Iron Loss Analysis of Interior Permanent Magnet Synchronous Motors by Considering Mechanical Stress and Deformation of Stators and Rotors

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Abstract—**The iron loss of interior permanent magnet motors driven by inverters are calculated by using the combination of stress analysis and electromagnetic field (EMF) analysis for the purpose of taking into account the effect of stress and motor-shape deformation. Both the stator stress caused by shrink fitting and the rotor stress caused by centrifugal force are considered in the stress analysis. In the EMF analysis, harmonic fields including inverter carrier is taken into account by coupling the finite element equations and the armature voltage equation. The permeability and the core-loss coefficient at each finite element are modified according to the stress distribution. In addition, the finite element mesh of the EMF analysis is also deformed according to the motor-shape deformation caused by the centrifugal force. The calculated loss is compared with the experimental loss in order to confirm the validity of the analysis. Several effects of the stress and the deformation on the iron loss of interior permanent magnet motors driven by inverters are revealed by this analysis.**

Index Terms—**Finite element methods, losses, synchronous motors, permanent magnets, stress.**

I. INTRODUCTION

It is well known that the mechanical stress causes characteristics deterioration of electrical steel sheets [1], [2]. The permeability decreases, whereas the core loss increases with the stress. In the application for rotating machines, most famous effect is the increase in stator-core loss with compressive stress caused by shrink fitting. Many papers have dealt with this phenomenon. However, only the increase in no-load iron loss has been estimated in most of the papers. It can be stated that the effects of the shrink fitting on the iron loss at load conditions have not clarified yet. In particular, the variable speed motors, for instance, interior permanent magnet synchronous motors (IPMSMs), are usually driven by PWM inverters. In this case, high-frequency harmonic iron losses are generated by the inverter carrier.

On the other hand, large mechanical stress is also generated at the rotors of IPMSMs at high speeds because of the centrifugal force due rotation [3]. As this stress is in tensile direction, the characteristics deterioration of the rotor core is relatively small. However, it is considered that the large deformation of the rotor core by the centrifugal force must cause the variation in the iron loss.

From these viewpoints, in this study, the iron loss of IPMSMs driven by PWM inverters are calculated by using the combination of stress analysis and electromagnetic field (EMF) analysis for the purpose of taking the effect of stress and motor-shape deformation. The calculated loss is compared with the experimental loss in order to confirm the validity
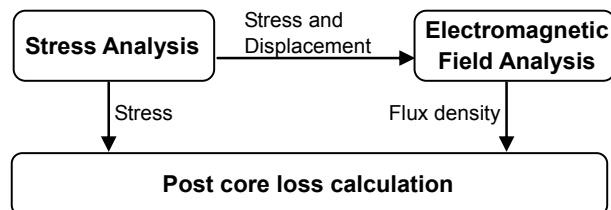

Fig. 1.Block diagram of combined stress-electromagnetic field analysis.

II. CALCULATION METHOD

Fig. 1 shows the block diagram of the proposed method. The linear static finite element method (FEM) is applied for the stress analysis for the estimation of the stress and the deformation caused by the stator shrink fitting and the rotor centrifugal force. On the other hand, the nonlinear time-stepping FEM coupled with armature voltage equation is applied for the EMF analysis in order to take into account the harmonic fields including inverter carrier. The result of the stress analysis is given to the EMF analysis in order to modify the permeability, which is assumed to be a function of both the flux density and the stress at each finite element. In addition, the finite element mesh of the EMF analysis is also deformed according to the motor-shape deformation caused by the centrifugal force. Then, the loss of the core is calculated from the time-variation in the flux density in the post calculation, which is reported in [4]. This calculation is based on the one dimensional nonlinear time-stepping FEM in order to consider the skin effect within the thickness of the electrical steel sheet used for the core The effect of the stress distribution is also considered in this calculation by regarding the core-loss coefficient at each finite element to be a function of both the flux density and the stress.

The detailed formulations will be described in the full paper.

III. RESULTS AND DISCUSSION

The proposed method is applied to an 8 pole, 100 kW class IPMSM employing Nd-Fe-B magnets. The maximum rotational speed is 10000 min^{-1}.

Fig. 2 shows the principal stress distribution obtained by the stress analysis. Circumferential compressive stress is observed at the stator yoke. This stress is generated by the shrink fitting of the stator core and causes a decrease in the permeability and an increase in the stator-core loss. On the other hand, large tensile stress is observed at the rotor surface and the rotor bridge between the inside magnet at the maximum speed. This stress is generated by the centrifugal
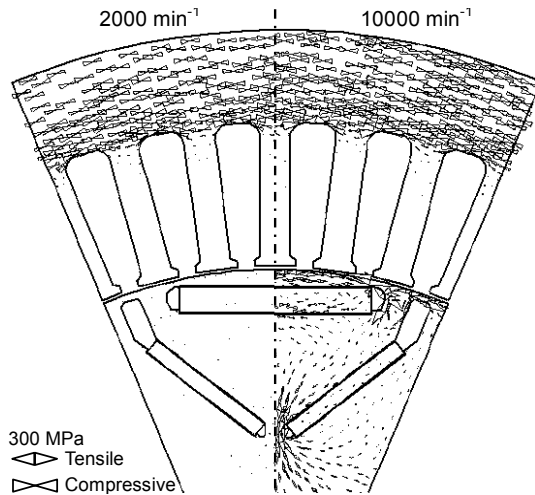
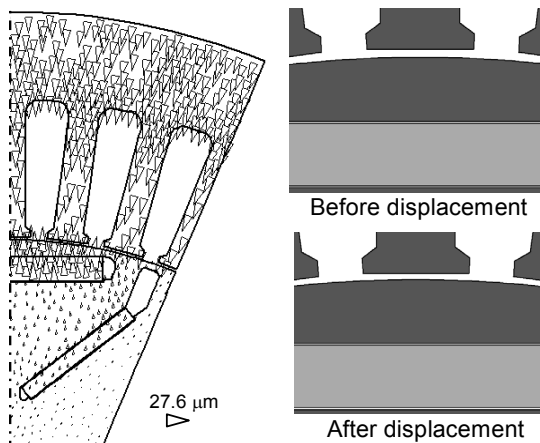Fig. 2. Calculated principal stress distributions.

Fig. 3. Calculated displacement at 10000min⁻¹.

(a): Considering stress and rotor deformation
(b): Considering stress and neglecting rotor deformation
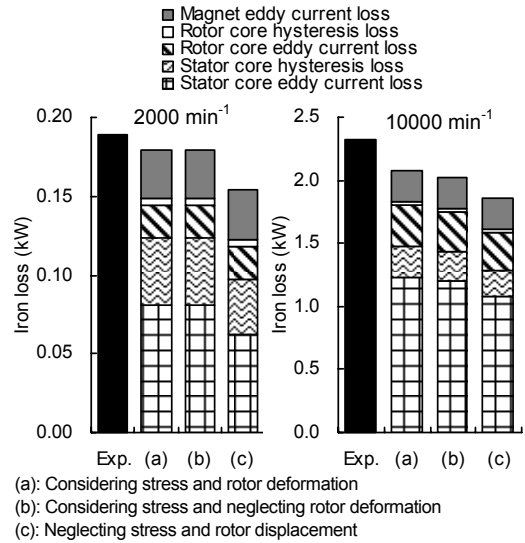(c): Neglecting stress and rotor displacement

Fig. 4. Experimental and calculated iron losses
(Armature current 300 A, Current angle 80 deg).
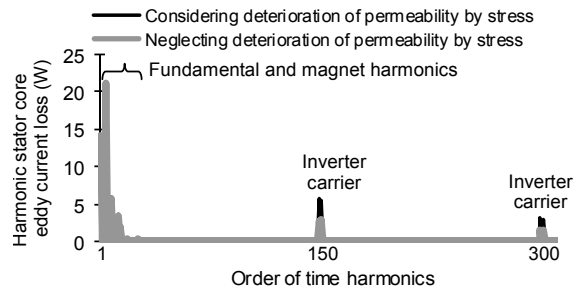
Fig. 5. Harmonic stator-core eddy-current losses (2000 min⁻¹).

force caused by the high-speed rotation.

Fig. 3 shows the displacement of the stator and rotor cores calculated by the stress analysis. The stator core is displaced to inside by the shrink fitting, whereas the rotor core is displaced to outside by the centrifugal force. The stator-core displacement is constant with the rotor speed and considered in the design of this motor in advance. On the other hand, the rotor-core displacement varies with the rotor speed. This displacement becomes nearly 5% of the air gap at the maximum speed.

Fig. 4 shows the experimental and calculated iron losses including the magnet eddy-current losses. The accuracy of the calculated iron loss is improved by considering the stress and the deformation. The effect of the rotor deformation on the loss is very small at low speeds, whereas it is not negligible at the maximum speed. In particular, the rotor-core loss increases by 5% only by the effect of the rotor deformation at the maximum speed. The figure also indicates that both the eddy-current and hysteresis losses of the stator core increase with the stress. These increases are mainly attributed to the compressive stress caused by the stator shrink fitting. However, the increase in the eddy-current loss cannot be explained only from the direct effect of the stress on the loss.

Fig. 5 shows the calculated stator-core eddy-current loss decomposed into harmonic components. The result that neglects the deterioration in permeability with stress is also shown. The figure indicates that the high-frequency harmonic eddy-current losses caused by inverter carrier become nearly twice by the deterioration of the permeability, whereas the low-frequency components are not considerably changed. This phenomenon is caused by the decrease in the skin effect on the electrical steel sheet with the decrease in the permeability.

IV. CONCLUSION

The effects of the stator and rotor stresses on the iron loss of variable-speed IPMSMs are investigated by using the combination of stress and EMF analyses. Several effects, which have not been reported, are revealed by this analysis. The proposed loss-calculation procedure is effective for accurate estimation of the iron loss in variable-speed IPMSMs.

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