Current Harmonics Loss Analysis of a 150kW-Class Traction Interior Permanent Magnet Synchronous Motor Through Co-analysis of *d-q* Axis Current Control and Finite Element Method

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Abstract— This paper was conducted to co-analysis of *d-q* axis current control and finite element method(FEM), in order to consider current harmonics loss of an interior permanent magnet synchronous motor. The existing motor analysis method has expected the loss and efficiency, by injecting current sources in it. However, this method doesn't consider the additional loss by current harmonics generated by PWM carrier frequency and PI current control. Therefore, this paper compared loss and output between the existing current source analysis and co-analysis. In addition, it verified the validity of the co-analysis suggested through FFT analysis of experiment current wave forms.

I. Introduction

This study was targeted at a 150kW-class interior perm anent magnet synchronous motor (IPMSM) for a shuttle bus. Its shape and design specification are displayed in Table 1. In general, IPMSM using current control expects its output and efficiency through analysis of ideal sinusoidal current sources. However for this analysis method, it is hard to figure out loss and output characteristics, correctly. Therefore, this paper compared motor loss and output characteristics between the existing current source analysis and co-analysis of *d-q* axis current control and FEM. Finally, it investigated the validity of the co-analysis proposed through FFT analysis of test current wave forms of the produced motor.[1][2]

TABLE I
IPMSM PERFORMANCE REQUIREMENTS

	Value	Unit
Continuous Power / Torque	75 / 204	kW / Nm
Maximum Power / Torque	150 / 409	kW/ Nm
Outer Diameter	350	mm
Stack Length	140	mm
Base Speed / Max. Speed	3500 / 10,000	rpm / rpm
Current Density	15	A/mm^2
Magnet(NdFeB)	1.17(20℃)	T
Operating Temp.	150	℃
Cooling	Liquid(Water)	

II. Current harmonics additional losses of IPMSM

First, in a permanent magnet which conductivity exists, eddy current loss(W_{mag}) is generated as in the following formula 1.

$$W_{mag} = \sum_n \left\{ \int_{magnet} \frac{|J_n|^2}{2\sigma} dv \right\} \qquad (1)$$

In this, Jn is the size of eddy current by nth time harmonics.

Second, in stator and rotor core, hysteresis losses(W_h) and eddy current loss(W_e) are generated as in formula 2.

$$W_e = \sum_n \left\{ \int_{iron} K_e D(nf)^2 (B^2{}_{r,n} + B^2{}_{\theta,n}) dv \right\}$$
$$W_h = \sum_n \left\{ \int_{iron} K_h D(nf)^2 (B^2{}_{r,n} + B^2{}_{\theta,n}) dv \right\} \qquad (2)$$

In this, K_e and K_h are test constants for core material. D is the density of core and f is basic frequency.

As we can see in above formula, additional loss is generated proportional to the square of harmonics eddy current size in permanent magnets, and additional loss is generated proportional to the square of frequency in cores. Besides, current ripple is also generated by DC link voltage and back emf, and the output current by DC link is shown in formula 3.

$$\frac{di_L}{dt} = \frac{V_{dc} - V_{out}}{L} \qquad (3)$$

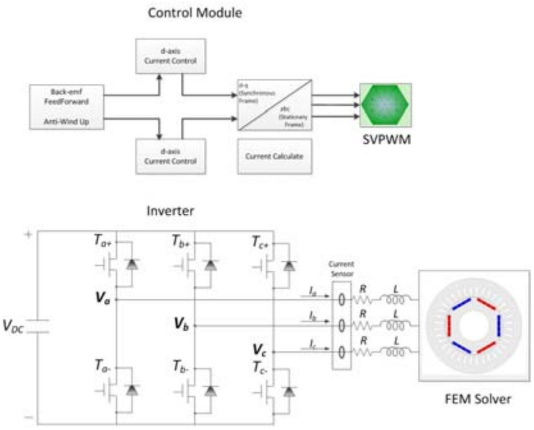
In this, L is inductance, V_{dc} is link voltage, V_{out} is back-emf, and i_L is output current.

Therefore, in PWM switching according to the voltage size of input DC link, the current ripple element by the angle of current wave form affects the losses also.

To conduct this loss analysis exactly, it is judged that the electromagnetic finite element analysis available of current control is needed. So, this paper suggested the electromagnetic finite element co-analysis(co-analysis for the rest) using *d-q* axis current control and analyzed characteristics.[3]

III. Configuration and characteristics of co-analysis

As Fig. 1, this study designed co-analysis that can control *d-q* axis PI currents. Then, losses and output characteristics were compared between 120kW and 150kW current source analysis and co-analysis at a rated speed of 3500rpm. As the result, current harmonics were considered as Fig. 1 and Table 2 prove, and it led to a large loss during the co-analysis.



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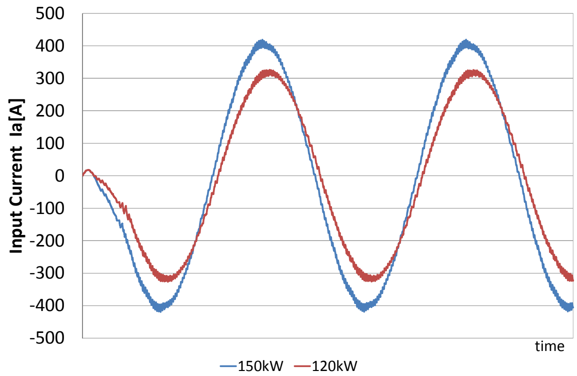

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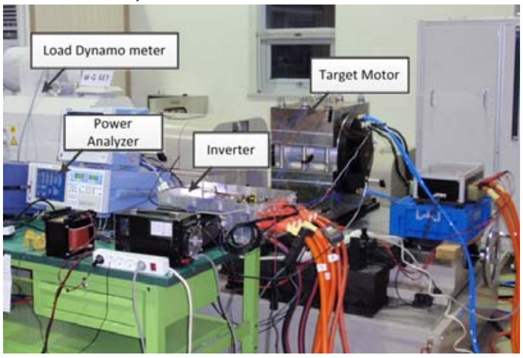
Fig. 1 Construction of Co-Analysis and Current Wave Form of Co-Analysis

TABLE II
RESULTS OF ANALYSIS METHODS

	Current Source FEM		Co-Analysis	
	120kW	150kW	120kW	150kW
Avr. Torque[Nm]	349.5	408.8	344.4	407.1
Core/Magnet Loss[W]	**857/46**	**911/74**	**1019/273**	**1167/345**
Efficiency[%]	98.1	97.75	97.7	97.4

IV. EXPERIMENT

When designing an experimental equipment as shown in Fig. 2 for an experiment, it was proved that the co-analysis proposed was valid, as shown in Table 3.



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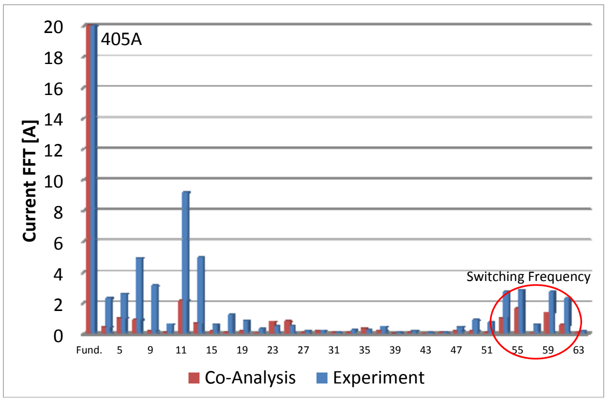

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Fig. 2 Construction of Experiment and Current FFT Analysis

TABLE III
RESULTS OF EXPERIMENT AT 3500RPM

	120kW	150kW
q-axis Current	-226.9A	-333.2A
d-axis Current	223A	229A
Average Torque	346.6Nm	408.5Nm
Efficiency	97.3%	96.7%
VS Efficiency of FEM	0.83%	1.06%
VS Efficiency of Co-Analysis	0.46%	0.71%

V. CONCLUSION

In this paper we examined the characteristics of a Permanent Magnet Synchronous Motor, using d-q axis current control co-analysis considering PWM carrier harmonics and PI control. This analysis method realizes properly the actual current wave form applied through a real motor controller and shows the characteristics of output and loss closer to the characteristics of real motors. Especially, it was certified that the current harmonics contributes largely to eddy current loss in permanent magnet. Accordingly, co-analysis method considering inverter voltage is essential to analyze accurate characteristic of Permanent Magnet Synchronous Motor, and Concentrated Winding Permanent Magnet Motor which is known to have large eddy current loss.

VI. REFERENCES

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