Performance of Fractional-Slot Winding PM Machines due to Un-even Coil Turns and Asymmetric Design of Stator Teeth

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ABSTRACT

PM machines in which slot number and pole number combination differs by one have to be configured with asymmetric winding pattern in order to maximize it back-emf performance. However, this asymmetric winding configuration inherently results an unwanted Unabalanced Magnetic Force (UMF). Investigations of electromagnetic performance of fractional-slot asymmetric winding PM machines using 2-D Finite-Element Analysis are presented. The investigations are mainly driven by the effort of minimizing the UMF. By employing techniques such as non-uniform number of coil turns in every tooth and asymmetric design of stator tooth, the UMF are expected can be minimized. The investigations show that the radial component of UMF has greater effect than the tangential component on the UMF itself. In all proposed techniques, a slight reduction of machine torque performance is inevitable.

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1. INTRODUCTION

The advantages of Permananet Magnet (PM) machines i.e. simpler construction as field windings are replaced by permanent magnet, high torque density due constant magnetic field produced by permanent magnets and flexible mode of ac or dc operation has attracted electric machine designer to consider the PM machines as an alternative instead of other conventional topologies of electric machine. However, some configurations of PM machine may naturally exhibit an UMF. This unwanted phenomenon is due to asymmetric distribution of phase coils. Integral-slot winding PM machines equipped with concentrated, overlapping windings are theoretically free from UMF due to symmetric distribution of phase coils. However, the UMF is naturally inevitable in Fractional-slot winding PM machines when the slot number, *Ns* and pole number, *2p* differs by one. For other machine, which *Ns* and *2p* differs by two, the UMF dissappears due to symmetric distribution of phase coils. The unsymetric and symmetric distributions of phase coils in the respective *Ns/2p* combination are inevitable as there is a need to achieve balanced emf vector in specified machines [1],[2]. Unbalance Magnetic Force (UMF) or Unbalance Magnetic Pull (UMP) are interchangeably used to define the total force that acting on the rotor. The phenomenon exists due to factors such as asymmetric pattern of phase windings and eccentric position of stator or rotor leading to a distorted airgap flux-density [3],[4]. Early detection of UMF due to similar number of slots and poles in which respective machines are presumed perfectly built have been reported in [5]-[7]. The UMF at no-load and on-load conditions respectively are directly influenced by the odd slot-number and asymmetric distribution of phase winding. Significant phenomenon of UMF in the machines equipped with asymmetric distribution of phase windings in internal and external rotor motors have been presented analytically [8],[9].

It is shown that the interaction between tangential and radial force components result either in a relative large or small UMF. An eccentric rotor position due to unbalanced rotor mass, imperfect magnetization of permanent magnets also result a relative large UMF. The UMF due to rotor ecentricity and imperfect magnetization of permanent magnets in the external and internal rotor topologies are comprehensively reported in [10]-[15]. A comparison of unbalanced magnetic force due to rotor eccentricity in between SPM and IPM machines equipped with integral-slot windings have been reported in [16]-[18]. A reduction of slot-opening does not eliminate the unbalanced magnetic force completely but it can reduce the force ripple [14],[19]. However, an implementation of tooth-notch can reduce an UMF significantly [20]. Basic test rigs to measure UMF in external and internal rotor machines have been proposed in [7],[21]. Furthermore, investigations of vibration and noise based on the characteristics of frequency harmonics of unbalanced magnetic force via Finite-element Analysis and analytical models have been reported in [12],[14],[22].

2. UNBALANCED FORCE CALCULATION

The radial and tangential force densities formulated from Maxwell stress tensor are as follows:

$$f_r = \frac{1}{2\mu_o}\left(B_r^2 - B_\alpha^2\right) \quad (1)$$

$$f_\theta = \frac{1}{2\mu_o}\left(B_r^2 B_\alpha^2\right) \quad (2)$$

where B_r and B_α are the radial and tangential components of flux-density and μ_o, is the free space permeability. The UMF acting on the rotor surface is calculated by integrating the force density component i.e. Fx and Fy over the respective surface area as follows [7]:

$$F_x = \frac{r l_{eff}}{2\mu_o}\int_0^{2\pi}\left[\left(B_\alpha^2 - B_r^2\right)\cos\alpha_r + 2B_r B_\alpha \sin\alpha_r\right]d\alpha_r \quad (3)$$

$$F_y = \frac{r l_{eff}}{2\mu_o}\int_0^{2\pi}\left[\left(B_\alpha^2 - B_r^2\right)\sin\alpha_r - 2B_r B_\alpha \cos\alpha_r\right]d\alpha_r \quad (4)$$

where r, l_{eff}, and α_r are the radius of middle airgap, effective rotor axial length, and relative rotor angular postion respectively. For a microscopic view, equations (iii) and (iv) can be extended equations (2a) and (2b) into radial and tangential elements as follows:.

$$F_{rx} = \frac{r l_{eff}}{2\mu_o}\int_0^{2\pi}\left(B_\alpha^2 - B_r^2\right)\cos\alpha_r d\alpha_r \quad (5)$$

$$F_{\alpha x} = \frac{r l_{eff}}{\mu_o}\int_0^{2\pi} 2B_r B_\alpha \cos\alpha_r d\alpha_r \quad (6)$$

$$F_{ry} = \frac{r l_{eff}}{2\mu_o}\int_0^{2\pi}\left(B_\alpha^2 - B_r^2\right)\sin\alpha_r d\alpha_r \quad (7)$$

$$F_{\alpha y} = -\frac{r l_a}{\mu_o}\int_0^{2\pi} 2B_r B_\alpha \sin\alpha d\alpha_r \quad (8)$$

The resultant of UMF is then deduced as:

$$UMF = \sqrt{F_x^2 + F_y^2}$$

3. ASYMMETRIC PHASE WINDING MACHINE EQUIPPED WITH NON UNIFORM NUMBER OF TURNS PER COIL

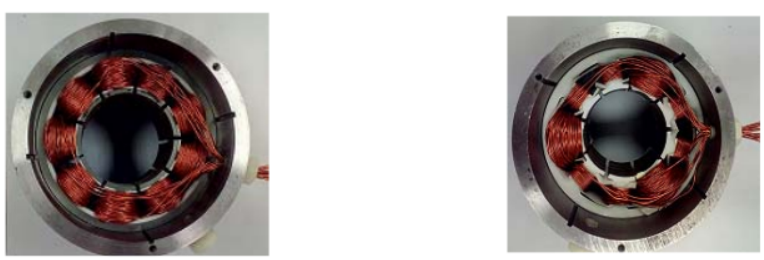
By using Finite-element analysis, the UMF in asymmetric phase windings machines of such configuration as shown in Figure 1 i.e. 9-slot/8-pole, 9-slot/10-pole, 15-slot/14-pole and 15-slot/16-pole have been investigated in [23]. The predicted results have confirmed that the UMF in the subjected machines can be reduced by employing non-uniform number of turns per coil in every respective phase. For validation purpose, prototype of 9-slot/8-pole machine which design specifications are tabulated in Table 1 is fabricated as shown in Figure 2. A comparison between previous simulated results and new measured results will be verified in the later section.

Table 1. Design specifications for 12-slot/10-pole machine

Parameter	Specifications
Supply voltage (V)	36
Rated torque (Nm)	10
Rated speed (rpm)	250
Stator outer diameter (mm)	120
Rotor outer diameter (mm)	60
Axial length (mm)	55
Magnet thickness (mm)	3
Airgap length	1
Slot Opening	2.9
Tooth tip thickness	3.1
Rated current (A)	10
Magnetization type	Parallel
Operating mode	BLDC

a) 9-slot stator b) 15-slot stator

Figure 1. Machine cross-sectional area



a) normal coil turns b) un-even coil turns

Figure 2. Prototype stator of 9-slot

4. ASYMMETRIC PHASE WINDINGS MACHINE EQUIPPED WITH ASYMMETRIC STATOR TEETH

Various stator designs of 9-slot/8-pole machine are shown in Figure 3. These designs are created from the motivation of previous study which uneven number of turns is considered for the reduction of UMF. Due to the additive behavior between UMF components in the 9-slot/8-pole machine, the machine becomes the main subject as it exhibit bigger UMF than the 9-slot/10-pole machine [8]. From previous section, it should be noted that the 9-slot stator is designed such that; i) all middle tooth of each phase are widened, ii) the thickness of all adjacent teeth equipped with less no of turns per coil are reduced and iii) eccentric design is applied to all adjacent teeth that equipped with less no of turns per coil.

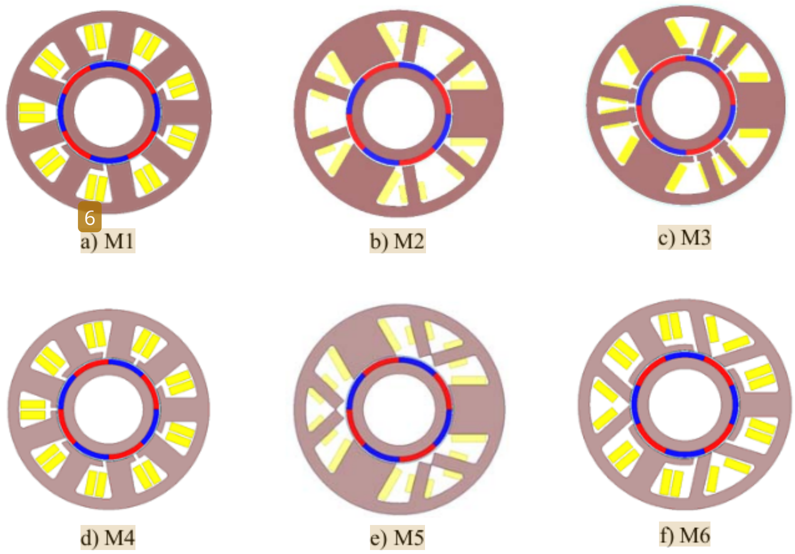
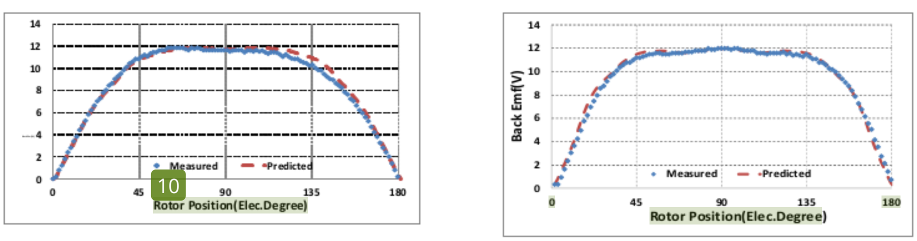


Figure 3. Various stator designs for 9-slot/8-pole machine

5. RESULTS AND ANALYSIS

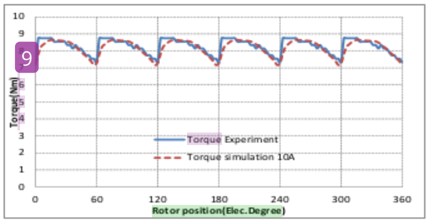
5.1. Influence of non-uniform numbers of turn per coils

Comparisons between predicted and measured phase back-emf and output torque in 9-slot/8-pole machine are shown in Figure 4 and Figure 5 respectively. A good agreement between predicted and measured results of phase back-emf is achieved. Some distortions on these results are due to the mechanical constraints during testing such as un-aligned coupling between machine shaft and torque sensor and non-uniform machine airgap thickness due to unbalanced rotor mass. These results verified the reduction of UMF that has been investigated earlier in [23] as shown in Figure 6. Figure 7 compares the predicted vibration in 9-slot machines. Although 9-slot/10-pole machine is not the main subject in this paper, it is worth to show that bigger vibration exist in 9-slot/8-pole machine than the 9-slot/10-pole when non-uniform numbers of turn per coil is employed. In other way, severe deformations of stator structure exist in the 9-slot/machine.

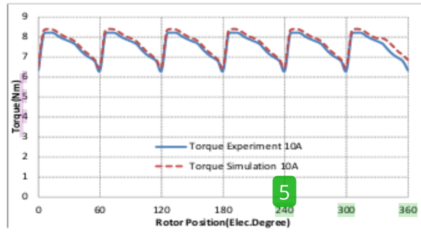


a) original design b) optimized design

Figure 4. Phase back-emf of 9-lot/8-pole machine – predicted vs measured

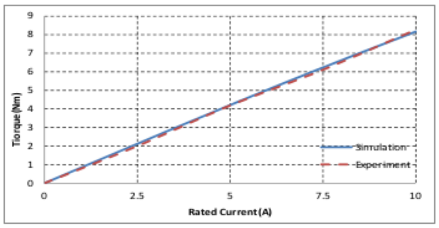


i) original design

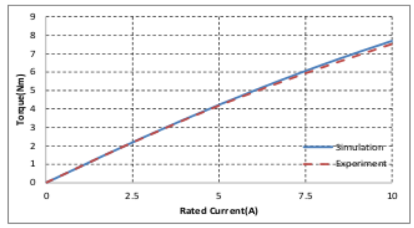


ii) optimized design

a) Torque profile

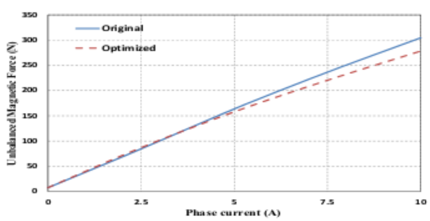


a) original design

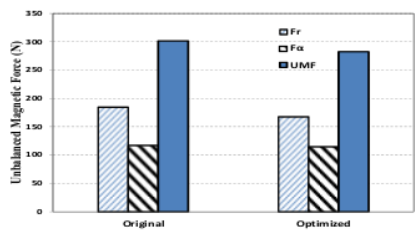


b) optimized design

Figure 5. Phase back-emf of 9-lot/8-pole machine – predicted vs measured

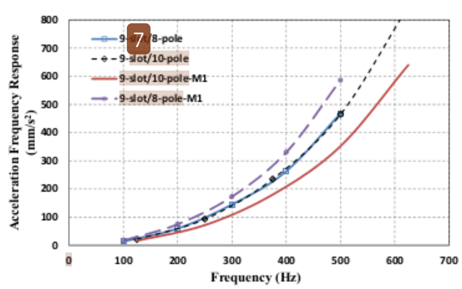


a) UMF vs phase current



b) UMF components

Figure 6. Predicted UMF in 9-lot/8-pole machine [23]

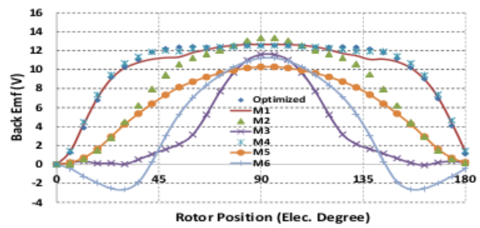


a) UMF vs phase current b) UMF components

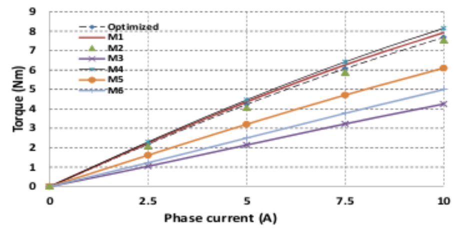
Figure 7. UMF in 9-lot/8-pole machine

5.2. Influence of asymmetric stator teeth

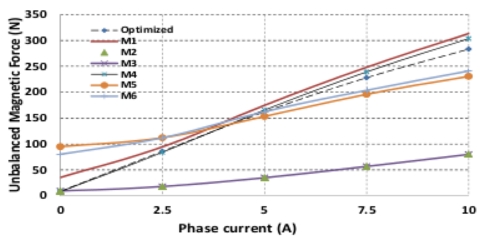
Predicted results due to asymmetric stator teeth in 9-slot/8-pole machine are shown in Figure 7. For phase back-emfs as shown in Figure 7a), there are only two designs, M1 and M4 that have similar waveform with the optimized design of 9-slot/8-pole. The missing shoes or tooth tip on M1 design results a more little dented on it peak. In term of torque performance, three designs i.e. M1, M2 and M4 have similar waveform as the optimized one but the M4 design is the best candidate as it results similar average torque as shown in Figure 7b). The UMF profiles shown in Figure 7c) results no significant change of UMF when asymmetric stator is employed. The M4 results smaller cogging torque than the reference design as tiny slot-opening or more closed-slot design is employed.



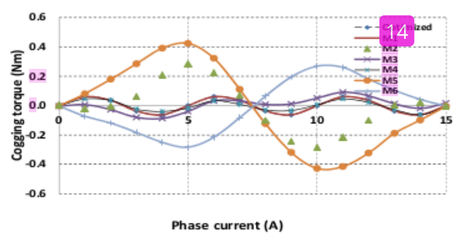
a) Phase back-emfs



b) Torque



c) UMF



d) Cogging torque

Figure 7. Predicted results due to asymmetric stator teeth in 9-slot/8-pole machine

6. CONCLUSION

From the investigation, the implementation of non-uniform number of turns per coil with proper allocation of coil turn can reduce UMF in asymmetric phase winding machines. The proposed technique is partially verified by the comparison between predicted and measured phase back-emf and output torque respectively. In other way, no significant reduction of an UMF when asymmetric stator teeth is employed.In term of vibration, an UMF has direct correlation with the machine vibration, however different pole number results different vibration trend even a reduction of an UMF is achieved.

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