Temperature Prediction of Oil-cooled IPMSM for In-Wheel Direct-Drive through Lumped Parameter Thermal Model

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Abstract — This paper focuses on estimating the temperature of end winding, in which the highest temperature exists out of all the components, in Interior Permanent Magnet Synchronous Motor (IPMSM) for in-wheel direct drive. A lumped parameter thermal model of IPMSM is suggested with considering core, copper, mechanical, and eddy current losses, which are the heat sources and calculated from finite element analysis to improve the accuracy of the prediction. In addition, the thermal model is comprised of thermal resistances and capacitances determined by the configurations and the dimensions of motor. Finally, an oil-cooling system is covered with the concepts of thermal conductivity, density, specific heat at constant pressure, dynamic viscosity, and flow rate.

I. Introduction

Damping and driving devices inside the wheels features In-wheel module. Since each motor drives a wheel without any helps of a series of power units, there is no loss generated in the courses of transmissions. Combined with other security systems such as smart parking assist system or electronic stability control system, it produces a considerable synergy effect. As an example of the advantages, the total weight is diminished and it enables to cut fuel consumption. In this mechanism, it is so crucial to predict the temperatures of individual components inside the motor because of dielectric breakdown of slot and end windings [1], [2].

A lumped parameter thermal model for the totally enclosed structure is suggested in this paper. It can be used to estimate the transient- and the steady-state temperatures. The dimensions of each component and the heat transfer coefficients for conduction and convection determine the thermal circuit network [3]. Additionally, it has an advantage that a shorter time is required in the solving process than 3-dimensional Finite Element Analysis (FEA). Hence, this would be an effective method to predict the temperatures of the rotary machine in the design procedure.

Even though the temperatures of all the divisions, which include frame, stator yoke, stator tooth, end winding, slot winding, air gap, end cap air, rotor, and shaft can be estimated by lumped parameter thermal model, end winding is only covered due to a turbulent flow the cooling-oil has and a spray-cooling in the limited space in usage in this paper. Once its material properties such as thermal conductivity, density, specific heat at constant pressure, dynamic viscosity, and flow rate are determined, the total equivalent thermal circuit network could be made [4].

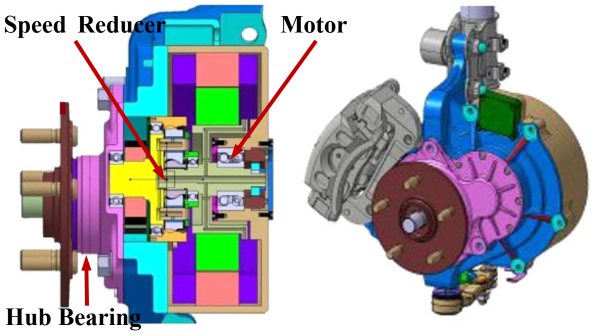

Fig. 1. In-wheel direct-drive system

II. Thermal Analysis Process

A. Analysis Model

First of all, it is required to identify the design specification in Table I and determine the ratio of stator to rotor sizes in regard to torque per rotor volume. Thereafter, a poles and slots combination that minimizes the vibration/noise described in (1), (2), and (3) and then an IPMSM with 8 poles and 48 slots is suggested in this paper.

$$\mu = \frac{\left|0.5 r_\lambda \mp s_1\right|}{p} = 1, 2, 3, \ldots \tag{1}$$

$$r_\lambda = 2(\mu p \pm k s_1) \tag{2}$$

$$f_\lambda = 2\mu f \tag{3}$$

Where p is pole pair, s_1 is the number of slots, μ is rotor MMF harmonic, f is input frequency, and r_λ is vibration and noise order. The higher the value of the order is, the less the magnitudes of noise/vibration. Eventually, the IPMSM prototype is made as a consequence of electromagnetic and structural analyses based on the theories above.

TABLE I
Design Specification of IPMSM Prototype

Division	Unit	Value
Number of poles / slots	-	8 / 48
Inner / Outer diameter of stator	mm	146 / 210
Inner / Outer diameter of rotor	mm	94 / 144.4
Stack length	mm	36
Stator material	-	35PN230
Residual flux density of PM @ 100℃	Wb/m^2 or T	1.137
Relative permeability of PM	-	1.05
Output power	kW	35
Maximum torque	Nm	75
Maximum / Base speed	rpm	4400 / 11000

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B. Equivalization of Motor Configuration

In order to apply an analysis model for lumped parameter thermal model, it goes through a simplification or an equivalization under some constraints. The priority is that original and equivalent models have to the same portions of conduction and convection parts. Moreover, the fundamental electromagnetic properties such as Back Electro-Motive Force (BEMF), torque, and output power should not be changed in this procedure. Equations (4), (5), and (6) are related to stator and (7), (8), and (9) to rotor [2].

For the stator

$$\left((R_0+x)^2-(R_i)^2\right)\pi-t(R_0+x+R_i)n=2\times A\times n \qquad (4)$$

$$\pi x^2-(2R_0\pi-nt)x+\left((R_0{}^2-R_i{}^2)\pi-(R_0-R_i)nt-An\right)=0 \qquad (5)$$

$$x=\frac{nt-2R_o\pi+\sqrt{(2R_o\pi)^2-4\pi\left((R_o{}^2-R_i{}^2)\pi-(R_o-R_i)nt-An\right)}}{2\pi} \qquad (6)$$

For the rotor

$$(R-l_m)\tan\theta_m\times l_m=\left(\left(R+\frac{x}{2}\right)^2-\left(R-\frac{x}{2}\right)^2\right)\pi\times\frac{\theta_m}{360} \qquad (7)$$

$$R_i=R-\frac{(R-l_m)\tan\theta_m\times l_m}{4R\pi}\times\frac{360}{\theta_m} \qquad (8)$$

$$R_o=R+\frac{(R-l_m)\tan\theta_m\times l_m}{4R\pi}\times\frac{360}{\theta_m} \qquad (9)$$

Where R_i is inner radius of stator and rotor, R_o is outer radius, R is mean radius, t is tooth width, n is number of models, A is slot area, l_m is height of middle magnet, and θ_m is pole arc. The dimensions of tooth, slot, yoke, permanent magnet, barrier, and etc. are eventually expressed in cylindrical coordinates.

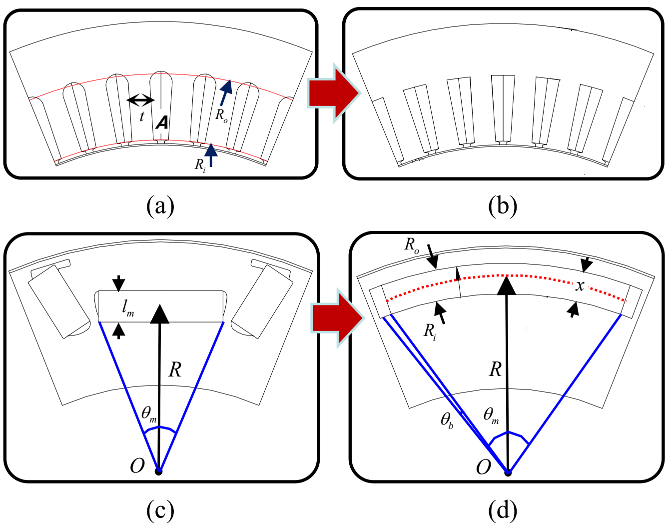


Fig. 3. Equivalization of prototype model (a) original stator, (b) simplified stator, (c) original rotor, and (d) simplified rotor

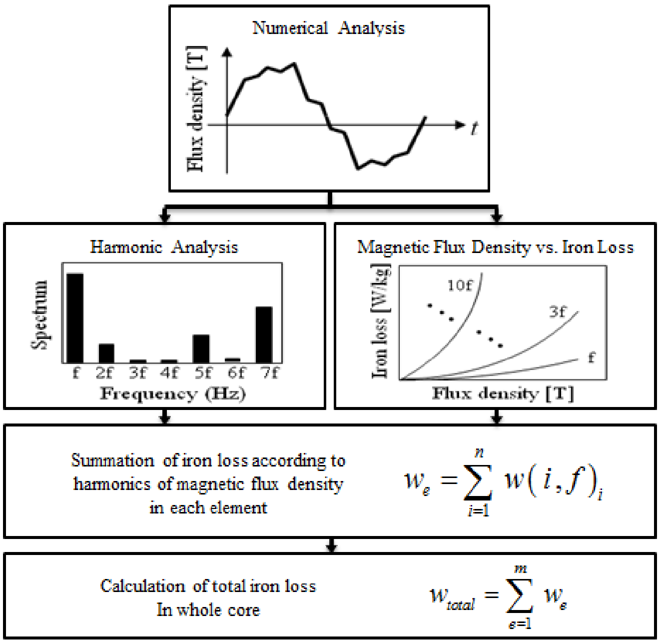


Fig. 4. Calculation procedure of core loss

C. Losses

Core loss: Fig. 4 shows the flow chart for the core loss calculation. The temporal and the spatial variations of the magnetic flux density waveforms are calculated by electromagnetic FEA. Spectrum analysis is used for the frequency analysis of the magnetic flux density at each element of FEA model. Under sinusoidal flux conditions, core loss is computed in the frequency domain using core loss data which is provided by manufacturer are described by frequency and flux densities.

Copper loss: It is term often given to heat produced by electrical currents in the conductors of stator and end winding. The loss results from Joule heating and so are also referred to as current I squared resistance R loss, in reference to Joule's first law. It is computed from analytical methods.

Eddy current loss: In order to decrease the eddy current loss, the stator and rotor cores are laminated by thin electric steel sheets. Compared to the laminated core, the permanent magnet, in general, has a single body or a few segments due to manufacturing procedures and cost reduction. Thus, the eddy current loss in PM is significantly larger than core loss of rotor, and may be larger than the copper loss of armature winding at high speed operation regions. It directly causes increasing the magnet, thereby, reducing the total efficiency of the motor. It is necessary to consider this type of loss in lumped parameter thermal model. In this paper, the eddy current loss of PM is calculated in transient 3-dimensional FEA.

Mechanical loss: it is involved with the friction loss between rotor and shaft, and windage loss by air resistance. Empirically, the loss is proportional to the square of speed and expressed as follows.

$$W_m=8D\times(L_1+15)\times V_a{}^2/10000/2 \qquad (10)$$

Where D, L_1, and V_a are, respectively, diameter, stack length, and surface speed of rotor.

D. Thermal Resistances and Capacitances

The thermal resistances of IPMSM are categorized into nine sections: air gap, end cap air, rotor, shaft, frame, stator yoke, stator teeth, end winding, and slot winding. All the resistances can be specified by dimensions and heat transfer coefficients as shown in (11) [3], [5].

$$R_n = \frac{1}{hA_n} \tag{11}$$

Where R_n is thermal resistance of nth component, A_n is surface area in contact with nth component, and h is convective heat transfer coefficient, which are divided into four cases.

i) h_1: heat transfer between external air and frame
ii) h_2: heat transfer between air gap and stator or rotor
iii) h_3: heat transfer between end cap air and stator iron, rotor end windings, or endcaps
iv) h_4: heat transfer between rotor cooling holes (barrier) and circulating endcap air

h_1 is a natural convective heat transfer coefficient that is determined empirically and h_2 is a forced convective heat transfer coefficient that is calculated by the air gap between the stator and rotor. The expression of Nusselt numbers for the small air gap machines in Taylor is

$$h_2 = \frac{N_{Nu} k_{air}}{l_g} \tag{12}$$

$$N_{Nu} = 2.2 \qquad N_{Ta} \le 41 \tag{13}$$

$$N_{Nu} = 0.23 N_{Ta}{}^{0.63} N_{\mathrm{Pr}}{}^{0.27} \qquad 41 < N_{Ta} \le 100 \tag{14}$$

Where the Nusselt number N_{Nu} for the convective heat transfer between two rotating smooth cylinders is given by Taylor. h_3 is a forced convective heat transfer coefficient that is calculated by the air gap between stator iron, end windings, or endcaps, and end cap air. h_4 is a forced heat transfer coefficient between rotor cooling holes, or barriers of magnets, and circulating endcap air.

$$h_3 = 21 \times \left(2\pi r_{rotor} \times \frac{speed}{60} \right)^{0.67} \tag{15}$$

$$h_4 = \frac{N_{Nu} k_{air}}{L} \qquad N_{Nu} = 0.83 \left(N_{\mathrm{Re}} N_{Ra} \right)^{0.2} \tag{16}$$

Where the dimensionless Rayleigh number N_{Ra} and Prandtl Number N_{Pr} are defined from the airgap size and fluid constants using the expressions given by Taylor. The critical value of 41 from the Taylor number refers to a change from laminar flow. The total thermal capacitance of the cylinder is found from the material density ρ, the specific heat C_p and the motor dimensions as

$$C = \rho C_p \pi \left(r_1^2 - r_2^2 \right) L \tag{17}$$

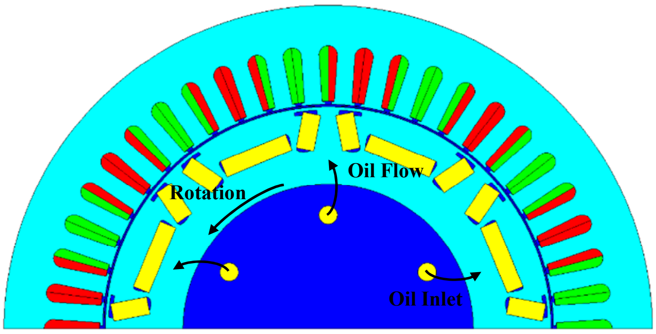


Fig. 5. Conceptual diagram for cooling flow channel

E. Oil-cooling System

On top of that, the flow of cooling oil is 3-dimensional, compressible, turbulent flows at unsteady state. Accordingly, it cannot be simulated precisely through computational fluid dynamics and the following variables are primarily based on experimental data. In addition, only the end winding, on which the highest temperature exists, is considered in this paper and the material properties of cooling oil are shown in Table II.

Thermal resistance: oil emitted from the shaft holes is assumed to be a forced convection based on centripetal and centrifugal forces. In the convection, thermal resistance is expressed by

$$R = \frac{1}{hA} \tag{18}$$

Fig. 5 describes x-y section view for oil flow at the rotating machine. In general, it is unpredictable because of its dynamic viscosity and density compared with a standard fluid, water. Equations (19) and (20) designate Nusselt, Prandtl, and Raynolds numbers based on experimental data.

$$N_{Nu} = \frac{f/8 \times \left(N_{\mathrm{Re}} - 1000 \right) \times N_{\mathrm{Pr}}}{1 + 12.7 \times \left(f/8 \right)^{0.5} \times \left(N_{\mathrm{Pr}}{}^{2/3} - 1 \right)} \tag{19}$$

$$f = \left[0.79 \times \ln(N_{\mathrm{Re}}) - 1.64 \right]^{-2} \tag{20}$$

Where f is friction factor and N_{Re} is Reynolds number. These dimensionless numbers are essential to analyze the fluid flow.

Thermal capacitance: as expressed by capacitance, it is related to a slope of temperature change likewise in the case of electromagnetics. The thermal capacity is a product of mass and specific heat. It can be divided into two types under constant volume and pressure and the former is as follows

$$C = \rho C_p V \tag{21}$$

TABLE II
MATERIAL PROPERTIES FOR COOLING OIL AT 60℃

Division	Unit	Value
Thermal conductivity	W/m·°C	0.1415
Density	kg/m^3	812.48
Specific heat at constant pressure	kJ/kg·°C	2.03
Dynamic viscosity	kg/m·s	0.0111
Flow rate	LPM	1.50

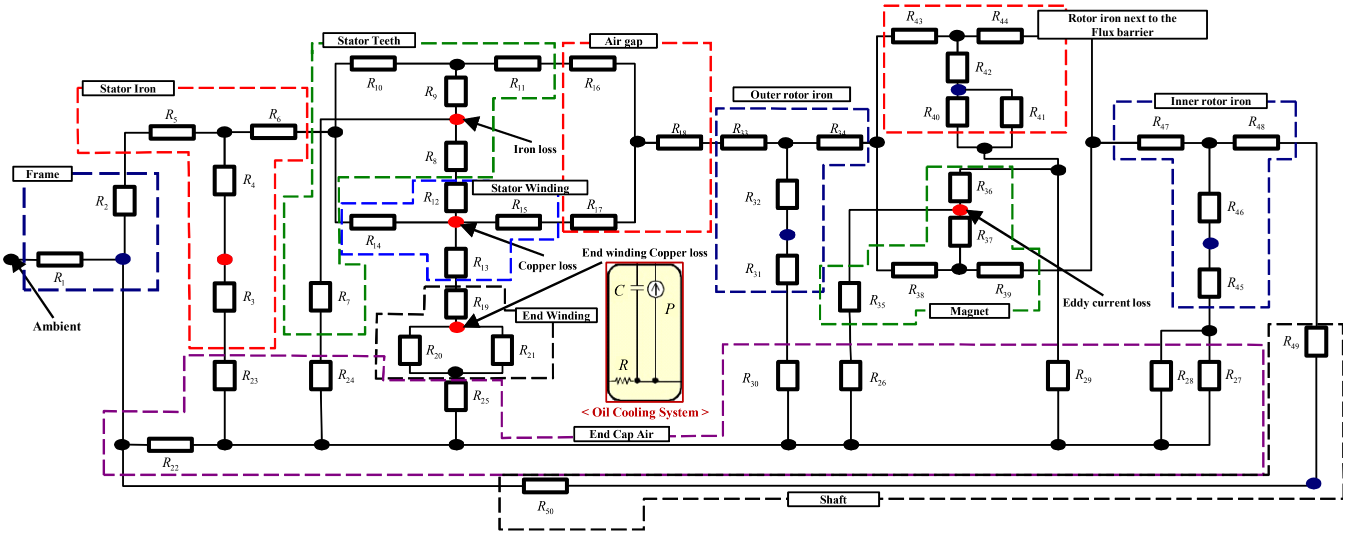


Fig. 6. Lumped parameter thermal model with oil-cooling system

Where ρ is density of cooling oil, C_p is specific heat, V is volume of cooling oil.

Radiant heat by cooling oil: a cooling oil radiates heat as it flows in rotating machine. Generally, losses are substituted with heat sources, which have positive values, in lumped parameter thermal model.

On the contrary, radiation heat stands for the heat transmitted from the inside to the outside and has a negative value. Quantity of radiant heat is connected to a ground and it means that heat is radiated to external areas by means of cooling oil. Consequently, it is probable that a direction of radiation heat for cooling oil is determined and we assume an equivalent effect on which an actual cooling oil has. It is described as follows.

$$P = \dot{q} \cdot dT \cdot \rho \cdot C_p \tag{22}$$

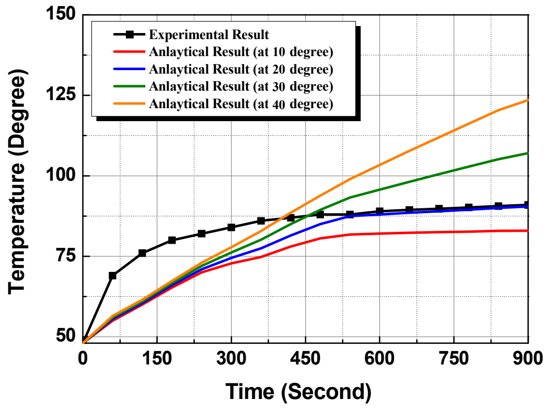
Where q is flow rate of cooling oil, dT is difference between inlet and outlet, ρ is density of cooling oil, and C_p is specific heat. That is, the quantity of radiation heat is relevant to the volume and the temperature change of cooling oil, and a thermal capacity as an ability that takes up heat in (22).

F. Lumped Parameter Thermal Model

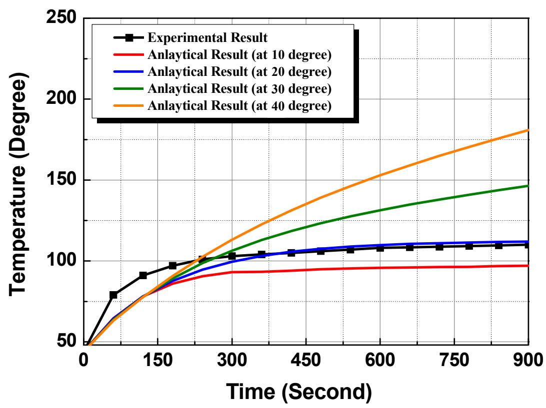
Fig. 6 shows a lumped parameter thermal model with oil-cooling system under rated load conditions. The cooling system with resistance, capacitance, and radiant heat is directly to the component of end winding and the analytical results are derived and compared with experimental ones as the temperatures change from 10 to 40 degrees as in Fig. 7. The errors at 20℃ are 0.78% and 1.02%, respectively, at base speed and maximum speed in regard to end point. However, the method has a limitation in predicting all the temperatures of components including magnets and stator core, and also in determining the precise patterns in the lower time region.

III. Conclusion

This paper suggests an analytical method of predicting the temperature of end winding through lumped parameter thermal model. Because of irregular and 3-dimensional flow of cooling, it indicates that its temperature should be anticipated to have a possible range. Furthermore, the results are being helpful in designing the rotating machine with oil-direct spray cooling for further projects.



(a)



(b)

Fig. 7. Temperature of end winding component at (a) base speed and (b) maximum speed under rated load conditions

Acknowledgment

This research was supported by the MKE (The Ministry of Knowledge Economy), Korea, under the CITRC (Convergence Information Technology Research Center) support program (NIPA-2013-H0401-13-1008) supervised by the NIPA (National IT Industry Promotion Agency).

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