnet synchronous motors in wide speed Range," *IEEE Trans. Industr. Inform.*, vol. 16, no. 7, pp. 4747–4758, July 2020. [CrossRef]
4. S. Özçıra, *Sabit mıknatıslı Senkron Motorun kontrol Yöntemleri ve endüstriyel Uygulamaları*. Yıldız Technical University, 2007. Available: http://dspace.yildiz.edu.tr/xmlui/handle/1/7698 [Accessed: September 14, 2022].
5. J. B. Park, M. Moosavi, and H. A. Toliyat, "Electromagnetic-thermal coupled analysis method for interior PMSM," Proceedings of IEEE International Electric Machines and Drives Conference (IEMDC 2015), 2015, pp. 1209–1214. [CrossRef]
6. E. Gundabattini, R. Kuppan, D. G. Solomon, A. Kalam, D. P. Kothari, and R. Abu Bakar, "A review on methods of finding losses and cooling methods to increase efficiency of electric machines," *Ain Shams Eng. J.*, vol. 12, no. 1, pp. 497–505, 2021. [CrossRef]
7. A. J. Grobler, S. R. Holm, and G. van Schoor, "A two-dimensional analytic thermal model for a high-speed PMSM magnet," *IEEE Trans. Ind. Electron.*, vol. 62, no. 11, pp. 6756–6764, 2015. [CrossRef]
8. O. Wallscheid, "Thermal monitoring of electric motors: State-of-the-art review and future challenges," *IEEE Open J. Ind. Applicat.*, vol. 2, pp. 204–223, 2021. [CrossRef]
9. O. Bilgin, and F. A. Kazan, "The effect of magnet temperature on speed, current and torque in PMSMs," Proceedings of 22nd International Conference on Electrical Machines, ICEM 2016, 2016, pp. 2080–2085. [CrossRef]
10. A. S. Deaconu, C. Ghiţă, V. Năvrăpescu, A. I. Chirilă, I. D. Deaconu, and D. Staton, "Permanent magnet synchronous motor thermal analysis", 6th IET International Conference on Power Electronics, Machines and Drives (PEMD 2012). Bristol, 2012, pp. 1–5. [CrossRef]
11. M. Ganchev, C. Kral, H. Oberguggenberger, and T. Wolbank, "Sensorless rotor temperature estimation of permanent magnet synchronous motor", 37th Annual Conference of the IEEE Industrial Electronics Society, Melbourne, VIC, Australia, 2011, pp. 2018–2023. [CrossRef]
12. M. A. Fakhfakh, M. H. Kasem, S. Tounsi, and R. Neji, "Thermal analysis of a permanent magnet synchronous motor for electric vehicles," *J. Asian Electr. Veh.*, vol. 6, no. 2, pp. 1145–1151, 2008. [CrossRef]
13. F. Chai, Y. Cao, and Y. Pei, "Design and analysis of high torque density permanent magnet synchronous motor based on heat pipe," 2022 25th International Conference on Electrical Machines and Systems (ICEMS), Chiang Mai, Thailand, 2022, pp. 1–6. [CrossRef]
14. I. Topaloğlu, "Optimization and prototyping of a brushless DC motor for torque ripple reduction using the shifted Hammersley sampling method," *Turk. J. Electr. Power Energy Syst.*, vol. 1, no. 2, pp. 108–117, 2021. [CrossRef]
15. K. Bennion, "Electric motor thermal management research," 2017. Available: https://www.nrel.gov/docs/fy18osti/67121.pdf [Accessed: February 23, 2023].
16. M. Bolontinha, "Common motor failures and faults", *Agu*, 2018. Available: https://www.researchgate.net/publication/326752460_Motor_Faults [Accessed: February 23, 2023].
17. E. Gundabattini, R. Kuppan, D. G. Solomon, A. Kalam, D. P. Kothari, and R. Abu Bakar, "A review on methods of finding losses and cooling methods to increase efficiency of electric machines," *Ain Shams Eng. J.*, vol. 12, no. 1, pp. 497–505, 2021. [CrossRef]
18. J. Urata, T. Hirose, Y. Namiki, Y. Nakanishi, I. Mizuuchi, and M. Inaba, *Thermal Control of Electrical Motors for High-Power Humanoid Robots*. Nice, France: IROS, IEEE Publications, 2008, pp. 2047–2052. [CrossRef]
19. H. Wu, D. Depernet, and V. Lanfranchi, "Comparison of torque ripple reductions and copper losses of three synchronous reluctance machines," 2017 IEEE Vehicle Power and Propulsion Conference, VPPC 2017. Belfort, France, 2017, pp. 1–6. [CrossRef]
20. M. A. Fakhfakh, M. H. Kasem, S. Tounsi, and R. Neji, "Thermal analysis of a permanent magnet synchronous motor for electric vehicles," *J. Asian Electr. Veh.*, vol. 6, no. 2, pp. 1145–1151, 2008. [CrossRef]
21. J. Nerg, M. Rilla, and J. Pyrhönen, "Thermal analysis of radial flux electrical machines with a high power density," *IEEE Trans. Ind. Electron.*, vol. 55, no. 10, pp. 3543–3554, 2008. [CrossRef]
22. A. S. Cabuk, *Investigation of Temperature Effects of in-Wheel Brushless Direct Current Motors with Thermal Circuit Model, Mühendislik Alanında Araştırma ve Değerlendirmeler (Chapter 6)*. Gece Kitaplığı, Ankara, Türkiye, 2019.
23. ABB, "Distribution automation handbook," 2019. Available: https://new.abb.com/medium-voltage/distribution-automation/misc/distribution-automation-handbook [Accessed: February 23, 2023].
24. ABB, "Motor protection calculation tool for SPAM 150 C, User's manual and technical description," 2002. Available: https://library.e.abb.com/public/9fa937448521cc28c2256bf1002d7252/FM_SPAM150C_750637_ENbab_2010 [Accessed: February 23, 2023].
25. T. Hakola, "Application guide for protection of synchronous machines, ABB Relays," 1982. Available: https://new.abb.com/medium-voltage/distribution-automation/numerical-relays/motor-protection-and-control [Accessed: February 23, 2023].