Parameter Sensitivities Analysis and Optimization Design for Permanent Magnet Flux-Switching Motor by Nonlinear Varying-Network Magnetic Circuit Method

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In this paper, a new sensitivity nonlinear varying-network magnetic circuit (VNMC) method is proposed for an outer-rotor I-shaped permanent magnet flux-switching (I-PMFS) motor. By integrating concept of sensitivity into the nonlinear VNMC method, the whole design efficiency can be improved effectively. In the optimization process, three design objectives are selected, containing output torque, torque ripple and the amplitude of back-EMF. Based on the sensitivity analysis, the parameters possessing the significant effects on the design objectives can be selected purposely, thus the whole amount of calculation is obviously reduced. After the determination of the sensitive parameters, the rest of optimization can be completed efficiently by the nonlinear VNMC method. Finally, a prototype motor is manufactured and tested. Both theoretical analysis and experimental results confirm the effectiveness of the proposed method.

***Index Terms*—Permanent magnet flux-switching motor, optimization design, varying-network magnetic circuit method, sensitivity.**

I. INTRODUCTION

IN RECENT years, permanent magnet flux-switching (PMFS) motors have received much attention mainly due to their the advantages of high torque density, high efficiency, simple and robust rotor structure [1]. Hence, it can be considered as one of the promising candidates for motor driving, which is suitable for electric vehicles (EVs). In such type of motors, the design concepts of double salient pole structure and modular stator are adopted, resulting in a large number of design parameters and complex parameter correlations. Then it infers that, to the PMFS motor, the unique structure design inevitably brings a challenge for realizing a systematical and efficient parameter optimization and performance analysis.

Generally, the motor studies are often conducted by two kinds of methods, consisting of finite element (FE) methods and conventional magnetic circuit methods [2], [3]. On the one hand, with the rapid development of computing technologies, the FE methods are favored by researchers and machine enterprises to conduct motor design, which are mainly realized by commercial soft-wares, such as ANSYS Maxwell, GMAG, and MAGNETS. Yet, it is worth noting that the prices of them are expensive, and it is time-consuming for calculating a complex FE model [2]. Thus, to the common researchers, a simple and efficient motor design is relatively difficult to be achieved in such way, especially in the initial stage of motor design. On the other hand, another type of analysis method, nominated as conventional magnetic circuit method, has attracted some attention in recent years, in which the electromagnetic field problem is transformed into the calculation of circuit [3]. And then the analysis time is reducing greatly, improving the design efficiency. However, the calculating accuracy of the method is relatively low, which limits its widespread application. To solve this problem, a varying-network magnetic circuit (VNMC) method is proposed in [4], successfully realizing a time-saving calculation and obtaining improved analysis accuracy.

Recently, a sensitivity analysis method is purposely applied into the motor design, which can effectively distinguish the significant design parameters from others, thus improving the whole design efficiency [5]. In this paper, by incorporating the concept of sensitivity into the VNMC method, an efficient optimization method is proposed for an outer-rotor I-shaped permanent magnet flux-switching (I-PMFS) motor. And a prototype motor is manufactured for the validity.

II. NONLINEAR VNMC MODEL

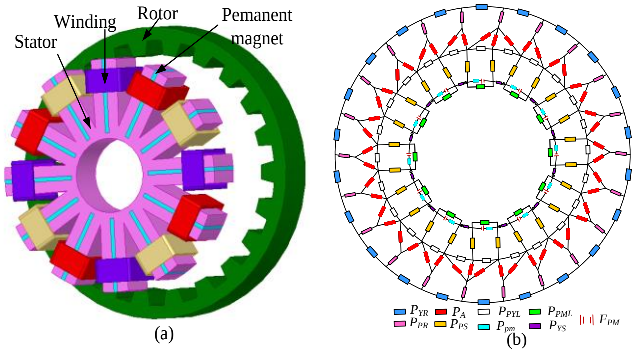

Fig. 1. Configuration of the 12/22 stator/rotor pole I-PMFS motor. (a) Topology. (b)Nonlinear VNMC model.

Fig. 1 (a) shows the 12/22 stator/rotor pole I-PMFS motor. In this motor, it can be observed that each stator pole of the I-PMFS motor is embedded with I-shaped PMs and wound with concentrated armature windings, while the rotor pole is simple only with 22 iron teeth. Furthermore, since the outer rotor pole consists of only silicon steel sheets, the simple rotor structure ensures the reliability of the motor, and meanwhile, high rotor pole number can provide high torque at low speed, which is essential for the in-wheel direct drive applications.

Then, the corresponding nonlinear VNMC model of 12/22-pole I-PMFS motor at typical rotor position, namely the minimum flux position of phase A, are demonstrated in the Fig. 1 (b). In the model, P_{PS}, P_{YS}, P_{PR}, and P_{YR} are the pole and yoke permeances of the stator and rotor, respectively, which vary with the nonlinear saturation in the corresponding magnetic paths. And the P_{PYL}, P_{PM}, P_{PML}, and P_A are the permeances of stator pole-to-pole leakage flux, PM flux, PM leakage flux, and air-gap flux, respectively, which are of constant permeability. Besides, the PM magnetizing force is represented by an equivalent magnetomotive force (MMF) F_{PM}. It is noted that both the value and the number of P_A in the model change with the rotor positions, thus resulting nonlinear VNMC model.

III. PARAMETER SENSITIVITIES CALCULATION

Sensitivity analysis method is considered as an effective way to recognize how each design variable affects the performance of the I-PMFS motor [5]. In order to identify the effect of each variable on optimization objectives efficiently and quickly, the sensitivity index is introduced based on sensitivity analysis. The corresponding sensitivity index can be described as:

$$S_{\mathrm{i}} = \frac{F(x_0 \pm \Delta x_i) - F(x_0)}{\pm \Delta x_i} \tag{1}$$

where ΔX_i is the increment of parameter X_i. In general, parameter variation method is employed to determine this increment, in which ΔX_i is usually defined as 10% or 20% of its initial value, thus the sensitivity index can be obtained.

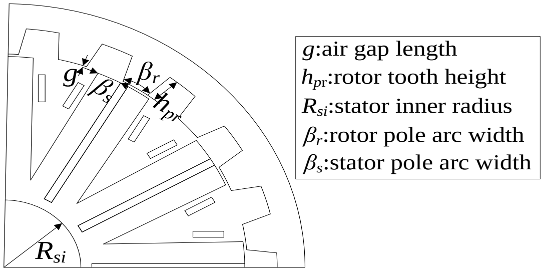

Fig. 2. Parametric model of the I-PMFS motor.

The parametric model of the I-PMFS motor is illustrated in Fig. 2. According to the equation (1), the values of sensitivity of the design variables can be obtained and illustrated in Fig. 3 (a), (b) and (c), respectively. According to the sensitivity values shown in Fig. 3, the design variables are divided into two levels: β_r, g, β_s and h_{pr} are significant design variables, and the remaining R_{si} is the non-significant design variable.

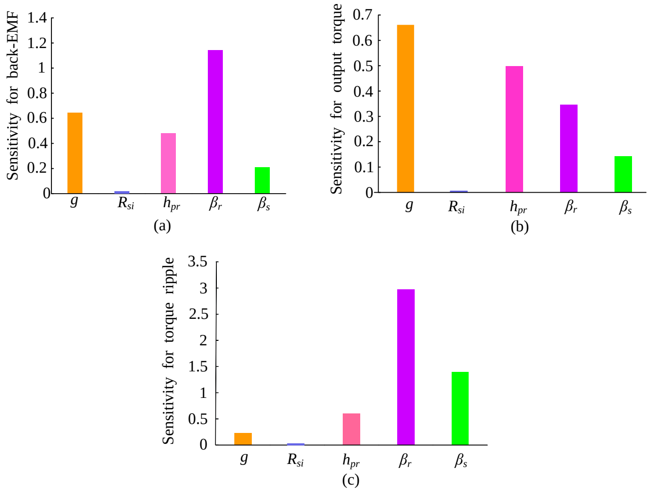

Fig. 3. Sensitivity analysis for three objectives. (a) Back-EMF. (b) Output torque. (c) Torque ripple.

IV. OPTIMIZATION AND PERFORMANCE ANALYSIS

Then, based on the sensitivities calculation results, the design variables are optimized respectively to improve the optimization efficiency. As shown in Fig. 4, to achieve a compromise between high output torque and low torque ripple, the g and β_r can be chosen to be 0.7mm and 7º respectively. Then a 2kW prototype machine is manufactured and tested for the expremental validation, as depicted in Fig. 5. Fig. 5 (a) shows the silicon steel sheet and the armature windings. And the measured back-EMF is given in Fig. 5(b), agreeing with the calculated results in nonlinear VNMC model. More detailed electromagnetic performances and experimental results will be presented in the full paper to verify the validity.

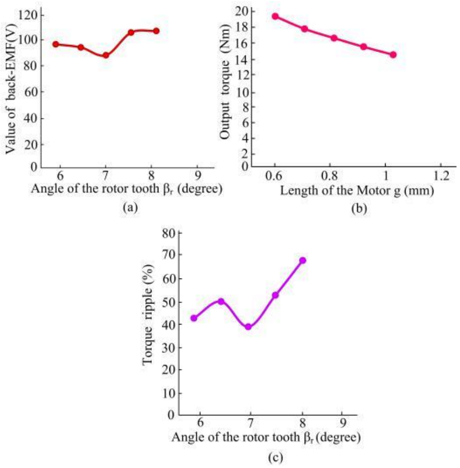

Fig. 4. Optimization results of the I-PMFS motor. (a) Variations of back-EMF to β_r. (b) Variations of output torque to g. (c) Variations of torque ripple to β_r.

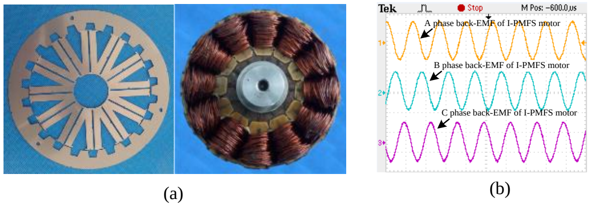

Fig. 5. Experimental validation. (a) Prototypes of I-PMF motors. (b) Measured back-EMF waveforms

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