A Novel Multiphysics Design Method of High Speed Permanent Magnet Synchronous Machine

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Abstract — The mulitphysics design method of high speed permanent magnet machine (PMSM) is proposed in this paper. To simplify the problems, the multiphysics design is broken down into three dual-coupled design problems, which are structural-electromagnetic, electromagnetic-thermal and thermal-structural. The three dual-coupled fields are designed iteratively, and linked through the coupling parameters. This method is a compromise between precision and rapidity that includes many important multiphysics coupling effects. The proposed multiphysics design method is applied to a 30kW, 100000rpm high speed PMSM used in mciroturbine generation system. It is shown that the method is feasible and efficient in developing time and cost, leading to more economical and safer products.

I. INTRODUCTION

Due to its high power density and small volume, the high speed Permanent Magnet Synchronous Machine (PMSM) is becoming increasingly popular in numerous applications, such as microturbine generation systems, machine tool spindle drives, flywheel energy storage systems, hybrid electric vehicles, centrifugal compressors, etc. [1].

The design of high speed PMSM is different from the low and medium speed electrical machine. Because of the high rotating speed and the high frequency of the alternative current in stator windings, the mechanical rotor construction and the minimization of losses are the main challenges [2].Thus, the electromagnetic parameters of the high speed PMSM have to be designed simultaneously with the mechanical and thermal parameters. As the forced cooling is usually used due to the high losses per unit volume, it is necessary to analyze the fluid dynamics to enhance the accuracy of the thermal analysis. In the conventional design methods, these coupling effects were either ignored or taken into account very approximately. These methods based on single field separately cannot satisfy the demand of high speed PMSM design, which has led to an intense research and development in the complete multiphysics design method [3]-[4].

Mathematically, multiphysics design problems of high speed PMSM are described by a set of coupled partial differential equations. However, the fully analytical model is hard to build because of its complicated structure and the nonlinearity of materials. The solution of these equations also poses a challenge to handle such interactions using a general and efficient method. The developed numerical computation techniques give the opportunity for finite element method (FEM) to solve the multiphysics problems [5]-[6]. The FEM has the advantage that it can solve complicated boundaries preciously. But the unified model and mesh for the direct multiphysics analysis is difficult to establish. An iterative method for multiphysics design is discussed in [7] and [8]. The two fields are coupled by applying results from the former field as the loads of the latter. But it is still designed based on the single physical field.

In this paper, a multiphysics design method of high speed PMSM is proposed. First, the interactions between the distinct physical fields are analyzed in section II. Then, the dual-coupled multiphysics design method is described in detail in section III. At last, the validity of the method is confirmed in section IV by designing a 30kW, 100000rpm PMSM used in the micrturbine generation system.

II. COUPLING RELATIONSHIP ANALYSIS

Compared to the low and medium speed PMSM, the electromagnetic, mechanical, thermal and fluid parameters in the high speed PMSM have the stronger coupling relationship inherently. The interactions between the distinct physical fields are shown in Fig. 1. The link between the fields is determined by material properties depending on the corresponding field quantities.

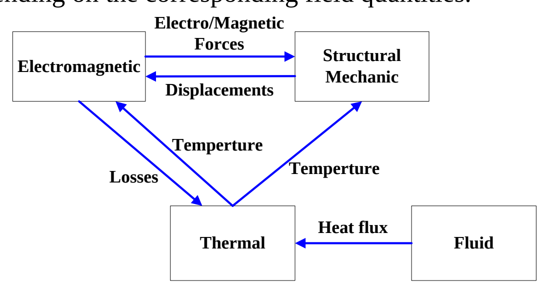

Fig. 1. The multiphysics coupling relationship in high speed PMSM

III. MULTIPHYSICS DESIGN METHOD

Considering the constraints in different fields, the initial structure is determined. And the multiphysics design flow is shown in Fig. 2.

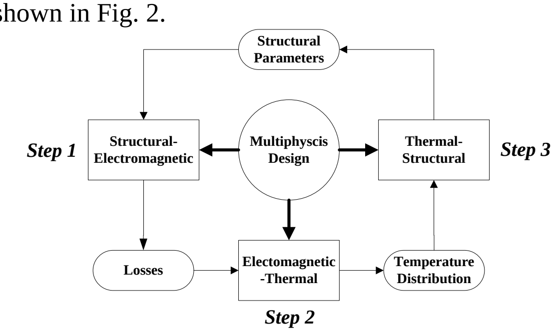

Fig. 2. The flowchart of the dual-coupled multiphysics design method

Step 1: The structural-electromagnetic design is performed. Both the structure and material of the stator and rotor are designed to satisfy the electromagnetic requirements, reduce losses and ensure that the rotor has sufficient strength to withstand the centrifugal force in high speed rotation. For high speed PMSM, besides the iron losses in the stator core and the copper losses in the windings, the air friction losses in the air gap and the eddy current losses in the rotor are also significant. The minimization of losses is one of the most important design objectives.

Step 2: The electromagnetic-thermal design is performed based on the heat transfer coefficients computed by fluid field analysis. The heat source is the loss from step 1. Utilizing the loss and the heat transfer coefficients, the temperature distribution inside the motor is obtained to ensure that the maximum temperature is acceptable. Based on the temperature distribution**,** the electromagnetic properties of the PMSM are verified.

Step 3: In the process of the thermal-structural design, the stress of the high speed PMSM are analyzed based on the temperature distribution from step 2. If the mechanical constraints are not satisfied, the modified mechanical parameters are transferred to structural-electromagnetic fields.

The proceeding design flow is performed until all requirements are satisfied.

IV. APPLICATION AND VALIDATION

The previous design flow is verified by designing a 30kW, 100000rpm PMSM used in the microturbine generation. The basic stator and rotor structure are shown in Fig. 3.

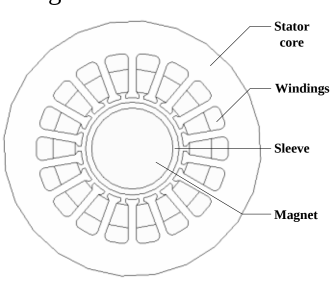

Fig. 3. Structure of the PMSM

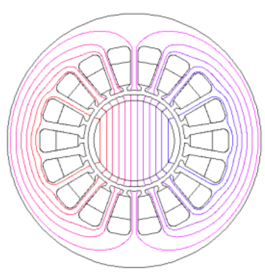

Fig. 4. Magnetic flux distribution

The low iron loss laminations are used in this design. The machine has a 2-pole cylindrical Sm_2Co_{17} permanent magnet encased in a nonmagnetic sleeve with an interference fit assembly. The retaining sleeve is used to limit the centrifugal force stress on the brittle magnet, and also used as the rotor shaft. The forced cooling air flows outside of the stator surface to reduce the temperature rise.

A. Structural- electromagnetic Design

The geometry of high speed PMSM design is focused on the thickness and material of the retaining sleeve. The magnetic flux density in air gap, the mechanical strength and the eddy current losses in the sleeve are affected by the thickness of the sleeve. Fig. 4 shows the magnetic flux distribution of the high speed PMSM.

B. Electromagnetic-thermal Design

The regional heat transfer coefficients are obtained by analysis of the cooling air. The losses computed in the proceeding stage and the heat transfer coefficients are transferred to the thermal field, and the temperature distribution inside the PMSM is acquired. The thermal limits are determined by the demagnetization of the magnets and the insulation.

The electromagnetic properties of the PMSM are checked in the condition of the temperature distribution.

C. Thermal-structural Design

Based on the previously obtained temperature distribution inside the PMSM, two main issues have to be considered: First, the stresses in the cylindrical permanent magnet and the sleeve; second, the contact pressure between the magnet and the sleeve.

V. CONCLUSION

The multiphysics design method of high speed PMSM is presented. The multiphysics design is broken down into three dual-coupled design problems. By this mean, the important multiphysics coupling effects are considered efficiently. Generally, to perform the design flow, plenty of iterations are required. The advantages are verified by applying the method to the 30kW, 100000rpm PMSM used in the microturbine generation. The design properties are compared to the experimental data, which show the multiphysics method is accurate and efficient in developing time and cost.

VI. REFERENCES

[1] L.M. Zhao, C. Ham, L.P. Zheng, T. Wu, K. Sundaram, J. Kapat and L. Chow, "A Highly Efficient 200000 RPM Permanent Magnet Motor System," *IEEE Trans. on Magn.*, vol.43, no.6, pp. 2528-2530, 2007.

[2] B. Riemer, M. Lessmann and K. Hameyer, "Rotor Design of a High-Speed Permanent Magnet Synchronous Machine rating 100,000 rpm at 10kW," *IEEE Energy Conversion Congress and Exposition*, pp. 3978-3985,2010.

[3] P.D. Pfister and Y. Perriard, "Very-High speed Slotless Permanent-Magnet Motors: Analytical Modeling, Optimization, Design, and Torque Measurement Methods," *IEEE Trans. on industrial electronics*, vol.57, no.1, pp. 296-303, 2010.

[4] D.J. Lee and J.H. Kim, "Integrated Design Method of Multi-Axis VCM Actuators Based on Coupled-Field-Analysis of Electro-Magnetics and Structure", *IEEE Trans. on Magn.*, vol.45, no.9, pp. 2340-2343, 2009.

[5] K. Hameyer, J. Driesen, H. D. Gersem, and R. Belmans, "The classification of coupled field problems," *IEEE Trans. on Magn.*, vol.35, no.3, pp. 1618-1621, 1999.

[6] F. Marignetti, V. D. Colli and Y. Coia, "Design of Axial Flux PM Synchronous Machines Through 3-D Coupled Electromagnetic Thermal and Fluid-Dynamical Finite-Element Analysis," *IEEE Trans. on Magn.*, vol.55, no.10, pp. 3591-3601, 2008.

[7] J. Legranger, G. Friedrichx, S.Vivier, and J. C. Mipo, "Combination of Finite Element and Analytical Models in the Optimal Multi-Domain Design of Machines: Application to an Interior Permanent Magnet Starter Generator," *IEEE Trans. on Industry Applications*, vol.46, no.1, pp. 232-239, 2008.

[8] Z. Kolondzovski, A. Belahcen and A. Arkkio, "Multiphysics thermal design of a high speed permanent-magnet machine," *Applied Thermal Engineering*, vol.29, no.13, pp. 2693-2700, 2009.