Torque Optimization of the Interior-Permanent Magnet Synchronous Motors using Design Sensitivity Analysis

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Abstract. This paper presents a shape optimal design approach to reduce the torque ripple of the interior-permanent magnet synchronous motors. The shape design sensitivity formula and the finite element method were employed for shape optimization of the machine. The numerical results show that the optimized motor has lower torque ripple and more average torque.

Key words

Design sensitivity analysis, shape optimization, 2D finite element method, torque ripple.

1. Introduction

Until recently, design sensitivity analysis for shape optimization was widely used [1]-[3]. In conjunction with the two-dimensional finite element method, the sensitivity analysis reported in [1] has been successfully applied to some optimization problems in magnetostatic systems. The shape optimization of the permanent magnet synchronous (PMS) motors was the subject of many papers. It is indicated the back-EMF waveform has an important role to produce the smooth torque. Lee and Park employed the shape design sensitivity formula and the finite element method for calculating the sensitivity of flux-linkage to the design variables determining the shape of iron pole piece [2].

Shape design sensitivity analysis in electromagnetic systems can be developed using two fundamentally different approaches. The one is the discrete approach, where design derivatives of a discretized system equation are taken to obtain sensitivity information. The other called the continuum approach, where design derivatives of the variational governing equation of the electromagnetic system are taken to obtain explicit design sensitivity formula in an integral form.

In the sensitivity analysis there are some design variables that are independent quantities are varied in order to achieve the optimum design. Upper and lower limits are specified to serve as constraints on the design variable. These limits define the range of variation if design variable. The sensitivity analysis method uses gradients of the optimization function with respect to design variables. For each iteration, gradient calculations (which may employ a steepest descent method) are performed in order to determine a search direction, and a line search strategy is adopted to minimize the optimization function. Thus each iteration is composed of a number of subiterations that include search direction and gradient computations.

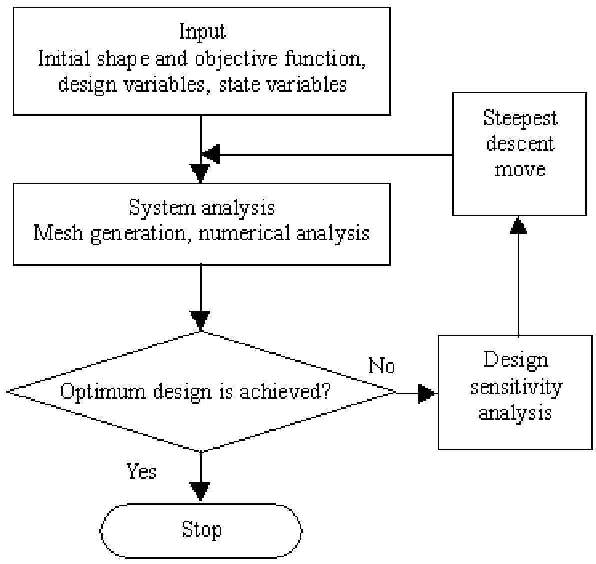

Fig. 1. Flowchart of the shape optimization

These iterations continue until convergence is achieved. The problem is said to be converged if the change in objective function from the best design to the current design is less than the objective function tolerance or the change in objective function from the previous design to the current design is less than the objective function tolerance.

Figure 1 shows the algorithm used for the shape optimization in 2D finite element model of the interior permanent magnet (IPM) motor.

For permanent magnet synchronous motors one of the most important parameters is the torque ripple when motor works in the steady-state situation. To improve the torque ripple, the motor sizes of magnet length, pole arcs, slot opening and skew have been controlled or the number of slots and pole arc chosen, but a substantial ripple still remains. In this paper, we want to obtain the torque ripple as low as possible, so the torque ripple selected as optimization function and minimized. For this purpose, we must obtain the torque waveform for each iteration when the motor rotates at synchronous speed.

2. Optimal shape design of IPM motor

We applied the design sensitivity analysis to a 2D finite element model of a three-phase, 4-kW, 380-Volt, 50 Hz, 4-pole IPM synchronous motor shown interior permanent magnet Fig. 2. This figure also shows its equi-potential lines obtained from the finite element model of the motor.

To obtaining a flux distribution as close as possible to the sinusoidal form, and have a smooth torque with lower ripple, we suggest some changes on the rotor structure. For that, we added some holes near the rotor surface as shown in Fig. 3. Twenty-four holes have been selected but because symmetrical shape of the rotor, three holes have been selected as design variables. Other holes had same position and radius symmetrically.

In this new-designed motor the radius and position of the holes on the rotor are taken as design variables so for these three holes nine design variables can be defined. These design variables allow the holes move through rotor and change the radius with some constraints to avoid overlapping the holes with PMs, airgap and each other.

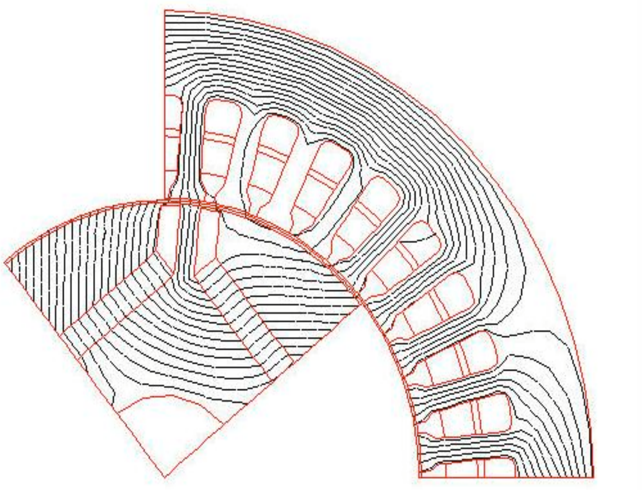

Fig. 2. Three phase interior permanent magnet synchronous motor flux lines used for simulation.

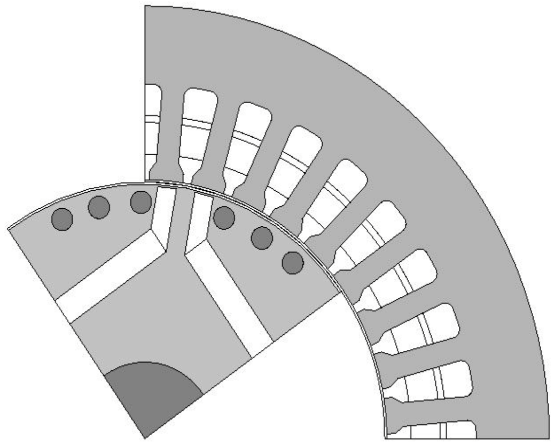

Fig. 3. The initial proposed IPM motor with the same holes near the rotor surface.

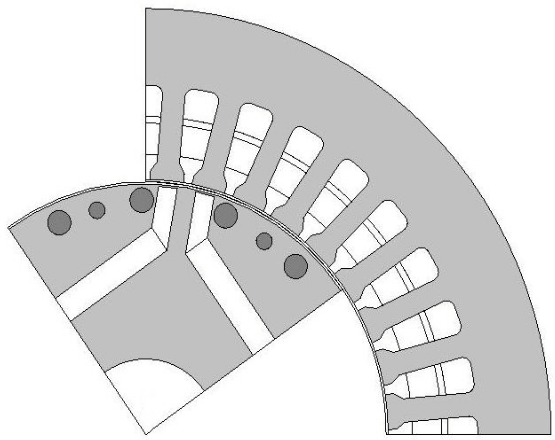

Fig. 4. The optimized holes of the simulated IPM motor.

The torque ripple selected as the optimization function to be minimized. The optimization technique of the steepest descent method is used for the search direction and the step size. The sensitivity of the optimization variable with respect to these design variables are calculated using sensitivity analysis on the finite element model of the motor.

3. Optimization results

The Finite element model of the IPM motor created and sensitivity analysis applied to the model of the IPM motor. The optimization function was torque ripple defined as $(T_{max}-T_{min})/T_{avg}$, where T_{max}, T_{min} and T_{avg} is the maximum, minimum and average values of the motor torque.

An optimization program wrote in according to the described flowchart above and after about eight iterations the problem converged. Figure 4 shows the optimized model obtained for the IPM synchronous motor from the sensitivity analysis in the 2D finite element method. It is obvious that the position and radius of holes has been changed from the initial values.

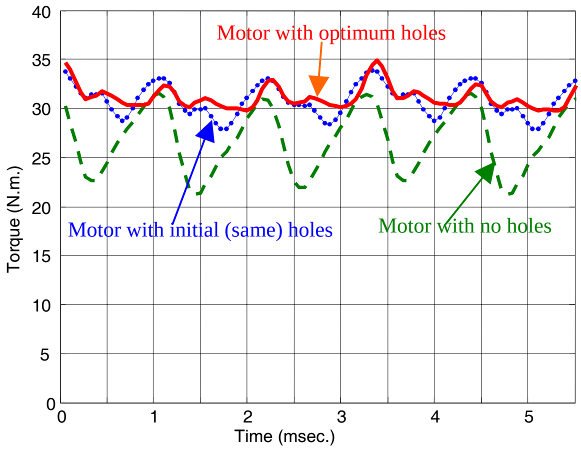

Fig. 5. Steady-state condition torque obtained for the simulated IPM motor at rated load.

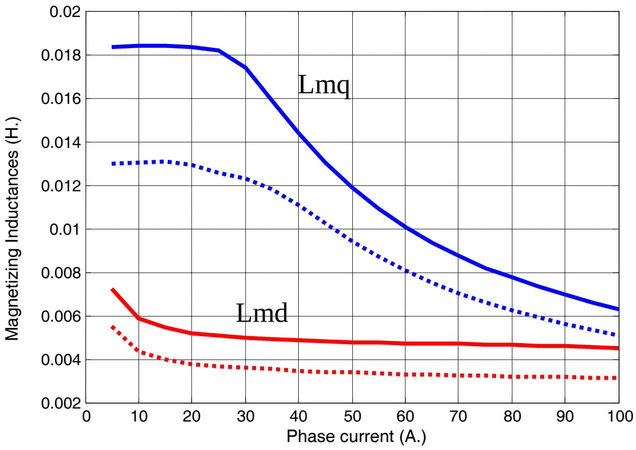

Fig. 7. D and Q magnetizing inductances for the IPM motor with no holes (continuous line) and that with optimized holes (dotted line).

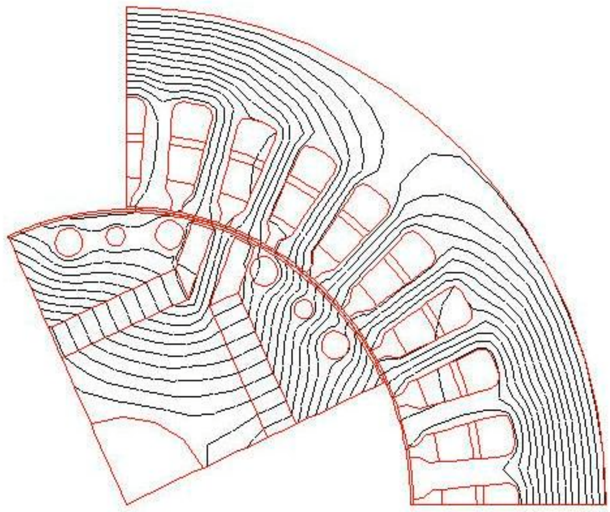

Fig. 6. Equi-potential lines in the optimized motor due working obtained using FE model of the motor.

TABLE I. - Torque average, Minimum and Maximum values

Motor type	Torque (N.m.) Tavg	Tmax	Tmin
IPM motor with no holes	27.76	31.54	21.25
IPM motor with holes have same radius	30.86	33.88	27.85
IPM motor with optimized holes	31.13	34.93	29.79

The torque at the steady-state condition and nominal load has been obtained. Figure 5 shows the torque for the IPM motor that has no holes and that obtained for the initial motor has the holes with same radius and the motor with the optimized holes. It is clear that the torque for the optimized motor has lower ripple and more average value. It is notable that these results obtained at same currents.

The average, minimum and maximum values of the torque of the different motors are shown in Table I. The flux distribution lines of the optimized motor also has been shown in Fig. 6.

The saliency, the d and q-axis magnetizing inductances and their ratio have considerable effects on the performance of such machine [4]. The effects of the holes in the motor model on the d- and q-axis magnetizing inductances are shown in Fig. 7. It must be explained that the d and q-axis of these motors (interior permanent magnet motors) is inverse than the known salient pole synchronous machines.

4. Rotor modal analysis

Modal analysis uses to determine the natural frequencies and mode shapes of a structure. These natural frequencies and mode shapes are important parameters in the design of a structure for dynamic loading conditions. They are also required if we want to do a spectrum analysis or a mode superposition harmonic or transient analysis. Finite element packages are able to give vibration modes and the corresponding natural frequencies

It is possible the drilled holes on the rotor affect the rotor mechanical structure. It is very important to study the rotor mechanical deformation when the rotation, because the high mechanical stress on the rotor ribs can dissolve the rotor structure. For that a mechanical finite element model of the rotor performed and a modal analysis made for initial and the optimized rotor to compare the results for the new designed rotor with the conventional rotor.

5. Modal analysis results

It is notable that the modes with higher frequencies will be excited hard, so only that modes have lower frequencies are considerable.

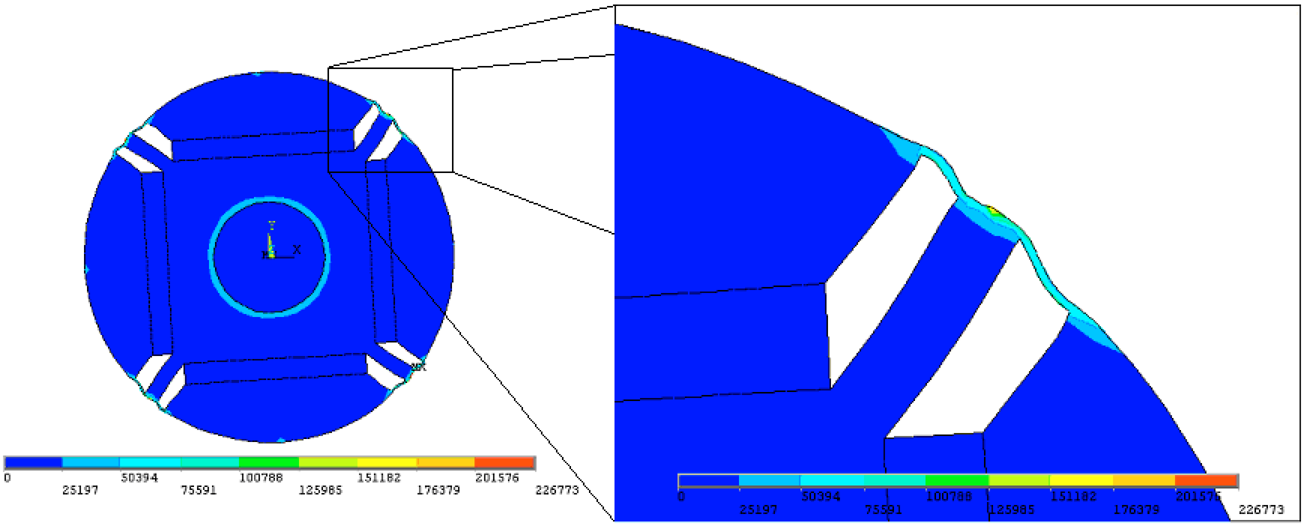

Fig. 8. Stress contour of the initial rotor for the most important vibration mode.

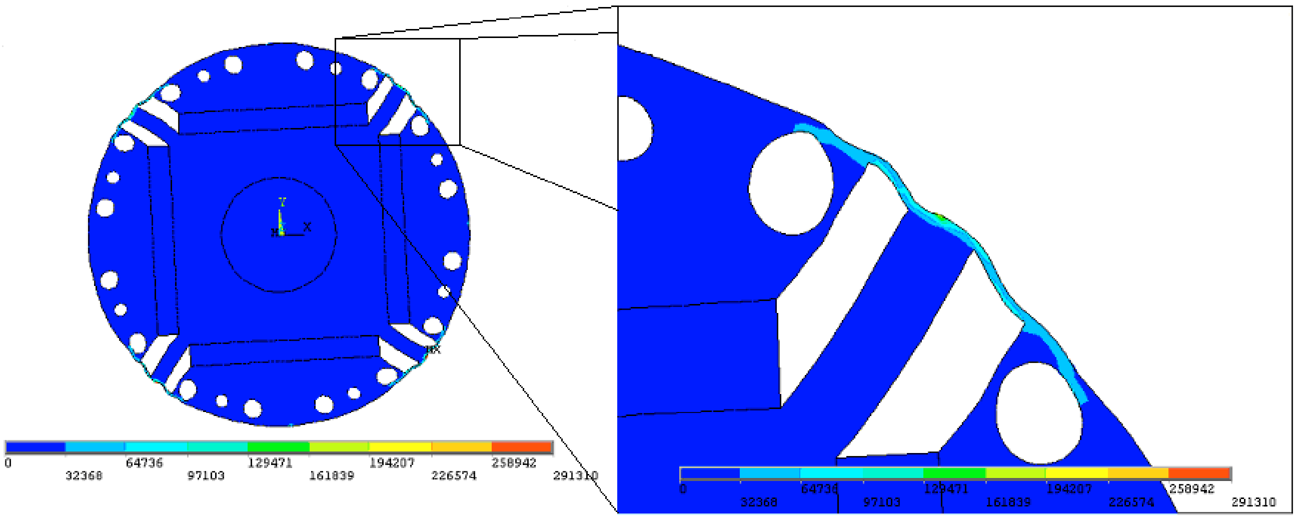

Fig. 9. Stress contour of the optimized rotor for the most important vibration mode.

Figure 8 shows the deformation of the rotor due to the most important mode that has affected the ribs for the conventional rotor shape with the natural frequency about 7950 hertz. The other natural frequencies obtained for the conventional rotor are 13800 and 21700 hertz.

Deformation of the rotor due to the most important mode that has affected the ribs for the optimized rotor shape has been shown in Fig. 9. This vibration mode has the natural frequency about 8350 hertz. The other modes have frequencies about 14300 and 22400 hertz.

6. Conclusion

The new design optimized IPM synchronous motor has more average torque with lower torque ripple. Rotor of this motor has the natural frequencies higher than conventional rotors. The drilled holes can be fulfilled with aluminum and used as a cage induction PM motor or as a damper to improve the motor behavior during the transient situations and mechanical resistance of the rotor.

References

[1] Il-Han Park, J. L. Coulomb and Song-Youp Han, "Implementation of continuum sensitivity analysis with existing finite element code," IEEE Trans. on Magnetics, vol. 29,no. 2, pp. 1787-1790, March 1993.

[2] Joon-Ho Lee, Il-Han Park, Dong-Hun Kim and Wan-Soo Nah, "Reduction of Back-EMF harmonics of permanent magnet motor by continuum shape design sensitivity analysis," 13th COMPUMAG Conference Proceeding, Evian, France, IV-159, July 2001.

[3] S. Wang and J. Kang, "Shape optimization of BLDC motor using 3-D finite element method," IEEE Trans. on Magnetics, vol. 36, no. 4, pp. 1119-1123, July 2000.

[4] I. Boldea, Synchronous Reluctance Motor Drives, CRC Press, Chapter 12, 2002.