Kriging assisted Multi-objective Design of Permanent Magnet Motor for position Sensorless Control

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This paper presents a novel formulation of electrical machine design for position sensorless control. Several quantitative characteristic values were defined for measuring the capacity of sensorless control. A multi-objective optimization is formulated for the design of a surface-mount permanent magnet motor in order to improve its sensorless capability without comprising the output torque. A surrogate-model based optimization algorithm is also proposed for reducing the number of evaluations of the computationally expensive finite-element analysis models.

***Index Terms*— Meta Modelling, Multi-objective Optimization, Sensorless Control**

I. Introduction

The recent development in position-sensorless control theory has provided a cost-efficient means for controlling AC permanent magnet machines without the installation of dedicated sensors. The anisotropy of inductance, known as “magnetic saliency”, resulted from the reluctance variation in the machine, can be used to estimate the rotor position [1]. The orientation defined by the anisotropy can be obtained from the high-frequency component of the terminal currents and voltages through injecting additional high-frequency signals [2]. In terms of better controlling, the maximum oscillation of the anisotropy can be used to determine the capability of the machine for sensorless control. In this paper, a multi-objecitve optimization problem is formulated for the design of a permanent magnet machine. The size of the rotor and PM bars are altered in order to find the best value of maximum oscillation without compromising too much the output torque. A kriging surrogate model is employed in conjunction with MOEA to reduce the computational time of the optimization.

II. Sensorless Control Methodology

A. Anisotropic Inductance

The anisotropic inductance can be decomposed into a maximum value of the inductance, denoted as l_x, along x-axis and a minimum value, l_y, along y-axis. Thus, the x and y components of the stator flux linkage of the injected signal can be expressed as:

$$\begin{pmatrix} \delta\psi_x \\ \delta\psi_y \end{pmatrix} = \begin{pmatrix} l_x & 0 \\ 0 & l_y \end{pmatrix} \begin{pmatrix} \delta i_x \\ \delta i_y \end{pmatrix}, \tag{1}$$

where δi is the injected current.

The complex stator flux linkage can be written, according to [2], as:

$$\delta\underline{\psi} = l_\Sigma \delta\underline{i} + L_\Delta \delta\underline{i}^* \text{ with } L_\Delta = l_\Delta e^{j2\varphi_x}, \tag{2}$$

where $\delta\underline{i}^*$ is the complex conjugate of $\delta\underline{i}$ and φ_x is the anisotropy angle defined as the angle between the x-axis and the real axis of the reference frame.

Combining (1) and (2), we have:

$$l_\Sigma = \frac{l_x + l_y}{2} \text{ and } l_\Delta = \frac{l_x - l_y}{2}. \tag{3}$$

l_Σ and L_Δ are both functions of the steady-state current in the stator and the rotor position. The anisotropy angle computed as $\varphi_x = \angle L_\Delta / 2$ can be used as the indicator of the rotor position.

B. Characteristic Values

Three simple quantitative characteristic values are defined for determining the capability of sensorless control.

1) The anisotropy ratio is defined as the average of the ratio during a revolution of the rotor,

$$\chi = \langle l_\Delta / l_\Sigma \rangle. \tag{4}$$

The anisotropy ratio is the proportion of the signals from which the rotor position can be extracted, thus, for a fixed high-frequency current amplitude and a fixed resolution of the current sensors, a higher anisotropy ratio implies a better signal-to-noise ratio in the position estimation.

2) The anisotropy shift is defined as the average of the misalignment during the revolution,

$$\zeta = \langle \varphi_x - \varphi_q \rangle, \tag{5}$$

where φ_q is the angle of the quadrature PM-axis. A large value of the shift implies a strong influence of the steady-state currents that can lead to risks of instability in the drive operations.

3) The oscillating part of the misalignment can be quantified as its maximum amplitude with respect to the shift,

$$\varepsilon = \max((\varphi_x - \varphi_q) - \zeta), \tag{6}$$

These oscillations may cause torque ripples in the control and their sources are the cause of harmonic losses. As a result, this effect should be reduced as much as possible in the machine design.

III. Optimal design of a PM motor

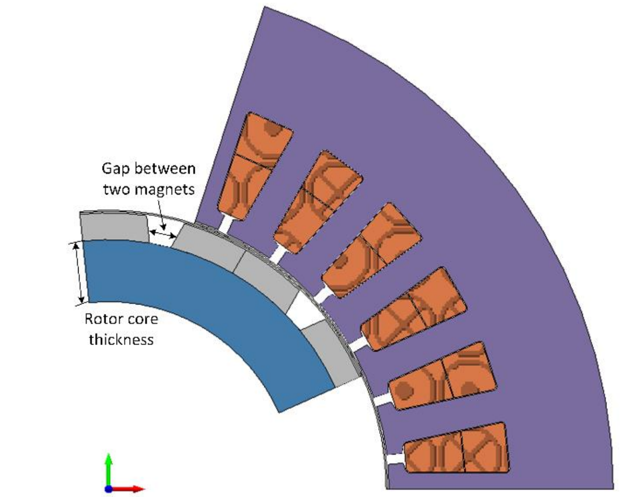

Fig. 1. The model of a PM motor.

Figure 1 shows the layout of a surface-mounted permanent-magnet (SPM) motor. The simulation of the motor is performed in the software MagNet [3] using a 2-D finite-element method (FEM) transient solver from 0 to 19.5 ms, with steps of 50 µs. High-frequency pulsating currents at 10 KHz, with amplitudes of 1 A, along two orthogonal axes, are injected on top of the different steady-state currents in the windings for the calculation of the anisotropic inductances.

The goal of the design is to find the best shape of the permanent magnet for the sensorless control of the machine without compromising the output torque. The design variables are the thickness of the rotor core and the gaps between the magnets. A multi-objective optimization is formulated as:

$$\min \begin{cases} \sum_{i=1}^{6} \varepsilon_i \\ -T_{average} = -\frac{\sum_{i=0}^{19.5} T_i}{N} \end{cases}, \quad (7)$$

where ε_i is the anisotropy maximum oscillation obtained from six different steady-state currents at [0, 10, 20, 30, 40, 50] A and T_{average} is the average of the torques obtained from N transient solutions.

IV. Kriging assisted MOEA

Multi-objective evolutionary algorithms (MOEA) [4] are popular methods for obtained Pareto optimal solutions in multi-objective optimization problems. In order to reduce the number of evaluations of the objective function, surrogate models can be used for function evaluations. A surrogate model fits a function through the evaluated points, and it in turn provides the prediction of the values of future search points. In this paper, we propose to use a kriging [5] model in conjunction with the MOEA. First, the kriging model is built by initial samples generated from a Latin hypercube design, and a MOEA is employed to find the non-dominated solutions using the predicted objective function values. Second, several points (through a screening criterion) on the Pareto front are evaluated using FEM and they are used to update the kriging model. Then the MOEA is resumed on the updated model. This procedure is continued until the budget on the number of FEM evaluations is run out. Compared to the conventional MOEA, the computational cost of the kriging assisted algorithm is small since only the Pareto optimal solutions obtained from each iteration are evaluated using the high fidelity model (e.g. FEM).

V. Numerical results

Figure 2 shows the Pareto front of the solutions to the design problem defined in (7) with 105 FEM evaluations. A trade-off between the average output torque and the sensorless control capability can be observed. From a designer's point-of-view, we may improve the sensorless control of the motor by choosing the design on the leftmost with only 6% loss of the average torque from the design with the maximum torque.

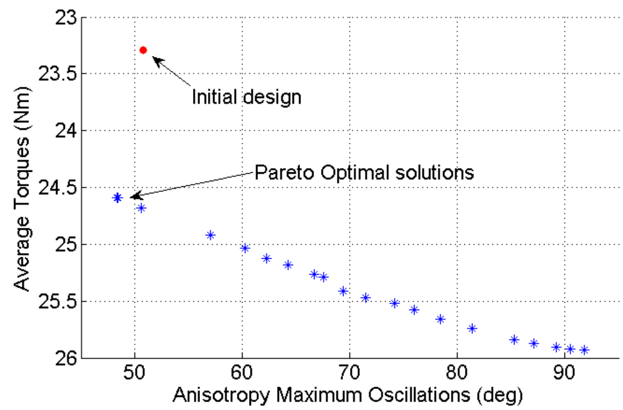

Fig. 2. A Pareto front of the solutions.

VI. Conclusion

This paper discussed about the design of a PM motor for sensorless control based on anisotropic inductance. Several performance indicators were defined for the design of electrical machine for sensorless control. A Pareto front of the trade-off, between sensorless control capability and average torque, solutions were obtained. The full paper will include torque ripple as a third objective and demonstrate the trade-off among the three design objectives.

VII. References

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