

Analysis of Interior Permanent Magnet Synchronous Motor according to Winding Method

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ABSTRACT: In this paper, the hairpin method is applied to an Electric Vehicle (EV) driving motor with a stator winding designed with a round copper wire. The hairpin method is a method to secure a high space factor by using round copper wire instead of round copper wire for the stator winding. The applicable model is a 300kW Interior Permanent Magnet Synchronous Motor (IPMSM), and the cooling method is water cooling. The current density has a proportional relationship with the thermal characteristics, and in the case of a round copper wire, a method of lowering the current density by using the stator winding as a stranded wire is used. However, when the hairpin method is applied, it is expected that the current density will be low as the area of the conductor is increased, but in reality, this is not the case in most cases. Accordingly, thermal characteristics are supplemented by using oil cooling rather than water cooling as the cooling method. However, in this paper, the thermal characteristic change is analyzed using the same cooling method.

The process of applying the hairpin method from the round copper wire method is sequentially described, and changes in the main electromagnetic characteristics of the motor are compared and analyzed. Additionally, by selecting an operating point, the thermal characteristics are also analyzed. In this study, the analysis is based on the finite element method (FEM)-based electromagnetic simulation.

General Terms: Electric Vehicle, Back ElectroMotive Force, Finite Element Method (FEM)

Keywords: Interior Permanent Magnet Synchronous Motor (IPMSM), Hairpin Method, Rectangular Copper Wire.

ARTICLE INFORMATION

Author(s): Chung-Hui Lee, Hui-Seong Shin and Ki-Chan Kim

Received: 11/04/2022; **Accepted:** 20/05/2022; **Published:** 10/06/2022;

e-ISSN: 2347-470X;

Paper Id: IJEER22TK403;

Citation: 10.37391/IJEER.100227

Webpage-link:

<https://ijeer.forexjournal.co.in/archive/volume-10/ijeer-100227.html>



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1. INTRODUCTION

Electric motors used to drive EVs are mainly induction motors (IM) and Interior Permanent Magnet Synchronous Motors (IPMSM). As the production of engine vehicles is limited due to carbon regulations, the production of EVs is increasing. However, the mileage of an EV on one charge is lower than that of an engine car, and in order to increase this, it is necessary to reduce the weight of the vehicle and increase the efficiency of electronic components [1]. On the side of the motor, losses must be reduced to increase efficiency. In addition, in order to reduce the weight, a design to improve the power density is required [2-4].

Recently, a mass-produced EV driving motor design technology mainly uses a hairpin winding technology for

designing a stator winding using a round copper wire [5-8]. The advantage of the hairpin winding technology is that it is possible to secure the fill factor, which is the ratio of conductors in the stator slot, to more than 70% [9-10]. In addition, the area of the winding required to produce the same output is required to be smaller than that of the round copper wire [12]. This is also related to the thermal properties. The selection of cooling conditions for the motor is closely related to the current density due to the current flowing through the stator windings [11]. This is because the higher the current density, the greater the Joule heat generated. In the case of water cooling, it is used when the current density of the stator winding is 10~20 A/mm². In the case of oil cooling, it is used when it is 20 A/mm² or more. In the case of hairpin winding, use the oil cooling type with a current density of 20 A/mm² or more [13-15].

In this paper, the design method by changing the stator winding from a round copper wire to a hairpin winding is described. Using the advantages of the hairpin method, the process of applying the hairpin method to the 300kW IPMSM is dealt with. In case of modification, it aims to describe the design process of the winding and to analyze its thermal properties. For the analysis, a FEM based simulation tool is used.

2. FEM ANALYSIS OF THE MODEL

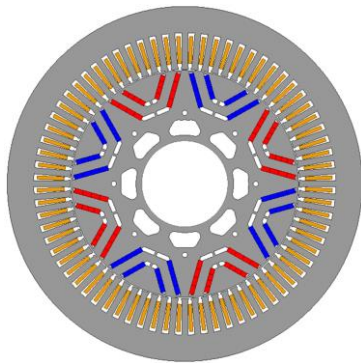


Figure 1 : 300kW Traction Motor 2D Model

Table 1. Specification of Motor

Parameter	Value	Unit
Power	300	kW
Outer Dia.(Stator / Rotor)	350 / 224	Φ
Stack length	201	Mm
Speed(Base / Max)	1,600 / 8,500	rpm

Figure 1 shows the 2D model of the target motor, and Table 1 shows the specifications of the target motor.

Before applying the hairpin winding method, the no-load characteristics and load characteristics are analyzed at the base speed. When applying the hairpin method, it is designed to have the same characteristics as the model before application. To satisfy this, it must have the same characteristics as the no-load Back Electro Motive Force (EMF) before design. Therefore, it is necessary to design the stator winding to have the same BEMF characteristic when applying the hairpin winding.

Figure 2 shows the no-load back EMF at the base speed, and Figure 3 shows the torque, voltage characteristics, and harmonic characteristics of the line voltage at the base speed and maximum speed under load. When deriving the characteristics, the battery voltage limit is 613.3 Vdc, and the characteristics are derived accordingly.

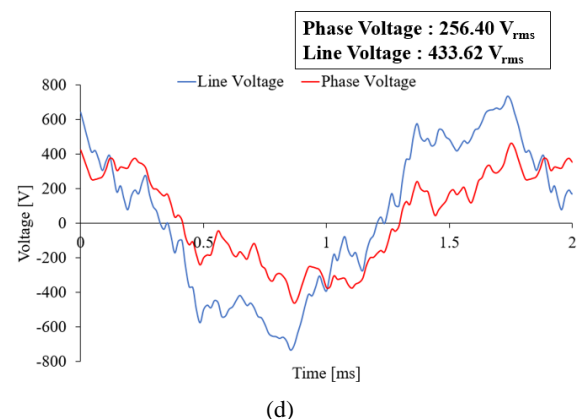
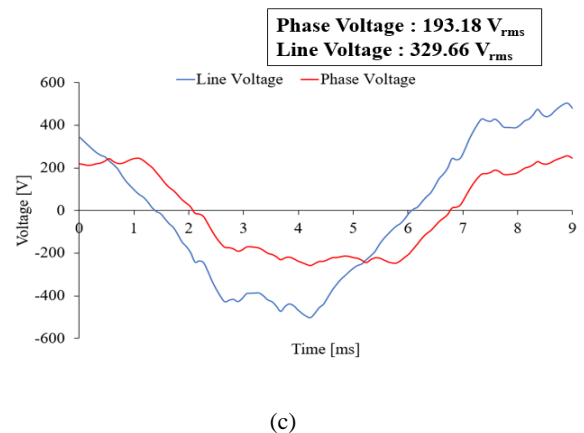
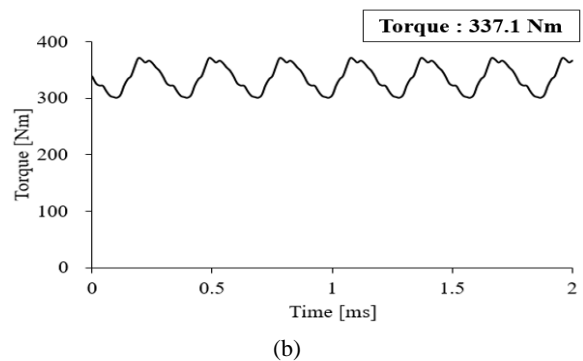
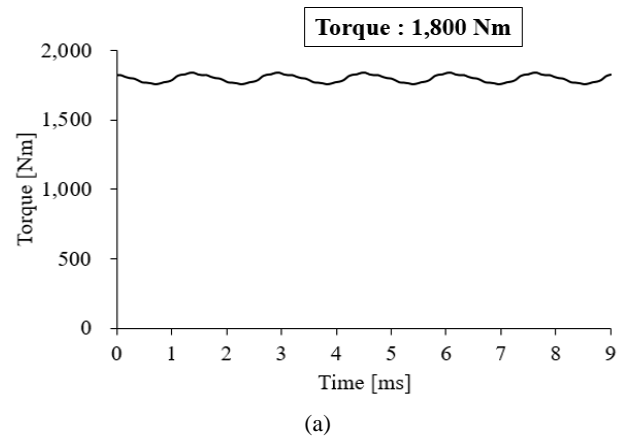
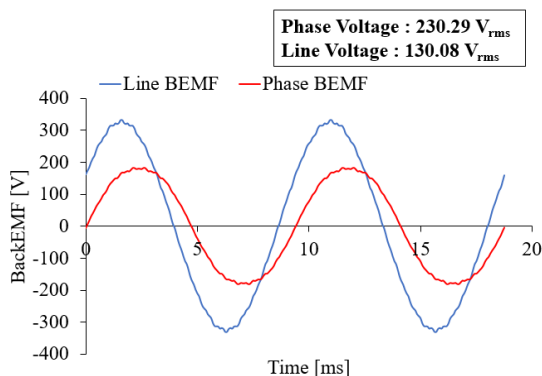


Figure 2: No-load Back EMF waveform at base speed (@ 1,600rpm)

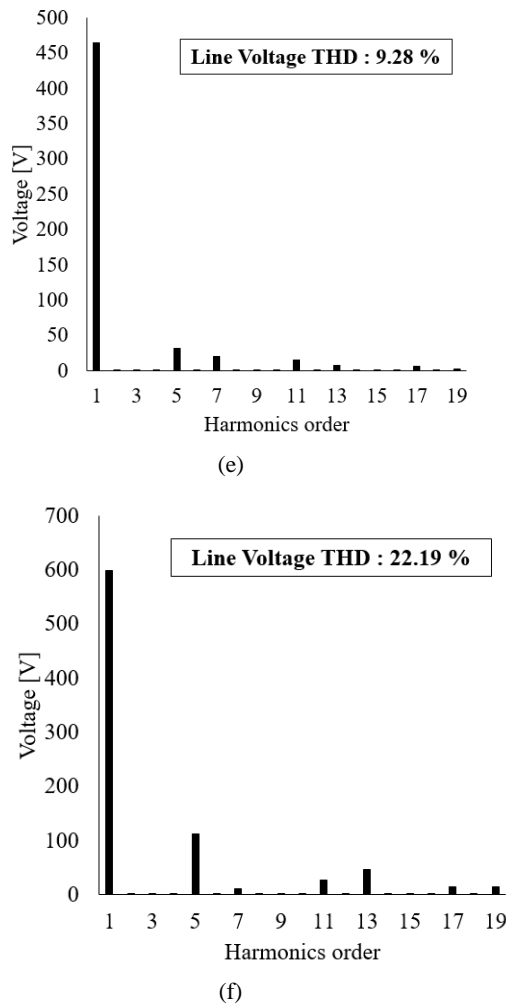


Figure 3: load characteristic waveform. Torque waveform (a) Base speed. (b) Max speed. Voltage waveform. (c) Base speed. (d)Max speed. Line-to-line voltage total harmonic distortion content (e) Base speed. (f) Max speed.

Figure 4 shows the saturation of magnetic flux density at base speed and maximum speed under load.

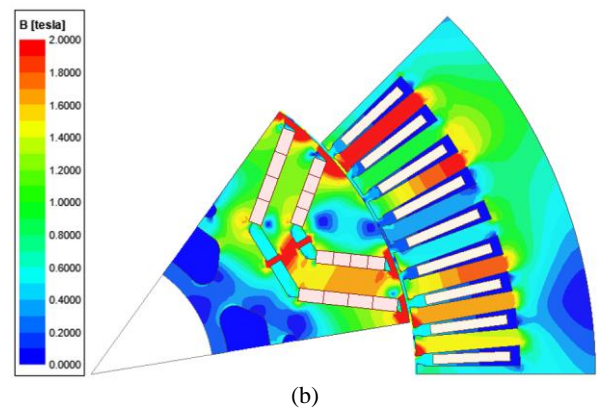
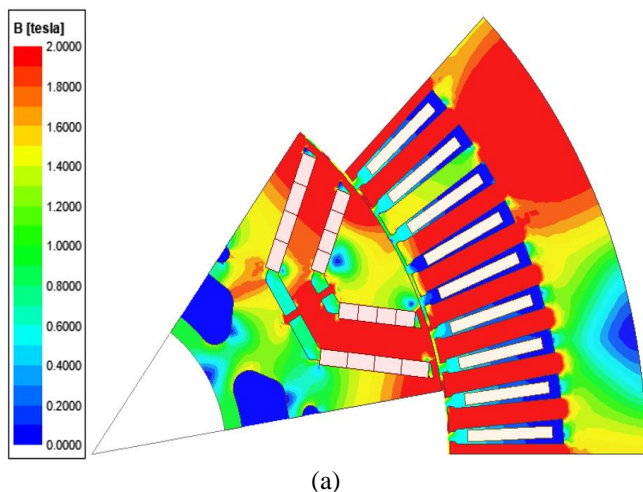


Figure 4: Saturation of magnetic flux density (a) Base speed (b) Max speed

3. HAIRPIN APPLICATION METHOD APPLICATION METHOD

Figure 5 shows the flow chart for applying the hairpin method. In order to apply the hairpin method, the number of conductors and the number of parallel paths that appear the same as the no-load Back EMF of the existing round copper wire model should be selected. In this process, the Back EMF according to the number of conductors is analyzed, and if the Back EMF does not match, the length of the stack is reduced to match the Back EMF. After that, a slot size is selected in consideration of tooth saturation, and a conductor size suitable for this is selected.

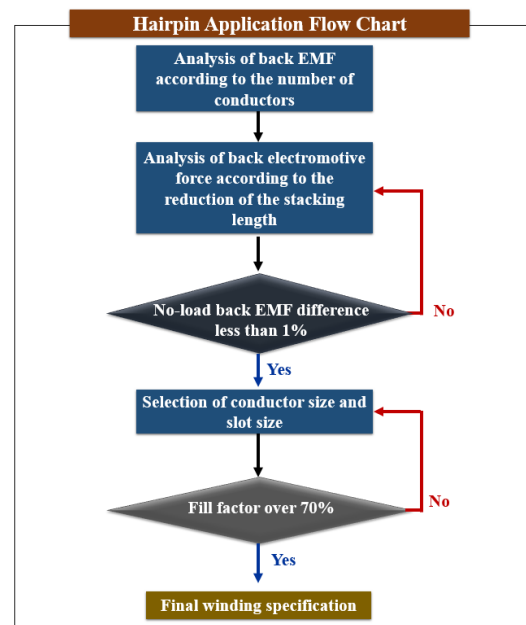


Figure 5: Flow chart of hairpin winding application method

3.1 Selection of the number of conductors and the number of parallel paths

The first process selects the number of conductors in the slot and the number of parallel paths. Since the back EMF component is proportional to the torque, the number of conductors in the slot and the number of parallel paths should

be selected first. *Figure 6* shows the back EMF according to the number of conductors.

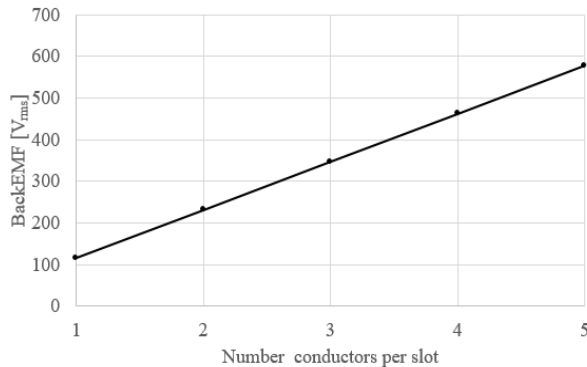


Figure 6: No-load Back EMF according to the number of conductors per slot

The number of parallel paths is set to 1, and the number of conductors is numbered from 1 to 5. This process is for deriving the number of effective turns that can generate back electromotive force [16]. The Back EMF of the existing model is 230.29V_{rms} between the no-load lines, and the Back EMF corresponding to the number of conductors is the closest. Since the difference between the no-load Back EMF and the existing round copper wire model is less than 1% at the number of conductors of 2, there is no need to change the stacking length. The next step is to analyze the losses in the windings by adjusting the number of conductors per slot and the number of parallel paths. *Figure 7* shows the DC loss, AC loss, and total loss according to the conductor condition. Finally, the winding condition of the model with the smallest total loss is 8 conductors and 4 parallel paths.

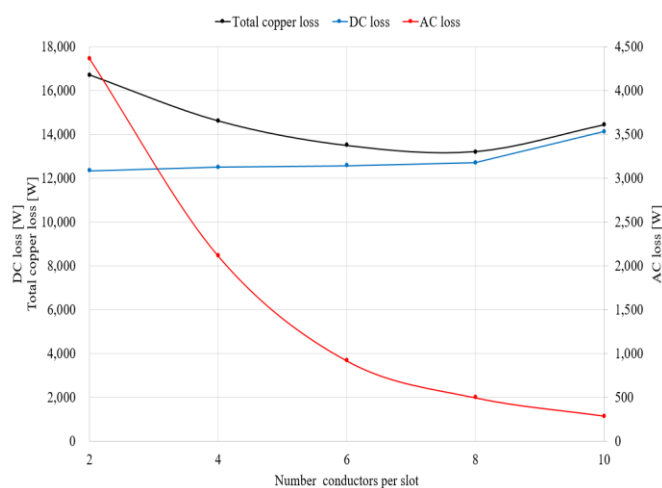


Figure 7: Loss analysis according to conductor combinations

3.2 Selection of slot size and conductor size

The second step is to select the slot size and conductor size. *Figure 8* shows the slot and conductor shape parameters.

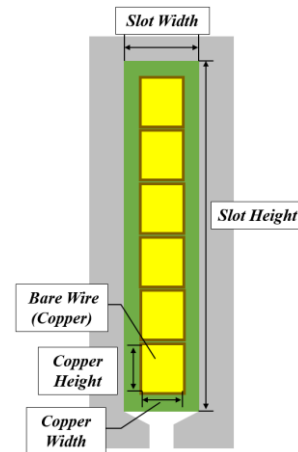


Figure 8: Slot and conductor geometry parameters

When the inner and outer diameters of the stator are fixed, the slot size is inversely proportional to the size of the teeth. If the tooth saturation is excessive, the motor characteristics deteriorate. Therefore, the size of the slot should be selected by analyzing the saturation characteristics of the teeth. The slot size is selected as a size that appears similar to the saturation state of the existing teeth. In addition, the saturation of the stator yoke must also be taken into account. The stator yoke width is the same as the existing designed size, and only the slot width is used as a design variable while the height of the slot is fixed. When the slot size is selected, the size of the winding that satisfies the fill factor of 70% or more must be selected. The fill factor is calculated without considering the insulation paper used inside the slot and the enamel coating of the winding. The reason why the standard of the fill factor was selected as 70% or more is to reduce the leakage flux in the slot and secure the current density as the fill factor increases.

3.3 Final hairpin model FEM analysis

Figure 9 shows the 2D shape of the finally selected hairpin application model through the design process. *Figure 10* shows the load characteristics and harmonic characteristics, and *Table 2* shows the characteristics comparison.

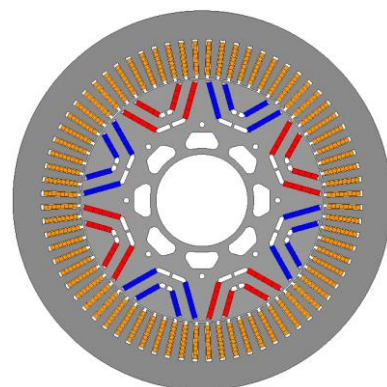
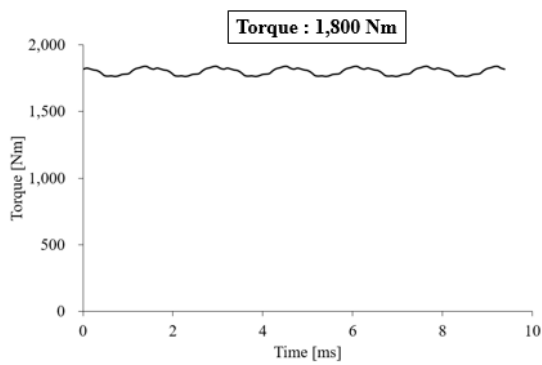
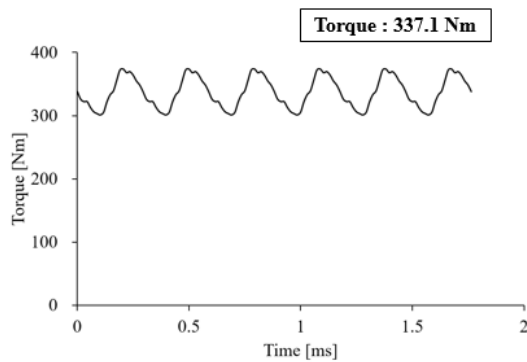


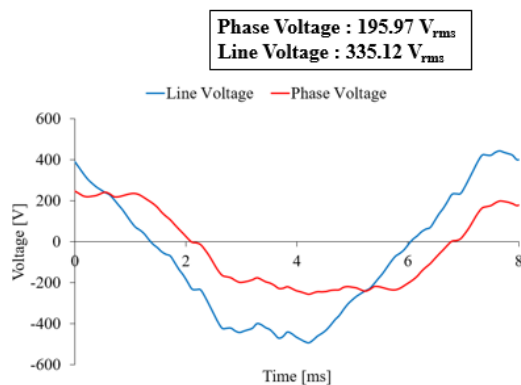
Figure 9: 2D geometry of hairpin applied model.



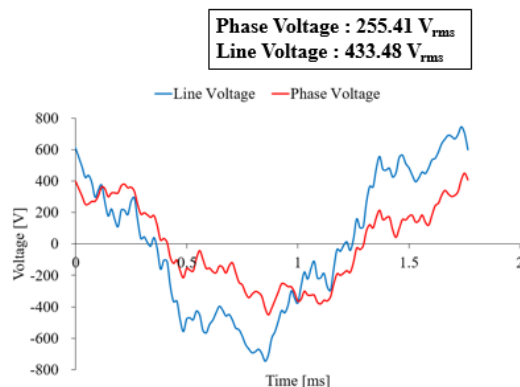
(a)



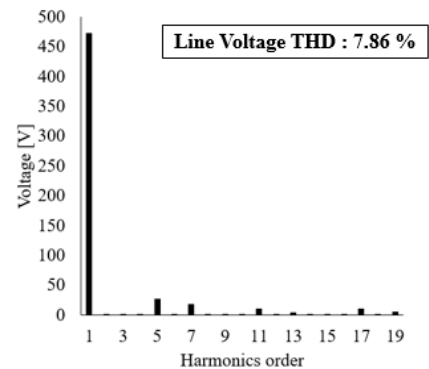
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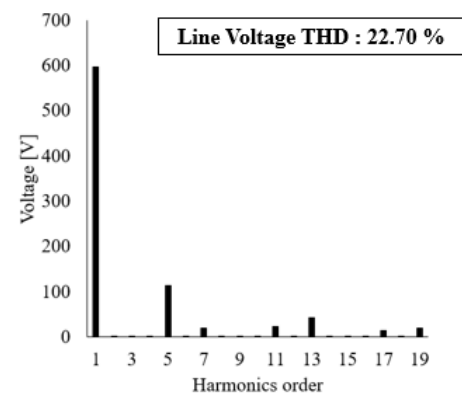
(c)



(d)



(e)



(f)

Figure 10: Hairpin model load characteristic waveform. Torque waveform (a) Base speed. (b) Max speed. Voltage waveform. (c) Base speed. (d) Max speed. Line-to-line voltage total harmonic distortion content (e) Base speed. (f) Max speed

Table 2. Characteristics Comparison

Parameter	Value				Unit
	Round copper model		Hairpin model		
Speed	1,600	8,500	1,600	8,500	rpm
Efficiency	93.87	96.63	95.62	97.13	%
Power factor	0.72	0.95	0.73	0.95	-

4. COMPARISON OF THERMAL PROPERTIES

Three operating points are selected to compare thermal characteristics. *Table 3* shows the defined operating points.

Table 3. Definition of Operating Point

Parameter	Value			Unit
	OP1	OP2	OP3	
Speed	1,600	2,100	2,520	rpm
Torque	1,800	910	625	%
Operating Time	10s	30m	2h	-

In order to proceed with thermal analysis at each operating point, an equivalent circuit is constructed for electromagnetic losses. *Figure 11 (a)* shows the inferior equivalent circuit for analyzing the thermal characteristics, and *(b)* shows the

location to analyze the thermal characteristics. Table 4 compares the thermal analysis results. In the case of the hairpin model, the Joule heat is reduced as the resistance of the stator winding and the amount of applied current are reduced compared to the existing model. This results in a decrease in heat.

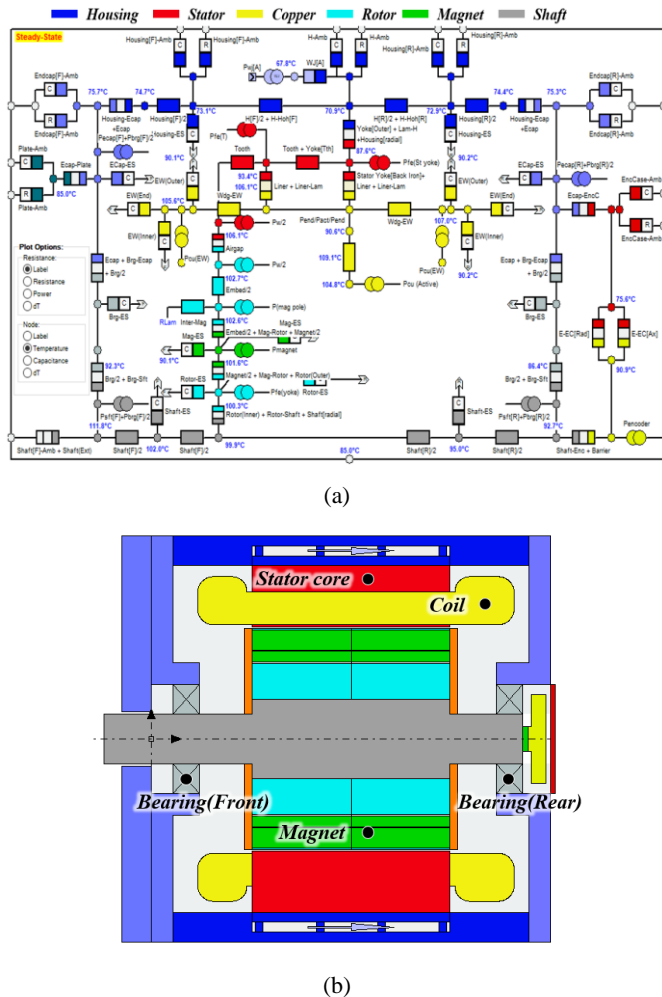


Figure 11: Equivalent circuit configuration for thermal characteristic analysis. (a) Thermal equivalent circuit. (b) Thermal characteristic analysis position definition

Table 4. Comparison of thermal properties

Parameter		Value					Unit
		Round copper model			Hairpin model		
Operating Point	OP1	OP2	OP3	OP1	OP2	OP3	°C
Coil	71.7	157.9	115.2	73.4	105.3	90.7	
Magnet	65.1	94.5	107.5	65	84	90	
Rotor Core	65.1	95.8	107.6	65	84.4	90.4	
Stator Core	66.2	132	111.1	65.4	86.9	80.5	

5. CONCLUSION

This paper describes the process of designing the stator winding of an EV driving electric motor designed with a conventional round copper wire as a hairpin winding. The

advantage of hairpin winding is that it is possible to secure a fill factor of 70% or more, reduce copper loss, and improve thermal characteristics through securing current density. The design process should analyze the number of effective turns in order to have the same characteristics as the model designed as a round copper wire. The process of converting to a hairpin winding is presented in the main text.

Then, the thermal properties of the round copper model and the hairpin model are compared. As a result of comparing the thermal properties under the same cooling conditions, the hairpin model is excellent. This has the following results because the hairpin model is excellent in electromagnetic loss. This means that for the same output, the volume of the hairpin model can be taken more compactly than the volume of the round copper model. Through this process, a design that can also increase the power density is possible.

6. DISCUSSION

Copper loss in the stator winding accounts for the largest proportion of electromagnetic losses in a motor. This loss appears as Joule heat and appears as a cause of temperature rise of the motor. Considering this point, the method to reduce the copper loss of the motor is to reduce the resistance. The hairpin method is effective in reducing the resistance of the conductor because the area of the conductor is large. Through this, the thermal characteristics can also be reduced.

The key content in [10-15] is research on optimizing the cooling method for high efficiency. It is mentioned that it is necessary to improve the thermal characteristics because the characteristics deteriorate as the high-temperature characteristics of the PM motor continue to be maintained.

As a result, if a high-efficiency, high-power-density motor is aimed at, the hairpin method is inevitable, and if the cooling method is additionally improved, the target can be further reached.

7. ACKNOWLEDGMENTS

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 20204030200080).

This work was supported by the Technology Innovation Program (20011435, Development of large capacity Etransaxle and application technology of 240kW class in integrated rear axle for medium and large commercial vehicles) funded By the Ministry of Trade, Industry & Energy(MOTIE, Korea).

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