Design Optimization of an IPMSM by Topology Optimization based on the Level Set Method

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Abstract — This study suggests sequential optimization method for an interior permanent synchronous machine (IPMSM). It is intended to suppress the torque ripple of an IPMSM caused by three torque components those are magnetic, cogging and reluctance torque. Firstly, magnetic and cogging torque terms are optimized by obtaining sinusoidal air-gap flux density distribution and then reluctance torque ripple can be minimized by matching sinusoidal inductance. Both processes are performed by the level set method based optimization process.

I. INTRODUCTION

An interior permanent magnet synchronous machine (IPMSM) is widely used in various fields because the IPMSM can generate high torque than other synchronous machines. An IPMSM generates reluctance torque as well as magnetic torque caused by high saliency [1]. However, the torque ripple value is relatively higher than other SM.

Since Bensøe and Kikuchi [2] firstly introduced the homogenization design method (HDM) in structural problems, the topology optimization scheme has been developed significantly. Nowadays, the level set based topology optimization which may overcome gray scale problem in case of using traditional methods such as the solid isotropic material with penalization method (SIMP) or homogenization design method is used in many fields. The level set method has been applied successfully to design electric rotary type machines, especially IPMSM [3, 4].

This study deals with two step optimization method for the IPMSM. Firstly, an optimal shape of the rotor iron part is obtained to make the air-gap flux density sinusoidal and it is directly related with reducing its magnetic torque ripple and cogging torque. Next, optimal shape of the stator slot is designed to satisfy sinusoidal inductance change and it is expected to make reluctance torque ripple vanish. These optimization steps are performed sequentially because they are almost independent to each other. Optimization results are verified considering its non-linear property.

II. FUNDAMENTAL RELATIONSHIPS

The torque terms of an IPMSM can be described as follows [5]:

$$T = \frac{1}{2} i^2 \frac{dL}{d\theta} - \frac{1}{2}\phi^2 \frac{dR}{d\theta} + i \frac{d\lambda_m}{d\theta} \tag{1}$$

The first term is generally called as reluctance torque generated by inductance change according to rotor angle. The second term is a torque component generated by reluctance change and generally called as cogging torque. The last term is associated with the coil flux leakage by permanent magnet (PM) and named as magnetic torque. The current is generally controlled to get sinusoidal waveform and the other components are determined by magnetic circuit design of the IPMSM. For a three-phase machine, if the current is controlled as sinusoidal and inductance and coil flux leakage are designed as sinusoidal i.e., $dL/d\theta=L_0 sin2\theta$ and $d\lambda_m/d\theta=\Lambda_0 sin\theta$, respectively, then the first and last torque components have constant values. Also, if reluctance is not changed in accordance with rotor angle change, i.e., $dR/d\theta=R_0$, then cogging torque becomes zero. Therefore, all torque ripple terms can be vanished theoretically.

III. OPTIMIZATION METHOD

A. Air-gap flux density optimization

If the air-gap flux density waveform becomes sinusoidal in a slotless model, two advantages in an SM can be expected. One is the sinusoidal coil flux leakage waveform and the other is constant reluctance. As a result, a constant magnetic torque and zero cogging torque can be expected. To make the air-gap flux density sinusoidal, the optimization problem is formulated as following:

$$\begin{aligned} &\text{minimize} \quad f(\phi) = \frac{1}{A_{slot}} \int_{\Omega_{slot}} \left(\frac{B_{radial}}{B_{target}} - 1 \right)^2 d\Omega \\ &\text{subject to} \quad \mathbf{KA}_z = \mathbf{J} \\ &\text{and} \quad \int_{\Omega} H(\phi) d\Omega = Vol^* \end{aligned} \tag{2}$$

where A_{slot} is the slot area, B_{radial} is the flux density to radial direction and Vol^* is the specified volume constraint. The targeting flux B_{target} is defined as

$$\begin{aligned} B_{target}(\theta_E) &= \sqrt{2} B_{RMS} \sin\theta_E \frac{r}{r_{mean}} \\ B_{RMS} &= \frac{1}{A_{slot}} \sqrt{\int_{\Omega_{slot}} B_{radial}^2 d\Omega} \end{aligned} \tag{3}$$

where r_{mean} is the radius of the slot and θ_E is the electrical measuring position.

B. Inductance optimization

The reluctance torque ripple can be reduced by making the inductance change sinusoidal. This method cannot eliminate torque ripple perfectly because the inductance waveform is changed by the amount of current loading due to the material non-linear property. In spite of the weakness, reluctance torque ripple can be reduced efficiently by the method not only at the designed current loading but also in the other operation range. To make the inductance sinusoidal, the optimization problem is formulated as

$$\begin{aligned} \text{minimize} \quad & f(\phi) = \sum_{i=0}^{N} \left(\frac{L_i - L_{mean}}{L_{\max} - L_{\min}} - \sin\frac{\pi}{2}\frac{i}{N} \right)^2 \\ \text{subject to} \quad & \mathbf{KA} = \mathbf{J} \\ \text{and} \quad & \int_{\Omega} H(\phi) d\Omega = Vol^* \end{aligned} \quad (4)$$

where i and N are the position number and total number of rotor rotational angles considered, respectively. L_{mean} is calculated by average value of inductance as $\sum_{i=0}^{N} L_i / (N+1)$.

IV. OPTIMIZATION RESULT

The optimization method is applied to the model described in Table 1. The rotor iron is assumed to be made of electric steel sheets having non-linear B-H characteristic. The remanent flux density of PM is taken 1.15T based on the Nd-Fe-B magnet property.

The optimization is performed without considering volume constraint. Fig. 1 shows the optimal shape of the rotor core portion designed to makes air-gap flux density sinusoidal and Fig. 2 displays the air-gap flux density distribution. The air-gap flux density is almost coincided with the targeting sinusoidal waveform although it is not matched perfectly. Because the fundamental air-gap flux density of IPMSM depends on the magnet position and the air barrier, optimization result is strongly related to initial design of rotor. With the result, it is expected that the magnetic torque ripple and the cogging torque may be reduced. Consecutive design process for inductance optimization will be performed to minimize the torque ripple caused by reluctance torque.

TABLE I
APPLICATION MODEL SPECIFICATIONS.

Type	IPMSM
Power	3 *kW*
Rotor speed	1800 *rpm*
Driving torque	16 *N· m*
Number of phase	3
Number of poles	8
Number of slots	24
Number of turns per slot	124
Phase current per conductor	11 *A* (rms)
Phase voltage	90 *V* (rms)
Air-gap radius	92mm

Fig. 1. Optimal shape of the rotor iron part.

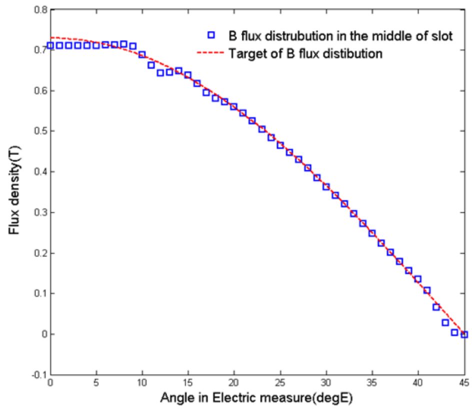

Fig. 2. Flux density distribution of the optimal rotor model.

V. CONCLUSION

The torque ripple of an IPMSM can be effectively suppressed by the air-gap flux density as well as the inductance change based optimization process suggested in this study. Proposed method can take advantage in the sensitivity calculation rather than using direct torque calculation. Also, the inductance ripple may coincide with the objected sinusoidal waveform in wide range despite of its non-linearity. It guarantees little reluctance torque ripple in wide current loading range near the current loading initially designed.

VI. ACKNOWLEDGEMENTS

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VII. REFERENCES

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