Magnetic Vibration Analysis of a New DC-Excited Multitoothed Switched Reluctance Machine

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***Abstract*—This paper proposes a combined numerical and analytical approach for magnetic vibration analysis of a new DC-excited multitoothed switched reluctance machine. This method is effective for analyzing the magnetic vibration of all doubly salient magnetless machines. The detailed calculation steps and results are given and discussed.**

***Index Terms*—Magnetic vibration, noise, doubly salient machine, multitoothed machine, switched reluctance machine.**

I. Introduction

In recent years, doubly salient magnetless (DSM) machines are re-attractive due to their cost benefit and acceptable performances [1],[2]. But these doubly salient machines have two obvious disadvantages, namely the torque ripple and noise, which greatly limit their applications [3],[4].

The acoustic noise in DSM machines can be divided into two types, magnetic and mechanical [5]. The corresponding mechanical noise greatly depends on the machine installation and other mechanical factors. The corresponding magnetic noise comes from the radial magnetic attraction between the stator and rotor poles, which is independent of the torque ripple and cogging torque [5],[6]. This attractive force dominates the vibration and hence the machine magnetic noise.

The purpose of this paper is to investigate the magnetic vibration and noise of a new kind of DSM machines, namely the DC-excited multitoothed switched reluctance (DC-MSR) machine. The key of this machine is to incorporate the concept of DC-excited field into the MSR machine, hence forming a new flux controllable, high torque density, low torque ripple and magnetless DSM machine. The time-stepping finite element method (TS-FEM) will be performed to calculate the machine radial force and torque. After that, a series of analytical equations will be formulated to calculate the radial pressure and the sound power of the machine surface. It is worthy to mention that this magnetic vibration and noise analysis approach is suitable for all DSM machines.

II. Machine Design

Fig. 1 shows the structure of the proposed DC-MSR machine, which consists of a 26-pole outer rotor and a 24-pole inner stator. The rotor is made of solid iron which has no permanent magnets (PMs) or copper windings, hence very robust for intermittent operation. The stator accommodates two sets of windings, namely the armature winding and the DC field winding. All windings are located in 6 stator slots, hence reducing the winding ends and shortening the flux paths.

The pole-pair selection criteria of the DC-MSR machine are governed by [1]: $N_{ss} = 2mk$, $N_{sp} = jN_{ss}$ and $N_{rp} = N_{sp} + 2k$, where m is the number of phases, N_{ss} the number of stator slots for armature windings, k the integer, N_{sp} the number of stator poles, j the number of poles per phase per armature slot, and N_{rp} the number of rotor poles. For the proposed machine, $m = 3$, $N_{ss} = 6$, $k = 1$, $N_{sp} = 24$, $j = 4$, and $N_{rp} = 26$.

Since this DSM machine adopts the DC winding to produce the magnetic field, it can utilize all torque producing zones. In this way, it operates like the PM brushless machine and hence is able to provide the high torque output. Moreover, the multitoothed structure can effectively reduce the torque ripple and the cogging torque at low speed operation.

III. Magnetic Vibration Analysis

The calculation steps of the magnetic vibration for the proposed DSM machine are summarized as follow. First, the TS-FEM is used for calculating the radial force of the machine. Then, the instantaneous value of radial pressure is obtained based on the radial force result. So, all the radial-position force and pressure results can be deduced based on the FEM results. Moreover, the values of sound power level due to magnetic radial vibration can be calculated based on the experience equation. The key equations of radial pressure P_r and sound power radial level P_s are governed by [5]: $P_r = F_{rad} / L_{ax} l$ and $P_s = 4L_{ax}\sigma\rho c\pi^3 f_{exc}^2 x^2 R_o$, where F_{rad} is the radial force, L_{ax} the machine axial length, l the circumferential line for pressure calculation, $\sigma = a^2 / (1 + a^2)$ and $a = 2\pi R_o f_{exc} / c$ the coefficients, ρ the material density, c the traveling speed of sound in the medium, f_{exc} the winding excitation frequency, x the radial displacement due to magnetic vibration (usually below 10 μm for kilowatt-order machine), and R_o the outer radius of machine. In addition, the sound power in dB can be expressed as [5]: $L_w = 10\log(2P_s/P_{sref})$, where $P_{sref} = 10^{-12}$ W is the sound power reference level.

IV. Verification Results

Based on the key data in Table I, the machine performances can be calculated by using the TS-FEM. Fig. 2 shows the airgap flux density with 500 A-turn excitation. As expected, there are six sets of 4 columnar poles within 360 degree. Also, with the DC field excitation, its value is up to 1.4 T. Also, Fig. 3 shows the torque performances of the machine with 500 A-turn excitation. It can be seen that its average steady torque is up to 16.0 Nm and the torque ripple is only 19.6%. Meanwhile, the maximum value of cogging torque is 0.8 Nm, which is quite small and only 5% of its steady torque.

Fig. 4 shows the radial force under the rated condition with 500 A-turn excitation. It can be found that the maximum radial force can be up to 1.8 N. Also, the corresponding radial pressure in the stator teeth is shown in Fig. 5. Its value is up to 34 N/m^2, which is not very high.

Table II gives the vibration results of the proposed machine at the radial direction under the rated condition with 500 A-turn excitation. Since the proposed machine is about 850 W, the maximum radial displacement due to magnetic vibration is set at 10 μm. It can be found that the maximum noise appears at the place of machine surface. And the corresponding magnetic noise is only 71.6 dB which is very acceptable when comparing with the conversation noise around 60 dB and the radio noise around 75 dB.

V. Acknowledgments

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TABLE I
KEY DATA OF PROPOSED DC-MSR MACHINE

Outer rotor outside diameter	280.0 mm
Outer rotor inside diameter	211.2 mm
Inner stator outside diameter	210.0 mm
Inner stator inside diameter	40.0 mm
Airgap length	0.6 mm
Axial length	80.0 mm

TABLE II
MAGNETIC VIBRATION RESULTS

Item	**Value**
Maximum Radial displacement	10 μm
Sound power at stator teeth	1.95 W
Noise level at stator teeth	70.9 dB
Sound power at machine surface	2.60 W
Noise level at machine surface	71.6 dB

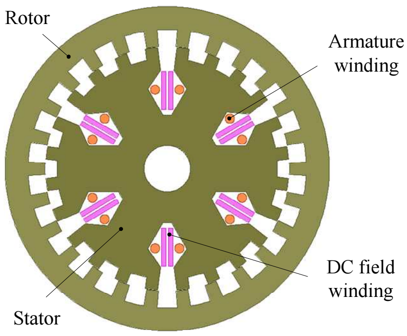

Fig. 1. Proposed DC-MSR machine.

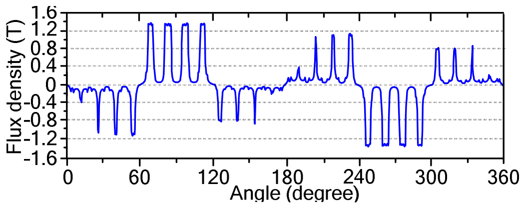

Fig. 2. Airgap flux density waveform.

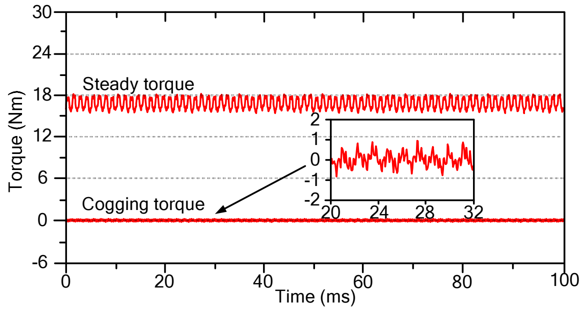

Fig. 3. Torque performances.

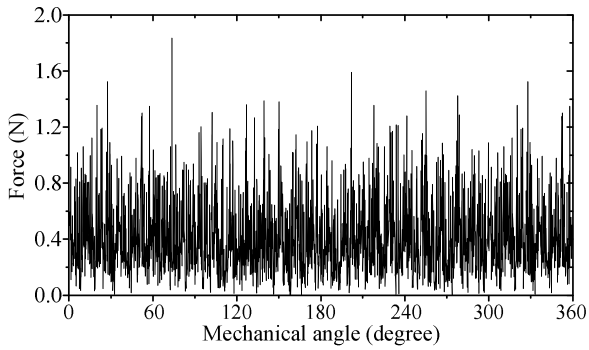

Fig. 4. Radial force at stator teeth under rated condition.

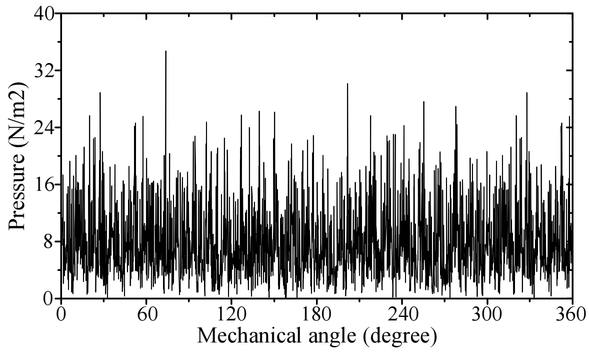

Fig. 5. Radial pressure at stator teeth.

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