

DESIGN OPTIMISATION OF PERMANENT MAGNET MOTORS USING RESPONSE SURFACE ANALYSIS

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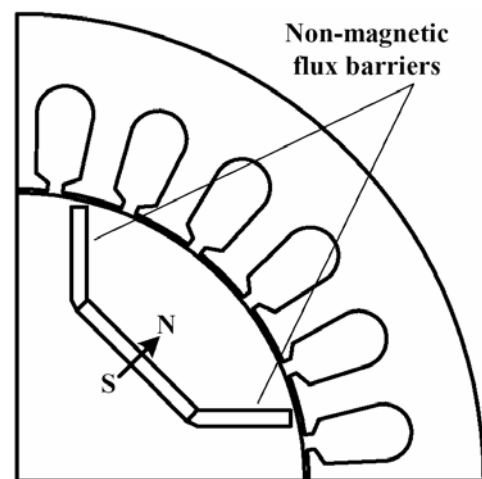
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ABSTRACT

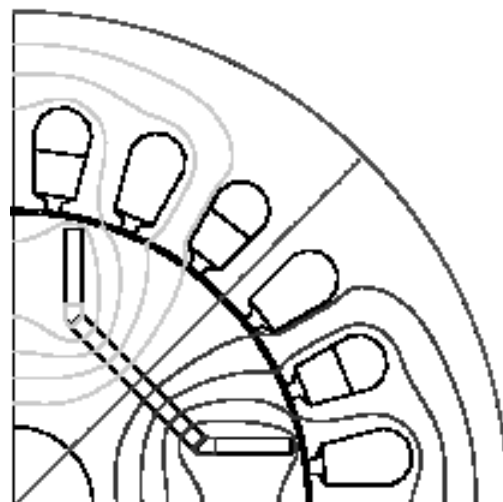
A new approach using response surface analysis has been attempted for the optimisation of designs of permanent magnet machines. In this new approach we used finite element numerical method of analysis for the design of experiments for the use of response surface analysis and the genetic algorithm as a searching tool for optimisation work. The response surface methodology (RSM) determines the empirical models relating the performance of a motor and the design variables. This design and optimisation approach resulted in enhancing the performance of permanent magnet motors. Results for interior permanent magnet synchronous type motors (IPMSM) are presented in this paper.

1. INTRODUCTION

In recent years steady state analysis and control methods for variable speed operation of PMSMs with current-regulated inverters have been described in several papers [1-3]. PMSM drives exhibit a constant torque region with increasing voltage and a decreasing torque region follows with a constant voltage. This extends up to the maximum operational speed. The high-speed constant voltage operation is achieved by reducing air gap flux linkage through an appropriate stator current distribution, and thus it is generally called "flux-weakening region". An earlier paper [4] investigated the field-weakening performance of the four main types of permanent magnet motors. This showed that the interior type PM motors have relatively higher rotor saliency ratio and d-axis inductance, which are important for the wide-speed operation. Fig.1(a) shows the architecture of such a motor geometry, while Fig.1(b) shows the flux distribution due to magnets alone. This paper investigates the appropriate rotor configurations of an interior PM motor for wide-speed applications. The design optimisation procedure is conducted to look for the optimal configuration of rotor design and the



(a) Stator and rotor structure



(b) PM flux plot

Fig. 1 Interior type permanent magnet synchronous motor

combination of PM flux linkage with d- and q-axis inductances. These three parameters mostly determine the performance of synchronous PM machines. Computational optimization is considered indispensable for electrical machine design. However, it is difficult to carry out optimisation work on PMSM structures that can provide good performance both in constant torque and flux-weakening regions within an acceptable computational time because of the complicated rotor configurations and the complex influence of magnetic saturation. In a previous paper [5], an effective computational approach was proposed with application of the response surface methodology (RSM) for the design optimisation of electromagnetic devices. In another paper [6], the design procedure combines the RSM and genetic algorithms (GA) and adopts the finite element method (FEM) as a magnetic field analysis method. In this paper we develop an objective function using RSM method and use GA for the search for optimum parameters. This enable us to approximate the objective physical quantities (PM flux linkage, d- and q-axis inductances, etc) by the polynomial representation containing design variables, i.e., thickness and width of rotor permanent magnets and the magnet pole arc in the optimising process.

2. MODELLING FOR PARAMETERS

There are many geometrical variables in the rotor design; optimisation of all the variables is impractical and may not be necessary. A selected critical number of variables can be optimized to achieve an economic solution. Three of these design variables have been discussed and analyzed in a previous contribution [7]. These variables are listed below:

- Magnet thickness (l_m)
- Magnet position (δ)
- Magnet pole angle (α)

Fig.2 shows these variables and their geometrical relationships for the PM machine under investigation. If the stator winding arrangement has been decided, the d- and q-axis inductances are determined by the rotor structure and PM flux linkages as determined by magnet configurations. Response surface analysis is then applied to optimize the design with respect these variables. In our case we applied a central composite design (CCD) for design experiments using finite elements. The model is depicted in Fig.3 and the coded variables are listed in Table-1. We have also examined the effect of CCD models using rotatable

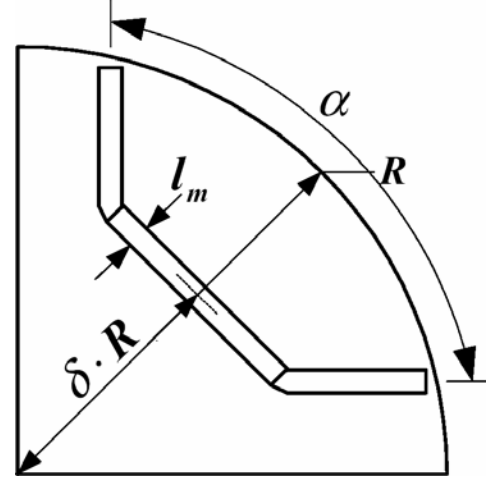


Fig. 2 Rotor configuration of Interior type PMSM

spherical models as well as cubic models for our optimization work. Results of numerical experiments show the differences in modeling proximities of design points. Genetic algorithm used with RSM provided the methodology for final optimization of the geometry for the motor.

A second-order response surface model that might describe this relationship among the design variables is given in equation (1).

$$y_i = \beta_{i0} + \beta_{i1}l_m + \beta_{i2}\delta + \beta_{i3}\alpha + \beta_{i4}l_m^2 + \beta_{i5}\delta^2 + \beta_{i6}\alpha^2 + \beta_{i7}l_m\delta + \beta_{i8}l_m\alpha + \beta_{i9}\delta\alpha + \varepsilon \quad (1)$$

where y_i can be the PM flux linkage or inductances, and ε represents the error estimate. This is a multiple linear regression model with three independent variables. The method of least squares is typically used to estimate the regression coefficients (the values of β_i). It is desirable that the number of experiments carried out by the FEM, is as small as possible in order to reduce the computational necessity. The appropriate selection of the points for experiments can reduce the variance of the coefficients, which makes the response surface more reliable. By utilizing the central composite design, 15 sets of design variables (l_m , δ , α) within the available value scopes are selected for FEM experiments to fit the second-order model.

Table-1: Coding and variables

	coded values				
	-1.732	-1	0	1	1.732
L_m (mm)	0.634	1	1.5	2	2.366
γ (%)	0.545	0.6	0.675	0.75	0.805
α (°)	54.5	60	67.5	75	80.5

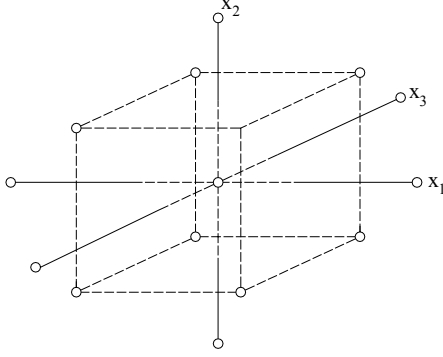


Fig.3 A Central Composite Design

This design consists of the 15 points, which are:

- (1) the vertices of a 3D cube in the space of coded variables: $(l_m; \gamma; \alpha) = (\pm 1; \pm 1; \pm 1; (1, 1); (-1, -1))$
- (2) the centre of this cube: $(l_m; \gamma; \alpha) = (0; 0; 0)$
- (3) the 6 other points called star points lay on the three axes $(\pm a; 0; 0)$, $(0; \pm a; 0)$ and $(0; 0; \pm a)$, the value of a being 1.732 for the design, so that all the points (except the centre point) of this design are on a sphere of radius 1.732. We shall call this design a "sphere design".

Design of experiments based on this CCD model was used with finite element computation to determine the solutions for all the 15 points as shown in this model. These solutions have been used in the response surface model shown in equation (1) in order to evaluate the coefficients of the response model. A regression type solution was sought and the square of the errors are minimized for minimizing variances. Response surfaces have been computed for the variation of all three variables in order to limit the search space when used with genetic algorithm for the optimum set of design variables.

3. OPTIMISATION PROCEDURE

Design experiments are carried out using finite element analysis and with the help of coded variables as shown in Table-1. These experiments are used to determine the coefficients of the response surface function. The next step in the design is to apply an optimisation process. Although any search technique can be applied in an appropriate manner, we used a genetic algorithm in our case. The constrained optimization problem can be expressed mathematically as follows:

$$\begin{aligned} & \min F(x_i), i = 0, 1, \dots, k \\ & \text{subject to} \\ & G_j(x_i) = 0 (\leq 0, \geq 0), j = 0, 1, \dots, m \\ & X_{iL} \leq x_i \leq X_{iU} \end{aligned}$$

The function $F(x_i)$ is the objective function. $G_j(x_i)$ is a set of constraint functions with the dimension of m . x_i are k design variables with lower and upper bounds of X_{iL} and X_{iU} respectively.

With regard to a search algorithm, the GA is used. The GA is a powerful method based on probabilistic evolution through generations. It is effective in finding the global optimum solution through the empirical model of interior PMSM by RSM. A general sketch of the GA procedure can be described as:

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gen = 0
initialize Pop(gen)
evaluate structure in Pop(gen);
while termination condition not satisfied do
{ gen = gen + 1;
select Pop(gen) from Pop(gen-1);
recombine structure in Pop(gen);
evaluate structure in Pop(gen);}
end

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A policy of mutation using the best fitness criteria has been used in this algorithm. The convergence based on the best fit and the average fit was quick. The sampling was pseudo random.

4. RESULTS AND DISCUSSION

The method of optimisation procedure has been developed in relation to the design of rotor configurations for a prototype PMSM which uses a given 3-phase, 4-pole, and 400 W induction motor frames, with modified winding distribution and NdFeB type magnets. The objective function determines the range of speeds with the power capability of the motor. However, in the constant power range, the flux weakening method is used with torque per ampere at maximum. The voltage limit determines the speed range, and as the back emf of the machine rises with the speed, the flux weakening capability also diminishes. The optimization procedure works within these constraints as it searches for the optimum set of design variables. A Part of the numerical results is shown in Table-2.

Table-2: Optimization results

Design Variables	Standard	Optimised
Magnet thickness l_m (mm)	1.50	1.00
Magnet position δ	0.70	0.67
Magnet Pole Angle α (degree)	70	75
PM flux linkage λ_m (Web)	0.369	0.324
d-axis inductance L_d (H)	0.059	0.070
q-axis inductance L_q (H)	0.181	0.135

Fig. 4 shows the power vs. speed characteristics with the same limits of inverter voltage and current ratings. It is worth noting that the optimised design is particularly advantageous for wide-speed operation. In fact, with the lower magnet volume but higher rotor saliency ratio, the optimised design develops similar rated power, but extending constant power speed range compared with standard design.

5. CONCLUSION

This paper described a novel optimisation procedure of an interior permanent magnet synchronous motor for wide-speed operation. The combination of Response Surface Methodology, Genetic Algorithm and Finite Element Analysis has proved an effective and practical tool for numerical simulation and optimisation process. This approach enables a fast design and an accurate performance prediction as demonstrated by comparing the numerical results of new method with conventional method.

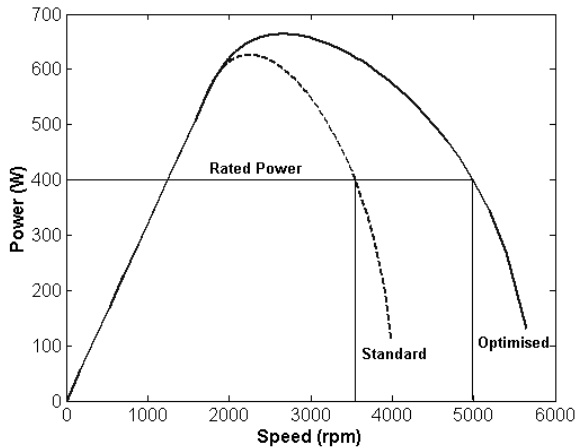


Fig. 4 Comparative study of torque-speed characteristics between two designs

6. REFERENCES

- [1] T. M. Jahns, "Flux-weakening regime operation of an interior permanent magnet synchronous motor drive," IEEE Transaction on Industry Application, vol. IA-23, no. 4, pp. 681-699, July/August 1987.
- [2] Gordon R. Slemon: "Operating Limits of Inverter-Driven Permanent Magnet Motor Drives," IEEE Transaction on Industry Applications, vol.23, Jan/Feb 1987, pp.327-332.
- [3] N. Bianchi and S. Bolognani, "Parameters and volt-ampere rating of a synchronous motor drive for flux-weakening applications," IEEE Transaction on Power Electronics, vol. 12, no. 5, pp. 246-252, Sept 1997.
- [4] Liu Qinghua, M. A. Jabbar, and A. M. Khambadkone, "Design optimization of interior permanent magnet synchronous motors for wide-speed operation," in Conf. Rec. Power Electronics and Drive Systems, 2001, vol. 2, pp. 475-478, April 2001.
- [5] Ruowen Rong and David A. Lowther, "Applying response surface methodology in the design and optimization of electromagnetic devices," IEEE Transaction on Magnetics, vol. 33, pp. 1916-1919, March 1997.
- [6] Y. Fulishima, S. Wakao, A. Yamashita, and T. Katsuta, "Design optimisation of a permanent magnet synchronous motor by the response surface methodology," Journal of Applied Physics, vol. 91, pp. 8305-8307, May 2002.
- [7] Liu Qinghua, M. A. Jabbar, and A. M. Khambadkone, "Design optimisation of a wide-speed permanent magnet synchronous motors," in Conf. Rec. Power Electronics Machines and Drives, 2002, No.487, pp. 404-408, April 2002.