ANALYSIS AND CONTROL OF A SMALL FLUX-REVERSAL DOUBLY-SALIENT PERMANENT-MAGNET MOTOR

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Abstract—In this paper, the design and main features of a small three-phase flux-reversal doubly-salient permanent-magnet (FRDSPM) prototype motor are first discussed, and its static and dynamic performance analysis using two-dimensional finite element method is carried out; the cogging torque reduction by rotor skewing and the quasi-sinusoidal waveform of the resulting back-emf are proved through preliminary tests on the built FRDSPM prototype motor. Then, two sinusoidal current control strategies are addressed and experimentally tested for the small FRDSPM motor.

I. INTRODUCTION

The flux-reversal doubly-salient permanent-magnet (FRDSPM) motor belongs to the class of DSPM machines with PMs on the stator. The robustness, easy-to-manufacture structure, high power density and a wide speed range of operation are its main features [1,2] which encouraged us to design and build a ‘proof-of-principle’ small three-phase FRDSPM prototype motor [3], Fig.1. As shown in Fig. 2, this prototype motor has six poles on the stator 1 and eight poles on the rotor 2. Each stator-phase winding 3 consists of two coil sides, which are wound on diametrically-opposed stator poles. The two PMs 4, under the same stator-pole surface, have alternate polarities, so that the PM-induced flux linkage in the stator-phase coils reverses polarity with the rotor movement. The star-connected phase windings come in addition to simplify the control of the small FRDSPM motor by using a conventional three-phase bridge-type voltage-source inverter. Therefore, the electronic commutation and basic driving control of the small FRDSPM motor are similar to those of brushless permanent-magnet motors.

II. SMALL FRDSPM PROTOTYPE MOTOR

Based on the design guidelines given in [4], a small three-phase FRDSPM prototype motor has been designed and built with the main data listed in Table I.

![Fig.1. General view of the prototype small three-phase FRDSPM motor.](image)

![Fig.2. Schematic configuration of a small three-phase FRDSPM motor.](image)

<table>
<thead>
<tr>
<th>Table I</th>
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<tr>
<td><strong>Main data of the small FRDSPM prototype motor</strong></td>
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<td>Rated output power</td>
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<tr>
<td>Airgap length</td>
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<tr>
<td>PM material</td>
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<tr>
<td>PM radial thickness</td>
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<td>Number of turns per coil</td>
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<td>Stator outer diameter</td>
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<td>Rotor pole height</td>
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<td>Stator and rotor stack length</td>
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<td>Stator phase resistance</td>
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<td>Stator phase inductance</td>
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A. Finite element analysis

The commercial software FLUX2D has been used, and a complete finite element analysis (FEA) for the static and dynamic performance of the small FRDSPM prototype motor has been carried out [5].

Fig. 3 gives the FE-computed result for the magnetic flux path when the rotor is aligned to the stator poles of one phase, whose flux linkage is zero at this position. It may be seen from the flux lines in the other two phases, that the leakage flux is quite significant for the FRDSPM prototype motor, mainly around two adjacent PMs of the stator.

The cogging torque (Fig. 4), which appears in the FRDSPM prototype motor, like in other PM machines, has to be reduced if an industrial drive application of it is intended. Therefore, rotor skewing has been chosen for the built FRDSPM prototype motor (Fig. 5).

B. Mathematical model

To point out the merits of the sinusoidal current control of the FRDSPM prototype motor, its basic mathematical model is discussed.

The flux linkage in the small three-phase FRDSPM prototype motor is given by

\[
\psi_{pu} = \left[ L_{u,v} \right] \left[ i_u \right] + \psi_{pnu},
\]

where \( u, v = a, b, c \).

The variation of the flux linkage \( \psi_{pnu} \) created by the PMs of the stator in each phase \( u=a, b, c \) is quasi-sinusoidal. This was confirmed through FEA in [5], Fig. 7.

The stator-phase voltage equation is

\[
v_u = \nu_i + \frac{d\psi_{pu}}{dt},
\]

where \( u = a, b, c \).

The inductances have a sinusoidal variation, and their values are fairly small (Fig. 8). Therefore, the interaction between PM field and stator coil mmf is the dominant component in the FRDSPM motor torque production. The developed electromagnetic torque is thus

\[
T_e = \frac{d(v_u)}{d\theta} = i_i \frac{d\psi_{pnu}}{d\theta}.
\]
III. SINUSOIDAL CURRENT CONTROL
OF THE FRDSPM PROTOTYPE MOTOR

In [7], the experimental results in the case of a 180-electrical-degree conduction-mode feeding scheme for the FRDSPM prototype motor have been provided. The obtained performance being satisfactory (Figs. 9 and 10), one can now associate to this electronic commutation pattern a sinusoidal current control strategy.

In Fig. 11, the experimental set-up to implement the sinusoidal current control for the small three-phase FRDSPM prototype motor is illustrated. The motor load is a small brushed PM motor with speed or current control facilities. Hence, one can perform satisfactorily the dynamic behaviour study of the FRDSPM prototype motor 2.

The command inputs for the IGBTs of the supplying bridge-type three-phase inverter 3 are generated by a dSPACE system in synchronism with the rotor position. An incremental encoder 4 and a hysteresis controller 5 are used to detect the rotor position and to impose the sine-wave phase current, respectively.

Fig. 7. Finite element-computed flux linkage of the small three-phase FRDSPM prototype motor.

Fig. 8. Finite element-computed self (a) and mutual (b) inductances of the small three-phase FRDSPM prototype motor.

Fig. 9. Experimental speed response of the small three-phase FRDSPM motor with 180-electrical-degree conduction-mode feeding scheme.

Fig. 10. Experimental FRDSPM motor stator-phase voltage and current at 500 rpm with 180-electrical-degree conduction-mode feeding scheme.

Fig. 11. Experimental set-up for testing the small three-phase FRDSPM prototype motor.
A. Open-loop sinusoidal current control

The first experiment regards the dynamic behavior of the small three-phase FRDSPM prototype motor in open-loop sinusoidal current. The general block diagram of the control system is shown in Fig.12. The DC voltage is set at 12V, and the current amplitude in stator phases is limited to 10A.

After the motor start-up, a step load is applied and the speed response (Fig.13) and developed torque are evaluated.

The FRDSPM motor speed and torque variations characteristics for different load torques are plotted in Fig.14. Phase voltage and current at low speed and for a load torque $T_L = 0.016 \text{Nm}$ are given in Fig.15. In Fig.16, the torque ripples for different speeds are displayed.

The experimental results prove that the small FRDSPM motor prototype has better torque performance than without current control. However, significant speed and torque ripple exists, especially at low speeds.

By advancing the stator-phase current commutation (at most with 30 electrical degrees) one can increase the motor speed range at higher values, but with the penalty of reduced developed torque.

B. Closed-loop sinusoidal current control

Closed-loop speed and sinusoidal current control is necessary if an industrial drive application is intended for the small FRDSPM prototype motor.

With the same DC-voltage and phase-current data as before, the reference phase currents are generated this time from the motor speed error (Fig.17). The reference speed is set at 1500rpm, and the regulator is designed as a PID controller with $K(s) = 3.5 + 0.0006s + 0.2/s$. The torque load is 0.005Nm and the developed electromagnetic torque is $T_e = 0.01 \text{Nm}$.
In Fig. 18, the FRDSPM motor speed response (for a reference speed of 1500 rpm) is displayed. It is to be noted that the transient response time depends on the motor-load inertia.

Considerable improvement in torque production performance has been observed in this case, i.e. the maximum developed torque is 0.012Nm, which means 20% greater than in the open-loop current control case.

IV. CONCLUSION

In this paper, design considerations and static performance analysis using two-dimensional FEA for a small three-phase FRDSPM prototype motor have been firstly presented. Then, experimental studies in order to establish the dynamic performance of the small FRDSPM motor under sinusoidal current control have been carried out. Two current control strategies have been used, and encouraging results have been obtained for future industrial drive applications of small FRDSPM motors.

REFERENCES


