Core losses of a permanent magnet synchronous motor with an amorphous stator core under inverter and sinusoidal excitations

Atsushi Yao, Takaya Sugimoto, Shunya Odawara, and Keisuke Fujisaki

Citation: AIP Advances **8**, 056804 (2018); doi: 10.1063/1.5005009
View online: https://doi.org/10.1063/1.5005009
View Table of Contents: http://aip.scitation.org/toc/adv/8/5
Published by the American Institute of Physics

AIP ADVANCES **8**, 056804 (2018)

Core losses of a permanent magnet synchronous motor with an amorphous stator core under inverter and sinusoidal excitations

Atsushi Yao,[1,a] Takaya Sugimoto,[1] Shunya Odawara,[2] and Keisuke Fujisaki[1]
[1]*Toyota Technological Institute, Nagoya 468-8511, Japan*
[2]*Kitami Institute of Technology, Kitami 090-8507, Japan*

(Presented 10 November 2017; received 15 September 2017; accepted 26 October 2017; published online 13 December 2017)

We report core loss properties of permanent magnet synchronous motors (PMSM) with amorphous magnetic materials (AMM) core under inverter and sinusoidal excitations. To discuss the core loss properties of AMM core, a comparison with non-oriented (NO) core is also performed. In addition, based on both experiments and numerical simulations, we estimate higher (time and space) harmonic components of the core losses under inverter and sinusoidal excitations. The core losses of PMSM are reduced by about 59% using AMM stator core instead of NO core under sinusoidal excitation. We show that the average decrease obtained by using AMM instead of NO in the stator core is about 94% in time harmonic components.
https://doi.org/10.1063/1.5005009

I. INTRODUCTION

Electric motors mainly have three types of loss: copper loss, mechanical friction loss and core loss (iron loss). Recently, many studies have focused on core loss reduction of the motor based on core with amorphous magnetic materials (AMM).[1–6] AMM offers potential reduction of iron loss, especially in high frequency region, in comparison with conventional non-oriented (NO) silicon steel. The goal of this study is to estimate core loss properties of motor with an AMM stator core under inverter and sinusoidal excitations.

In motor drive system, pulse-width-modulation (PWM) inverters are often used to control the rotational torque and speed of an electrical motor. The PWM technique results in higher harmonic components in the inverter outputs. Due to higher harmonic components, in the magnetic materials, the input supplied by the PWM inverter increases iron losses compared to the sinusoidal input.[7–12] Thus, in order to realize core loss reduction of the motor system, it is necessary to correctly understand the influence of higher harmonic components (time and space harmonic components) in the motor.

AMM has recently been used for the motor core such as switched reluctance motor (SRM), induction motor (IM), permanent magnet synchronous motors (PMSM), and so on.[1–6,13–17] PMSM offers the advantage of a higher torque per volume and usually have higher efficiency compared to SRM and IM.[5] Previous studies have shown that PMSM using AMM have low core losses under PWM inverter excitation. Thus, the next phase is to examine the core loss properties of sinusoidal-fed PMSM with the AMM core.

The evaluation of core under sinusoidal excitation allows us to measure the smallest core losses of the motor core at the same experimental conditions that correspond to the same speed, torque, and vector control method because the sinusoidal-fed core does not have time harmonic components. It is well known that the core losses under PWM inverter excitation depend on both time and space

[a]Electronic mail: yao@toyota-ti.ac.jp

harmonic components but those under sinusoidal excitation relate to only space harmonic components. Thus, we can estimate time harmonic components of the core losses by comparing losses under inverter and sinusoidal excitations.

This study focuses on the core losses of PMSM with the AMM core under PWM inverter and sinusoidal excitations. The comparison with a conventional NO core excited by sinusoidal and inverter inputs is also performed. Based on both experiments and numerical simulations, we estimate higher harmonic components, which correspond to time and space harmonic components, of core losses in the sinusoidal- and inverter-fed PMSM.

II. EXPERIMENT AND NUMERICAL METHODS

A. Experimental setup of motor tests

Figure 1 shows a schematic of the motor and its control system for the no-load test. In the PMSM, the stator core made of NO electrical steel sheets (35H300) or AMM (SA1) is used and the rotor core is still made of NO sheets. From here on, the PMSM made of NO sheets (AMM) is called NO-PMSM (AMM-PMSM).

In our study, we perform two kinds of motor tests under no-load condition. The first motor test is carried out under sinusoidal excitation by using three linear amplifiers (HSA 4014, NF). The second test is to measure the motor core excited by three-phase voltage source inverter with classical PWM control. In both cases, a standard vector control is implemented for the speed control.

In the experiments, the core losses P_{core} under no-load condition can be calculated by

$$P_{\text{core}} = P_{\text{in}} - I_{\text{motor}}^2 R - P_{\text{m}}, \quad (1)$$

where P_{in} is the active input power, R is the winding resistance, I_{motor} is the total rms current, and P_{m} is the mechanical loss. In our study, the mechanical losses P_{m} are measured by using a rotor without magnetization, but with the same shape and the same bearings (see Ref. 6 for the details of the mechanical loss measurements.).

In the following experiments, the DC bus voltage V_{dc}, the switching dead time, and the carrier frequency f_{c} are set to 250 V, 3500 ns, and 1 kHz, respectively. The tests are performed at a rotational speed of 750, 1500, 2250, and 3000 rpm that correspond to electrical frequency f_{e} of 50, 100, 150, and 200 Hz, respectively. The PMSM is operated by zero d-axis current control.

B. Numerical simulation method

Figure 2(a) shows an analysis model for the finite-element method (FEM) (see Ref. 5 for more details of the FEM model and the characteristics of the motor core.). In numerical simulations, two-dimensional (2D) non-linear magnetic field analysis with A-method is performed.[5] The core losses of the motor correspond to the stator, rotor and magnets losses. The experimental trials give the total core losses but not the loss repartition between the stator, rotor and magnets. In order to discuss the

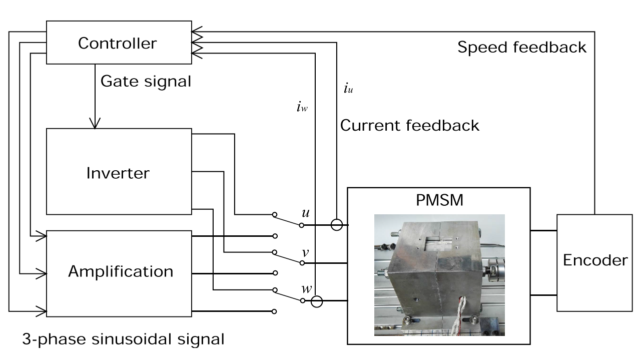

FIG. 1. Schematic of core loss measurement set up for motor under no-load condition. In this experimental system, we perform two excitation methods: sinusoidal excitation by using three linear amplifiers and three-phase inverter excitation with classical PWM control.

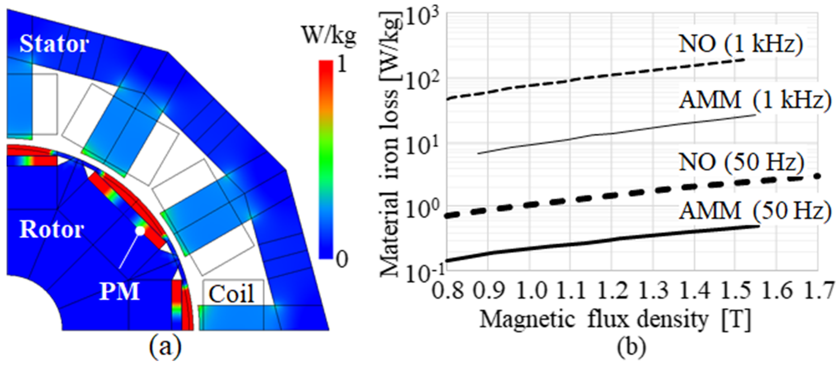

FIG. 2. (a) Schematic of numerical model (1/4-region model) and core loss density distributions at 750 rpm of AMM-PMSM under sinusoidal excitation simulated by JMAG software. (b) Representative iron loss characteristics (at 50 Hz and 1 kHz) of NO material and AMM as a function of the magnetic flux density. In the JMAG software, iron loss characteristics of the materials at 50, 100, 400, 1k, 2k, 5k, and 10k Hz are used as the input of the numerical analysis.

core loss repartition and characteristics, we perform the numerical analysis, which is a time-stepped simulation. Phase voltages obtained from the experimental data are used as the input of the numerical analysis. The electrical conductivity of the permanent magnets (PM) is set to 6.25×10^5 S/m and then eddy currents flow in only the PM.

In our simulations, iron losses of the soft magnetic cores W_{fe} are calculated from Steinmetz equation. In addition, the magnet losses W_{mag} are calculated by using the electrical conductivity and the analyzed eddy current density. Therefore, the entire core losses W_{nuloss} in numerical simulations are described by

$$W_{\mathrm{nuloss}} = W_{\mathrm{mag}} + W_{\mathrm{fe}} = W_{\mathrm{mag}} + W_{\mathrm{hys}}^{\mathrm{rotor}} + W_{\mathrm{eddy}}^{\mathrm{rotor}} + W_{\mathrm{hys}}^{\mathrm{stator}} + W_{\mathrm{eddy}}^{\mathrm{stator}}, \tag{2}$$

$$W_{\mathrm{fe}} = \sum_{ie=1}^{ne}[\sum_{k=1}^{N}\{\alpha(|B_k|)f_k\}]v_{ie} + \sum_{ie=1}^{ne}[\sum_{k=1}^{N}\beta(|B_k|,f_k)f_k^2]v_{ie}, \tag{3}$$

$$W_{\mathrm{mag}} = \frac{1}{T}\sum_{t=1}^{step}\sum_{ie=1}^{ne}\frac{J(t)_{ie}^2}{\sigma_{ie}}v_{ie}\Delta t, \tag{4}$$

where α denotes the coefficient of hysteresis loss, β is the coefficient of eddy current loss, B is the magnetic flux density, f is the frequency, v is the volume obtained by multiplying the element area by the core length, T is the fundamental period, J is the eddy current density, σ is the conductivity, ie is the element number, and k is the harmonic order. Here, $W_{\mathrm{hys}}^{\mathrm{rotor}}$ and $W_{\mathrm{eddy}}^{\mathrm{rotor}}$ ($W_{\mathrm{hys}}^{\mathrm{stator}}$ and $W_{\mathrm{eddy}}^{\mathrm{stator}}$) denote hysteresis and eddy current losses in the rotor (stator), respectively. α and β are calculated by using iron loss characteristics of the materials (NO sheets and AMM) as shown in Fig. 2(b).

III. RESULTS AND DISCUSSION

Figure 3(a) shows experimental total core losses with respect to the rotational speed under no-load condition. In our experiments, NO- and AMM-PMSM under sinusoidal and PWM inverter excitations (four cases) are evaluated. The core losses under sinusoidal and PWM inverter excitations increase with the increase of rotational speed. The core losses of the sinusoidal-fed motor sensibly decrease compared to the case of inverter-fed operation. These results in the case of sinusoidal-fed operation correspond to the smallest core losses of the manufactured motor core at each rotational speed. In addition, replacing the NO stator core of the proposed PMSM by the AMM stator core leads to a reduction of the core losses both under sinusoidal and PWM inverter excitations. In average, under sinusoidal (PWM inverter) excitation, the total core losses of the AMM-PMSM are 59% (72%) lower than those of the NO-PMSM.

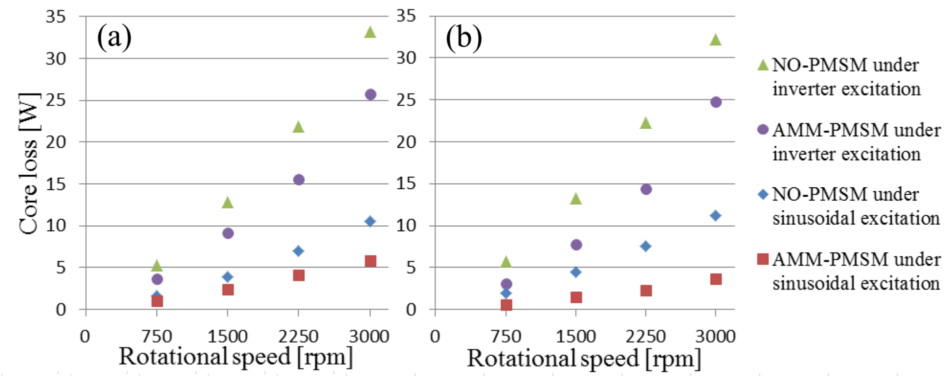

FIG. 3. (a) Experimentally obtained total core losses as a function of rotational speed. The core losses are measured for four cases (NO and AMM stators under sinusoidal and PWM inverter excitations). (b) Corresponding numerical total core losses by 2D FEM.

Figure 3(b) shows the entire core losses of both cores (AMM and NO cores) calculated by the FEM software as a function of the rotational speed. The experimental results shown in (a) are quantitatively consistent with the calculated results shown in (b). Thus, by using numerical simulations, we quantitatively discuss the core loss repartition. Here, the average difference between experimental and numerical results is about 16%. This is mainly due to the fact that the mechanical stress on manufacture process, the layer insulation, and the slight unbalance of three phase are not taken into account in the numerical simulations. Figure 2(a) also shows the numerically obtained core loss density distributions at 750 rpm of AMM-PMSM under sinusoidal excitation.

Figure 4 shows core loss repartition between the stator, rotor and magnets for every tested condition. The average W_{mag} of the inverter-fed NO and AMM cores accounts for 45% and 76% of the total core losses, respectively. On the other hand, in average, W_{mag} of NO and AMM cores under sinusoidal excitation accounts for 5.6% and 16% of the total core losses, respectively. It is found that the inverter tests show drastically large magnet losses compared with those of the sinusoidal tests. Therefore, the sinusoidal excitation in the experiments can estimate detailed changes of properties

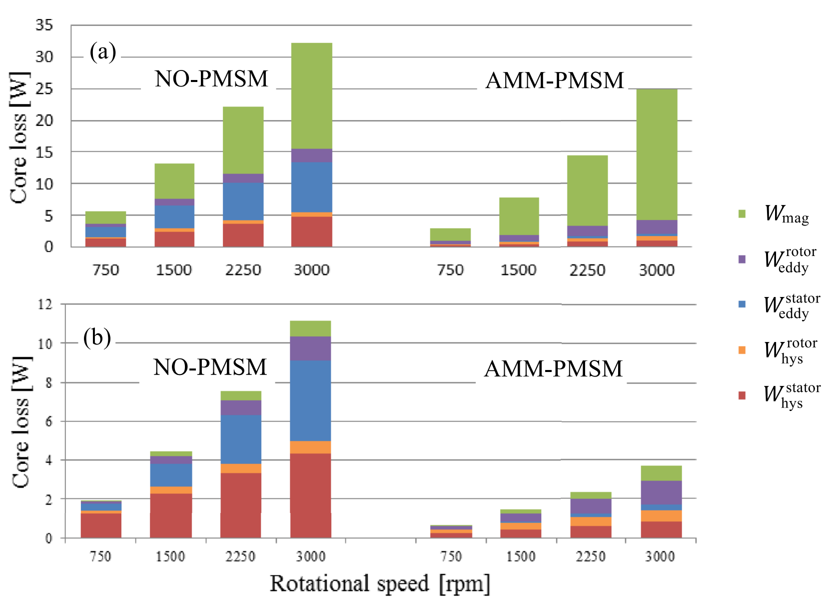

FIG. 4. Numerical iron loss repartition obtained from Eqs. (2), (3) and (4). The total losses of NO-PMSM (left) and AMM-PMSM (right) in this figure corresponds to those in Fig. 3: (a) Inverter excitation, (b) Sinusoidal excitation.

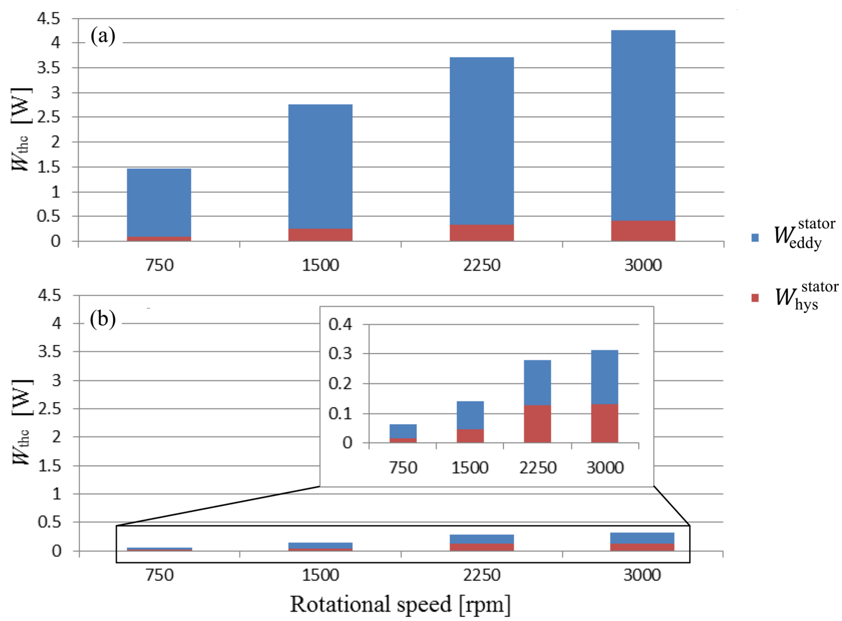

FIG. 5. Numerical core losses caused by time harmonic components. These results are calculated by using Eq. (5). (a) NO stator, (b) AMM stator. Inset: magnified figure of W_{thc}.

dependent on soft magnetic materials such as NO sheets and AMM compared to the case under inverter excitation.

According to the numerical simulations, the NO (AMM) stator core exhibits core losses of about 3.5 W and 6.2 W (0.51 W and 0.65 W) at 1500 rpm under sinusoidal and PWM inverter excitations, respectively. The average core loss reduction in the stator only under sinusoidal (PWM inverter) excitation is about 86% (89%) that depends on only space (both time and space) harmonic components. The core losses, which depend on time and space harmonic components, in the AMM stator are very low in comparison with those in the NO stator.

Finally, we discuss the core losses caused by time harmonic components in the stator. As mentioned above, the core losses under PWM inverter excitation (sinusoidal excitation) is caused by both time and space harmonic components (only space harmonic components). Therefore, the core losses caused by time harmonic components W_{thc} in the stator is given by

$$W_{\mathrm{thc}} = W_{\mathrm{inv}}^{\mathrm{stator}} - W_{\mathrm{sin}}^{\mathrm{stator}}, \tag{5}$$

where $W_{\mathrm{inv}}^{\mathrm{stator}}$ ($W_{\mathrm{sin}}^{\mathrm{stator}}$) denotes the stator core losses, which correspond to the sum of $W_{\mathrm{hys}}^{\mathrm{stator}}$ and $W_{\mathrm{eddy}}^{\mathrm{stator}}$, under PWM inverter (sinusoidal) excitation.

Figure 5 shows the calculated W_{thc} results for each of the tested rotational speed. For W_{thc}, the average decrease obtained by using AMM instead of NO in the stator core is about 94% in no-load condition. The core losses caused by the carrier frequency in the stator of the AMM-PMSM are drastically smaller than those of the NO-PMSM. These results confirm the benefit of using AMM to reduce the motor core losses, especially in time harmonic components (in high frequency region).

IV. CONCLUSION

Through the experiments and numerical simulations, this study addressed the core losses of PMSM with the AMM and NO core under PWM inverter and sinusoidal excitations. It is found that the sinusoidal excitation in the experiments can estimate detailed changes of properties dependent on soft magnetic materials such as NO sheets and AMM compared to the case under inverter excitation. In addition, we estimated higher (time and space) harmonic components of the core losses under inverter and sinusoidal excitations. The average core loss reduction in the stator under sinusoidal excitation was about 86% that depends on only space harmonic components. In time harmonic components, the average decrease obtained by using AMM instead of NO in the stator core was about 94%. These results confirmed the benefit of using AMM to reduce the motor core losses, especially in high frequency region (time harmonic components caused by inverter-fed operation). By evaluating the core losses under sinusoidal and inverter excitations, these results open the way to further research in core loss reduction of the motor system.

[1] Y. Enomoto, M. Ito, H. Koharagi, R. Masaki, S. Ohiwa, C. Ishihara, and M. Mita, IEEE Transactions on Magnetics **41**, 4304 (2005).
[2] Z. Wang, Y. Enomoto, R. Masaki, K. Souma, H. Itabashi, and S. Tanigawa, in *Power Electronics and ECCE Asia (ICPE & ECCE), 2011 IEEE 8th International Conference on* (IEEE, 2011) pp. 1940–1945.
[3] R. Kolano, K. Krykowski, A. Kolano-Burian, M. Polak, J. Szynowski, and P. Zackiewicz, IEEE Transactions on Magnetics **49**, 1367 (2013).
[4] M. Dems and K. Komeza, IEEE Transactions on Industrial Electronics **61**, 3046 (2014).
[5] S. Okamoto, N. Denis, Y. Kato, M. Ieki, and K. Fujisaki, IEEE Transactions on Industry Applications **52**, 2261 (2016).
[6] N. Denis, Y. Kato, M. Ieki, and K. Fujisaki, AIP Advances **6**, 055916 (2016).
[7] M. Kawabe, T. Nomiyama, A. Shiozaki, H. Kaihara, N. Takahashi, and M. Nakano, IEEE Transactions on Magnetics **48**, 3458 (2012).
[8] K. Fujisaki and S. Liu, Journal of Applied Physics **115**, 17A321 (2014).
[9] S. Odawara, K. Fujisaki, and F. Ikeda, IEEE Transactions on Magnetics **50**, 1 (2014).
[10] T. Taitoda, Y. Takahashi, and K. Fujiwara, IEEE Transactions on Magnetics **51**, 1 (2015).
[11] A. Yao, K. Tsukada, S. Odawara, K. Fujisaki, Y. Shindo, N. Yoshikawa, and T. Yoshitake, AIP Advances **7**, 056618 (2017).
[12] A. Yao, A. Adachi, and K. Fujisaki, in *2017 IEEE International Electric Machines and Drives Conference (IEMDC)* (IEEE, 2017) pp. 1–7.
[13] A. Chiba, H. Hayashi, K. Nakamura, S. Ito, K. Tungpimolrut, T. Fukao, M. A. Rahman, and M. Yoshida, IEEE Transactions on Industry Applications **44**, 699 (2008).
[14] G. S. Liew, W. L. Soong, N. Ertugrul, and J. Gayler, in *Universities Power Engineering Conference (AUPEC), 2010 20th Australasian* (IEEE, 2010) pp. 1–6.
[15] Z. Wang, Y. Enomoto, M. Ito, R. Masaki, S. Morinaga, H. Itabashi, and S. Tanigawa, IEEE Transactions on Magnetics **46**, 570 (2010).
[16] Z. Wang, R. Masaki, S. Morinaga, Y. Enomoto, H. Itabashi, M. Ito, and S. Tanigawa, IEEE Transactions on Industry Applications **47**, 1293 (2011).
[17] T. Fan, Q. Li, and X. Wen, IEEE Transactions on Industrial Electronics **61**, 4510 (2014).