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Thermal-loss Coupling Analysis of an Electrical Machine Using the Improved Temperature Dependent Iron Loss Model

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Abstract— **In this study, the iron loss models for electrical machines are firstly reviewed. One of the most accurate iron loss models, when the temperature is constant, is identified. An improved temperature dependent iron loss model is also introduced. By applying the improved iron loss model to the electrical machine thermal analysis, the thermal and loss analyses can be fully coupled. Based on this, an improved thermal-loss coupling analysis method for electrical machine is developed in this study. The electrical machine iron loss tests are carried out. The analysis and measurement results are then compared in order to validate the improved thermal-loss coupling analysis method. The comparison results indicate that the temperature prediction accuracy can be significantly improved by using the improved thermal-loss coupling analysis method.**

Topic— **Electrical machine, Iron loss, Thermal analysis, Temperature.**

I. INTRODUCTION

Accurate temperature prediction is essential for electrical machine design regarding cooling, insulation, demagnetization, etc. In electrical machines, the accurate prediction of temperature relies on the accurate prediction of losses. Iron loss is one of the major losses in electrical machines although the percentages of iron loss in the total loss vary in different machines [1] [2]. The iron loss can be the dominating loss when the frequency is high since the magnetic field changes fast. In high-speed electrical machines, the iron loss can be over 80% of the total loss [3]. Therefore, iron loss prediction is very important for the temperature evaluation of electrical machines. On the other hand, the iron loss is also influenced by the temperature significantly [4] [5]. Therefore, it is necessary to couple the thermal and iron loss analyses for electrical machines to predict iron loss and temperature accurately.

Many models have been developed for the iron loss prediction of electrical machines. The models developed in [6]-[9] are most commonly used iron loss models for electrical machines. With the help of variable loss coefficients, the iron loss model developed in [9] is experimentally confirmed as the most accurate iron loss model when the flux density alternates sinusoidally and the temperature is constant [10]. However, none of these iron loss models considers the temperature dependency of iron loss while the temperature can influence the iron loss significantly. In [4] [5], it is experimentally confirmed that the both the hysteresis and eddy current loss of steel laminations vary with the temperature variation. This is due to the fact that the hysteresis and eddy current losses are determined by the permeability and resistivity respectively, which are affected by temperature. In order to fully consider the temperature dependency of the iron loss, an improved iron loss model which can consider temperature dependencies of hysteresis and eddy current losses separately is developed in [11].

In this study, the application of the improved temperature dependent iron loss model in electrical machines thermal-loss coupling analysis is discussed in detail. In Section II, the iron loss models are introduced. In Section III, the thermal analyses are carried out. The thermal model of a 12-slot/10-pole IPM machine is built by MotorCAD at first. The heat transfer network of the machine is also established. An improved thermal-loss coupling analysis method is then developed. The temperatures of the 12-slot/10-pole IPM machine are then calculated by the existing and the improved analysis methods. In order to evaluate the improved thermal-loss coupling analysis method, electrical machine tests are carried out in Section IV. The temperatures at different positions of the 12-slot/10-pole IPM machine are measured. The measured results are compared with the calculated results. The improved thermal-loss coupling analysis method based on the temperature dependent iron loss model is then evaluated.

II. IRON LOSS MODELS

The iron loss model developed in [9] is experimentally confirmed as the most accurate iron loss model when the temperature is constant with the help of variable coefficients [10]. This iron loss model can be expressed as:

$$p_{\mathrm{Fe}} = k_{\mathrm{h}}(f, B_{\mathrm{m}}) f B_{\mathrm{m}}^{2} + k_{\mathrm{e}}(f, B_{\mathrm{m}}) f^{2} B_{\mathrm{m}}^{2} \tag{1}$$

where p_{Fe} is the iron loss density. f is the frequency. B_{m} is the peak value of alternating flux density. $k_{\mathrm{h}}(f, B_{\mathrm{m}})$ and $k_{\mathrm{e}}(f, B_{\mathrm{m}})$ are the hysteresis loss and the eddy current loss coefficients, respectively. The measured $k_{\mathrm{h}}(f, B_{\mathrm{m}})$ and $k_{\mathrm{e}}(f, B_{\mathrm{m}})$ of the 0.35mm thick steel lamination V300-35A at different flux density and frequency are shown in Fig. 1. In order to make sure the iron loss model can be applied for~~in~~ a wide range of frequency, the measurement is carried out at different frequencies between 50Hz and 1000Hz.

According to [11], both the hysteresis loss coefficient $k_{\mathrm{h}}(f, B_{\mathrm{m}})$ and the eddy current loss coefficient $k_{\mathrm{e}}(f, B_{\mathrm{m}})$ vary not only with frequency and flux density but also with temperature. Therefore, the improved iron loss model is then developed and can be expressed as:

$$p_{\mathrm{Fe,T}} = k_{\mathrm{th}}(T,f,B_{\mathrm{m}})fB_{\mathrm{m}}^2 + k_{\mathrm{te}}(T,f,B_{\mathrm{m}})f^2B_{\mathrm{m}}^2 \tag{2}$$

where $p_{\mathrm{Fe,T}}$ is the iron loss density at the actual temperature T. $k_{\mathrm{th}}(T,f,B_{\mathrm{m}})$ and $k_{\mathrm{te}}(T,f,B_{\mathrm{m}})$ are temperature dependent hysteresis loss and eddy current loss coefficients, respectively. The measured $k_{\mathrm{th}}(T,f,B_{\mathrm{m}})$ and $k_{\mathrm{te}}(T,f,B_{\mathrm{m}})$ of the 0.35mm thick steel lamination V300-35A at different flux density, frequency and temperature are shown in Fig. 2.

The iron loss model (2) is validated in [11] by steel lamination tests and electrical machine iron loss tests. By using the iron loss model (2), the temperature influence on iron loss can be fully considered. The thermal and iron loss analyses can be then coupled by utilizing the iron loss model (2).

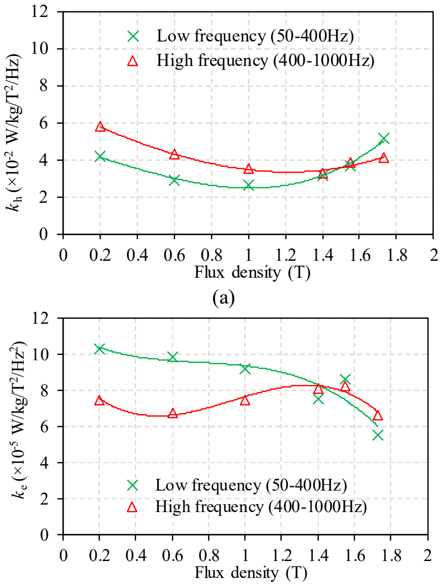

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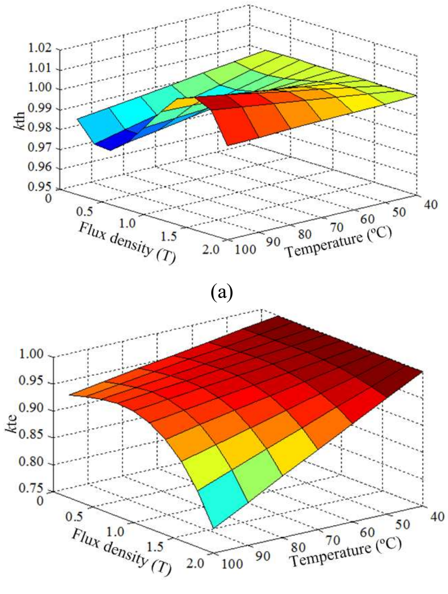
Fig. 1. Hysteresis loss and eddy current loss coefficients of model (1). (a) k_{h} (b) k_{e}.



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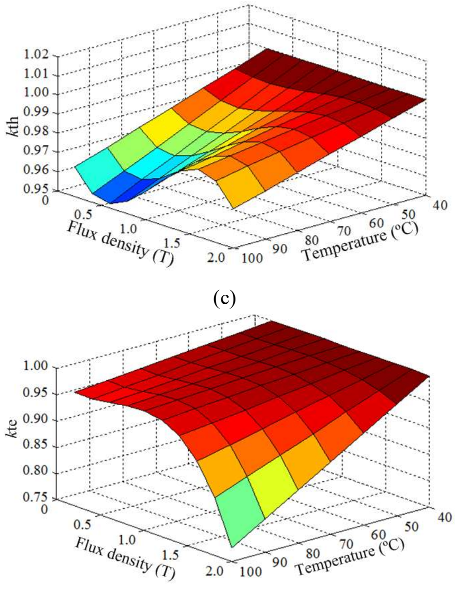


(c)

(d)

Fig. 2. Temperature dependent hysteresis loss and eddy current loss coefficients of model (2). (a) k_{th} within 50-400Hz. (b) k_{te} within 50-400Hz. (c) k_{th} within 400-1000Hz. (d) k_{te} within 400-1000Hz.

III. THERMAL ANALYSES OF AN ELECTRICAL MACHINE

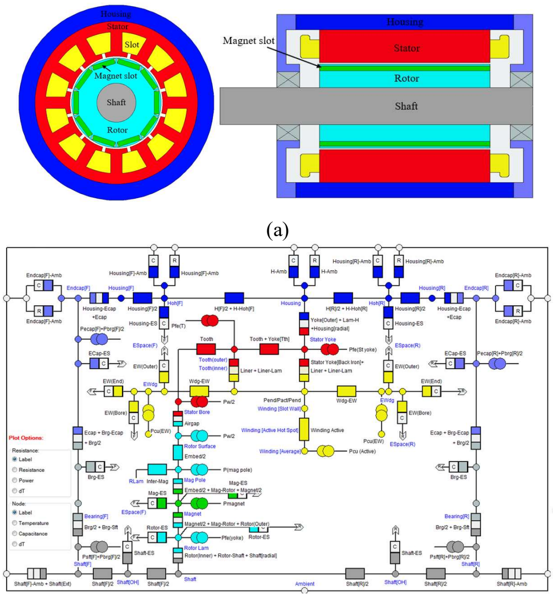
In this study, thermal analyses are carried out based on a 12-slot/10-pole IPM machine. The parameters of the electrical machine are listed in Table 1. The Motor-CAD is used for the thermal modelling and analysis of the machine [12]. Fig. 3(a) shows the thermal model of the 12-slot/10-pole IPM machine. In order to eliminate the influence of magnet eddy current loss, the magnets are removed from the electrical machine. It should be noticed that the magnet will be also removed in the measurement in this paper in order to make sure the modelling and measurement conditions are the same. Analytical lumped-circuit techniques are used for the thermal analysis for the electrical machine. The heat transfer network is shown in Fig. 3(b).

Fig. 4 shows the thermal analysis methods. Since the magnets are removed, only iron loss and copper loss are included in the input power to the thermal model. Fig. 4(a) shows the existing thermal analysis method by utilizing the iron loss model (1), where only the temperature dependency of copper loss is considered. The calculated copper loss varies with the temperature change and feedbacks to the input power during the analysis. The iron loss keeps constant during the analysis since the temperature dependency of iron loss is not taken into account in this analysis. On the other hand, the improved thermal-loss coupling analysis method is shown in Fig. 4(b). By using the temperature dependent improved iron loss model (2), temperature dependencies of both iron loss and copper loss are taken into account. Both the calculated iron loss and copper loss vary with the temperature change and feedback to the input power during the analysis. The thermal and loss analyses are then fully coupled. In the electrical machine, 0.7 mm thickness wires are used for the stator winding. The skin depth of the wire at 1000Hz (the~~Our~~ maximum test frequency) is 2.06 mm, which is much higher than the wire thickness. Therefore, the skin effect on the copper loss can be neglected in the calculation.

The thermal FEA calculated temperature distributions of the 12-slot/10-pole IPM machine are shown in Fig. 5. Convection boundary condition is used for the outer boundary of the machine. Both the copper and iron losses are used as the heat source. The results are obtained when the phase current I=3.11A in RMS value, frequency f=1000Hz and time t=120 min. For both two analysis methods, the coils reach the maximum temperature while the minimum temperature occurs at the housing after two hours heating by the losses. On the other hand, the predicted temperatures by the improved thermal-loss coupling analysis method are significantly lower than that by the existing analysis method. This phenomenon can be explained in Fig. 6. Fig. 6 shows the iron and copper losses at different operating points for different analysis methods. It can be seen that the calculated iron losses of the improved method decrease with temperature rise, while that of the existing method keeps constant.

TABLE I. PARAMETERS OF ELECTRICAL MACHINE

Stator material	V300-35A	Rotor material	V300-35A
Slot number	12	Tooth body width	7.1mm
Pole number	10	Slot opening	2mm
Stator outer radius	50mm	Stack length	50mm
Stator inner radius	28.5mm	Air gap length	1mm
Rotor outer radius	27.5mm	No. turns per phase	132



(a)

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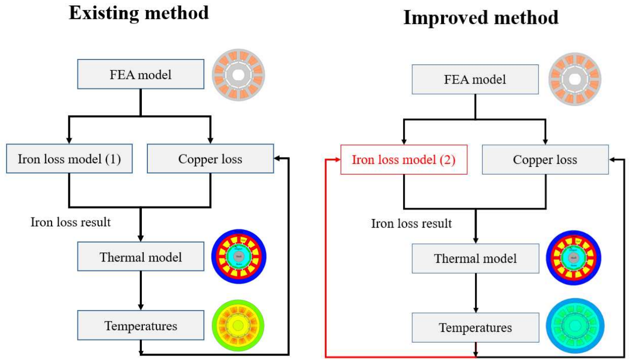
Fig. 3. Thermal models and heat transfer network of 12-slot/10-pole IPM machine. (a) Thermal models. (b) Heat transfer network.



(a)

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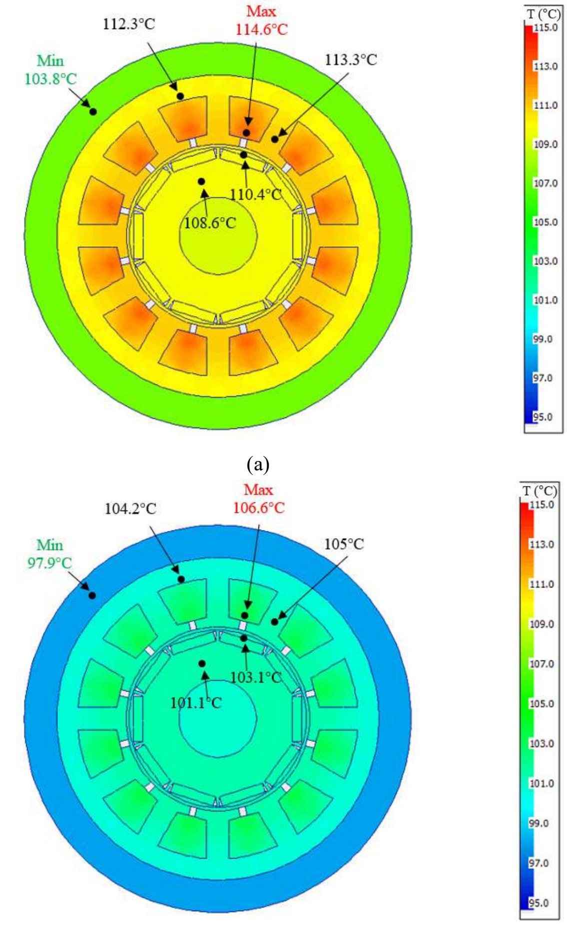
Fig. 4. Thermal analysis methods. (a) Existing thermal analysis method. (b) Improved thermal-loss coupling analysis method.



(a)

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Fig. 5. Predicted temperature distribution when I=3.11A, f=1000Hz, t=120 min. (a) Existing thermal analysis method. (b) Improved thermal-loss coupling method.

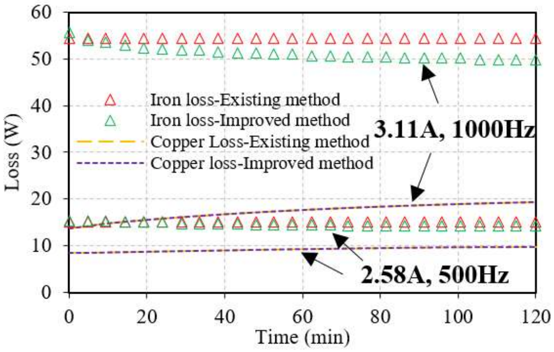


Fig. 6. Predicted losses by different thermal analysis methods.

IV. EXPERIMENTAL VALIDATION

In order to validate the thermal analysis methods, the electrical machine tests are carried out. The schematic diagram of the test system is shown in Fig. 7. The 12-slot/10-pole IPM machine is connected to a three phase AC power source. The phase current supplied by the power source is sinusoidal. Hence, there is no time harmonic in the phase current. During the electrical machine test, the magnets are removed. Therefore, the eddy current loss in the magnet can be eliminated. On the other hand, the rotor is locked. The influence of mechanical loss is then removed. In this case, only the iron loss and the copper loss are included in the total loss of the machine, which makes the measurement more accurate and simple. As shown in Fig. 8, four thermal couples are equipped in the electrical machine to measure the temperature at different positions, i.e., two thermal couples are stuck on the stator tooth and yoke faces, respectively. One thermal couple is installed inside the magnet slot, and one thermal couple is stuck on the rotor yoke face. The tests are carried out at two operating points, i.e. I=2.58A RMS, f=500Hz and I=3.11A RMS, f=1000Hz.

Fig. 9 shows the comparisons of the measured and predicted results by the existing thermal analysis method and the improved thermal-loss coupling analysis method. The numerical results at t=120 min are also listed in Table 2. It can be observed that the predicted temperatures by the existing thermal analysis method become inaccurate when the temperature is high. This is due to the fact that the existing iron loss model (1) cannot consider the temperature dependency of the iron loss. The input iron loss keeps constant while the actual iron loss of the electrical machine decreases significantly with the temperature rise.

On the other hand, by using the improved thermal-loss coupling analysis method, the predicted temperatures keep good accuracy within the whole test range even when the temperature reaches 100ºC or higher. This is due to the fact that the improved iron loss model (2) considers the temperature dependency of the iron loss. The input iron loss vary with the temperature rise, which is more closed to the actual condition in the electrical machine. On other words, the thermal and loss analysis can be fully coupled with each other by using the improved thermal-loss coupling analysis method.

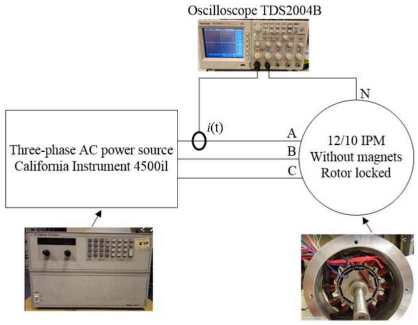


Fig. 7. Electrical machine test system.

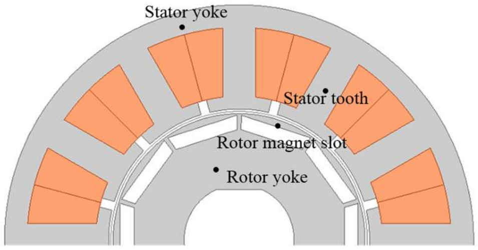
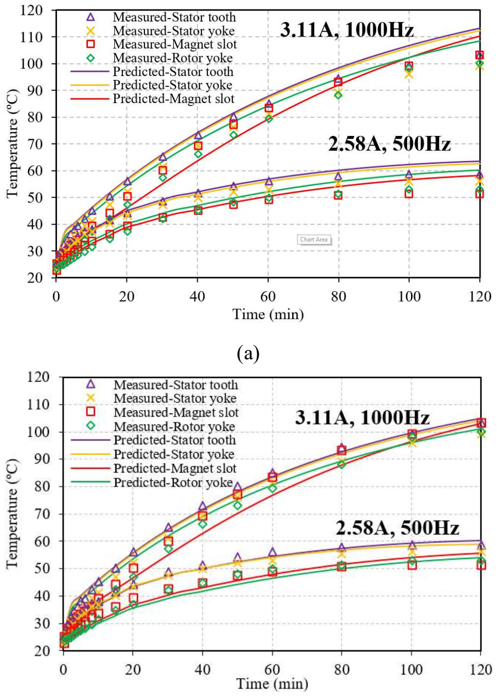


Fig. 8. Thermal couples equipped in the electrical machine.



(a)

(b)

Fig. 9. Comparison of predicted and measured temperatures by using (a) Existing thermal analysis method. (b) Improved thermal-loss coupling method.

TABLE II. TEMPERATURE RELATIVE PREDICTION ERRORS

Positions	Existing (%)	Improved (%)	Existing (%)	Improved (%)
	2.58A, 500Hz		3.11A, 1000Hz	
Stator tooth	8.6	2.9	10.0	2.0
Stator yoke	11.8	5.4	13.4	5.2
Magnet slot	13.8	8.5	7.2	0.1
Rotor yoke	14.1	2.5	8.6	1.1
Average	**12.1**	**4.8**	**9.8**	**2.1**

V. CONCLUSIONS

In this study, the application of the improved temperature dependent iron loss model in electrical machines thermal-loss coupling analysis is discussed. The improved temperature dependent iron loss is firstly introduced. By utilizing the improved iron loss model, the thermal and loss analyses for the electrical machine are fully coupled. An improved thermal-loss coupling analysis method is then developed in this study. Furthermore, the improved thermal-loss coupling analysis method is validated by electrical machine tests carried out in a 12-slot/10-pole IPM machine. Some conclusions can be summarized as below:

1) By using the improved iron loss model (2), the temperature influence on iron loss can be fully considered.

2) By applying the improved thermal-loss coupling method, the thermal and loss analyses of electrical machines can be fully coupled. The predicted temperatures by the improved thermal-loss coupling method are significantly lower than that by the existing thermal analysis method.

3) According to the electrical machine test results, the prediction accuracy can be significantly enhanced by using the improved thermal-loss coupling analysis method.

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