Dynamic Analysis of Rotor Eccentricity in Switched Reluctance Motor with Parallel Winding

Jian Li, Dawoon Choi and Yunhyun Cho
Dept. of Electrical Engineering, Dong-A University,
840 Hadan 2 dong, Saha-gu, Busan, 604714, KOREA

Abstract

This paper presents dynamic characteristics in Switched Reluctance Motor (SRM) with rotor eccentricity and proposes the reduction method of rotor eccentricity effects by the different winding connections. These characteristics investigations are computed by 2D transient magnetic FEM analysis coupled with external circuits. The radial and unbalance magnetic force in the stator, which is the main exciting force of the vibration, is calculated using Maxwell stress method and compared with the performance characteristics according to the serial and parallel connections of windings. The influence of winding method counteracting unbalance forces on the rotor vibration behavior is estimated by the current waveforms of the paralleled paths under rotor eccentricity.

Key words—parallel winding, rotor eccentricity, switched reluctance motor

1. Introduction

The switched reluctance motor (SRM) have been attractive to the industry for several decades. Their advantageous characteristics, e.g. robustness, permanent magnetic-free rotor, thermal robustness, simple stator windings, easy manufacture. Design choice for high power density requires a relatively smaller size air gap. This will also force the machine into a highly saturated operation, accompanied by high radial forces causing mechanical vibration of stator core and housing in radial direction [1]. The air gap of SRM in fractional horsepower applications is usually 0.2mm-0.4mm which is much smaller than PM motors and induction motors and is more sensitive to rotor eccentricity. Due to the fabrication tolerances a relative eccentricity between the stator and rotor of 10% is common [2]. It is therefore essential to keep the rotor eccentricity to a minimum by using strict control of manufacturing and assembling procedures. However, for economic reasons, and especially for mass produced machines, it is not always possible to do so. The air gap nonuniformity or rotor eccentricity has been studied in [2]-[4] mainly about the torque and flux density. However, the connection methods of coils were ignored and little attention in literature has been paid to unbalanced magnetic force (UMF) which will cause vibration. The unbalanced magnetic force is too considerable to neglect because it can severe the vibration by agitate additional vibration modes and twist the shaft or even cause the bearing broken. This paper mainly investigated the characteristics of a SRM with relative eccentricity rotor and firstly reveals that torque characteristic changed with winding methods and it has more influence on magnet force than torque. Proper connection of coils can reduce torque ripple greatly, balance the radial force on symmetrically distributed stator poles and restrain the magnetic force acting on shaft.

In this paper, a 12/8 SRM with relative eccentricity between the stator and rotor axes is studied dynamically using a two – dimensional (2-D) finite-element analysis (FEA). Various parallel connections of coils were modeled in the external circuit. Current profiles of paralleling branches, torque profile and unbalanced magnetic forces are obtained and compared. The proposed winding method which has two parallel branches with neighboring coils in series and an equalizer is found to reduce the unbalance forces on the rotor vibration behavior.

2. Modeling of SRM with relative eccentricity

2.1 Motor specifications

The SRM studied in this paper is a three phase 12/8 motor. One phase has four stator poles and four coils as denoted A1, A2, A3, and A4….The cross section and distribution of coil groups are shown in Table I. The specifications of motor are given as illustrated in Fig. 1.

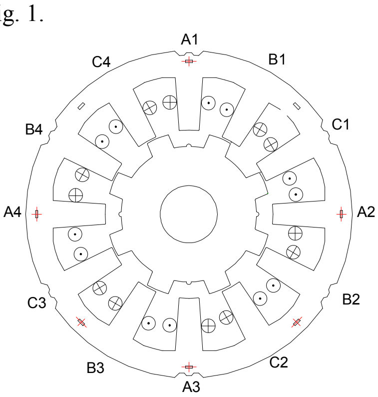


Fig. 1. Cross section of the analyzed motor and distribution of coil groups.

Table 1 Motor specifications

Item	Values	Item	Values
No. of phases	3	Shaft diameter(mm)	24
No. of stator/rotor poles	12/8	Stack length (mm)	80
Stator diameter (mm)	135	Turns per pole	100
Rotor diameter (mm)	68	Wire (mm)	0.7
Stator pole arc (degrees)	14	DC voltage (V)	310
Rotor pole arc (degrees)	16	Rated Torque (N.m)	4.9
Air-gap length (mm)	0.3	Rated Speed (rpm)	3600

2.2 Relative eccentricity

The percentage of relative eccentricity is shown in Fig. 2 and defined by

$$\varepsilon = \left(\frac{r}{g}\right) \times 100$$

(1)

where ε is the relative eccentricity between the stator and rotor axes, g is the air gap length in the case of the uniform air gap or no eccentricity and r is the eccentricity in the vertical direction. The rotor axis of the motor analyzed here is 0.1mm above the stator thus a relative eccentricity 33% is caused.

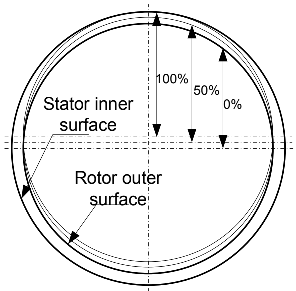


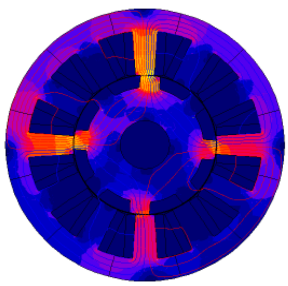
Fig. 2. Illustration of relative eccentricity rotor.

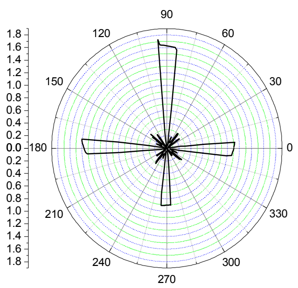
The two-dimensional transient magnetic FEA model of the prototype motor is created in Credit FLUX2D FE analysis package. A FEA model is formed by three main parts. The first part is geometry including a relative eccentricity of 33%. The second is an electrical circuit, which represents connections, couplings and electrical parameters. The last part includes material properties, such as electric and magnetic characteristics. An asymmetric bridge converter with two transistors per phase is used in the external circuit. The control algorithm is developed in Malab/Simulink and coupled with FLUX2D.

3. Motor performance according to winding method

3.1 Proposition of parallel winding method

The proposition for parallel paths can be explained as follows: Fig. 1 shows the schematic diagram of a 12/8 SRM stator winding arrangements having concentric-type pole windings. Let us assume that the rotor is shifted upwards. If the windings in each phase are connected in series (no parallel paths), e.g. A1, A2, A3 and A4 are in series and carry the same current, then the magnetic flux produced by A1 would be larger than that produced by A3 as shown in Fig. 3. The magnetic flux per pole produced by coil A3 is less than that by coil A1 since the flux in A3 has to pass through a larger air gap. In other words, the inductance of coil A3 is less than that of coil A1. Thus the magnetic force acting on A1 is larger than that on A3. When this unbalanced magnetic force is applied to rotor, it tends to pull the shaft upward and make the rotor eccentricity more severely.


(a)



(b)

Fig. 3. (a) Unbalanced flux density and flux contours when minimum air gap is under Pole A1; (b) Distribution of flux density on air gap.

The inductances of coils are different due to different air gaps. With the same turn on angle, the currents excited in parallel paths rise to different peak values. If windings A1, A2, A3 and A4 are connected in parallel, the currents flowing in different paths can be equalized automatically. Four winding connections are proposed for comparison as shown in Fig. 4:

1) two parallel paths with neighboring coils in series and without an equalizer;
2) two parallel paths with opposite coils in series and without an equalizer;
3) adding an equalizer to 1);
4) adding an equalizer to 2);

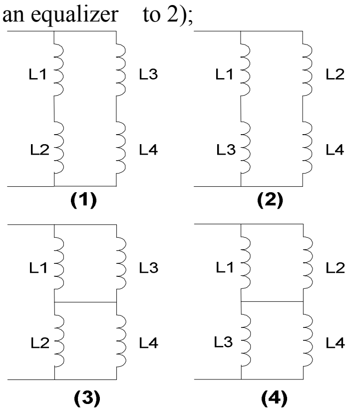


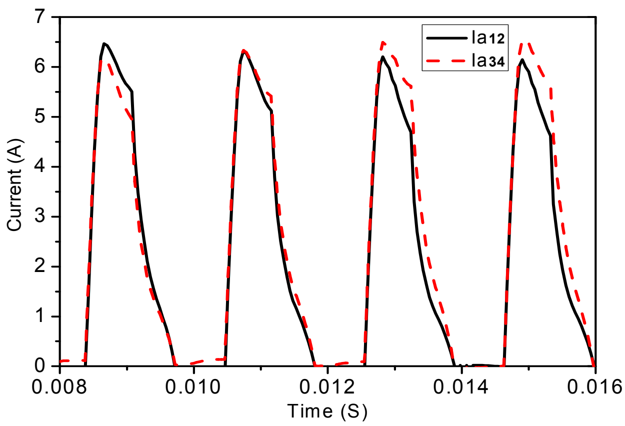
Fig. 4. Coil connections of different winding methods.

3.2 Comparison of Results

Four models with above winding methods were simulated with same turn on, off angles. The rotor rotates in 'CCW' direction at a constant speed of 3600rpm.

1) Currents in Parallel Branches and Torque

The rotor rotates 180° from initial position (t = 0). The minimum air gap also rotates from pole A1 to A3. As shown in Fig. 5. (a), (c) and (d), the currents rises to different peak value due to unequal inductances which restrain current rising. In Fig. 5. (b), currents in parallel paths are almost the same but their peak values vary a lot. The current balancing effect doesn't appear with this connection. This is because the parallel branch contains two coils at opposite position, the air gaps and inductances of individual paths are equal to each other. The torque profiles are given in Fig. 6 which shows that torque curve of Method 2 contains larger torque ripple while the other methods have similar torque curve with healthy motor. So far, it is verified that proper parallel connection of coils can balance the currents in parallel paths and restrain torque ripple caused by eccentricity rotor while the other methods will make it worse.

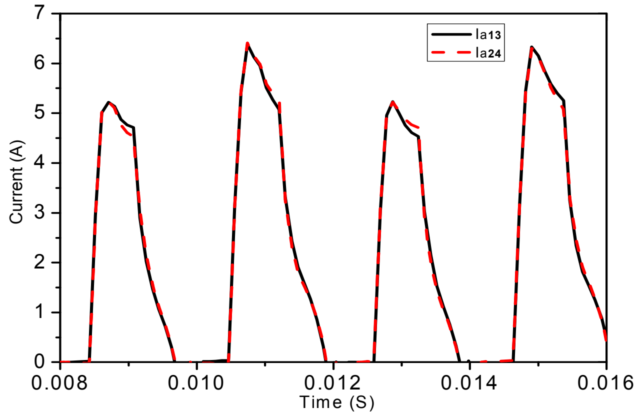


(a)

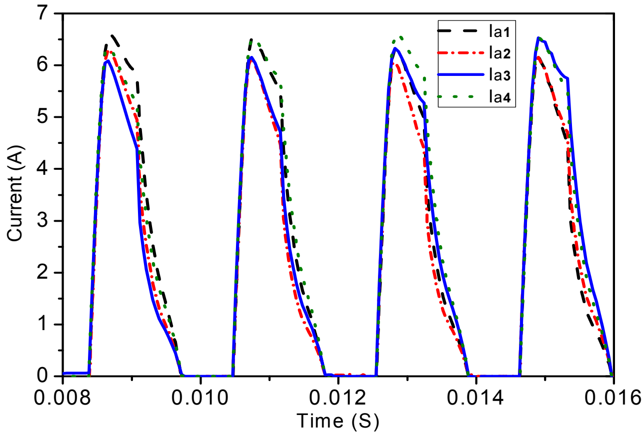
2) Unbalanced Magnetic Forces

Rotor eccentricity generates UMF that acts between the rotor and stator. This force can be resolved into two components: the radial one and the tangential one. Acting roughly in the direction of the shortest air gap, the UMF tries to further increase the eccentricity magnitude and may cause serious damage to the machine or even the whole drive. Besides, UMF also leads to vibration and acoustic noise. From calculation results, the tangential force is quite smaller than radial one, thus it's neglected here. From Fig. 5 (a), (c) and (d), it can be observed that the parallel windings can effectively reduce the UMF magnitude by adjusting currents in parallel branches. The UMF acting on the rotor and shaft is obtained as shown in Fig. 7. Compared with serial windings, method 3 mostly effectively reduces the UMF while method 2 seems to enlarge it on the contrary. So method 2 has to be definitely avoided.

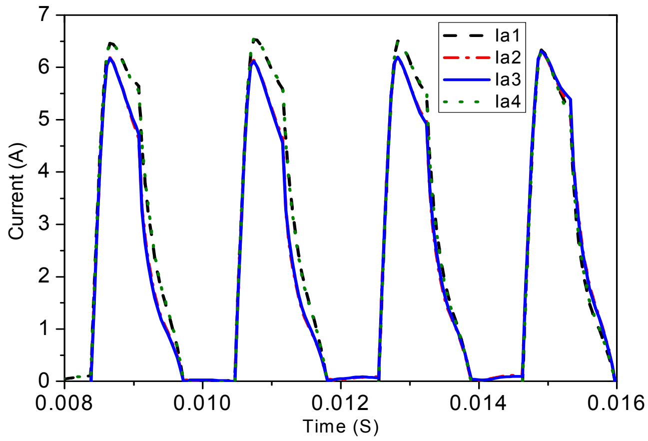
As shown in Fig. 4-(3), the current flowing in A1 would be larger than that in A3 since the inductance voltage drop per unit current in A1 is smaller than that in A3. The large current in A3 will offset, to a certain extent, the unbalance in magnetic flux distribution, and hence will reduce the UMF and noise emission.



(b)



(c)



(d)

Fig. 5. Currents in parallel branches of different winding methods: (a) method 1; (b) method 2; (c) method 3; (d) method 4.

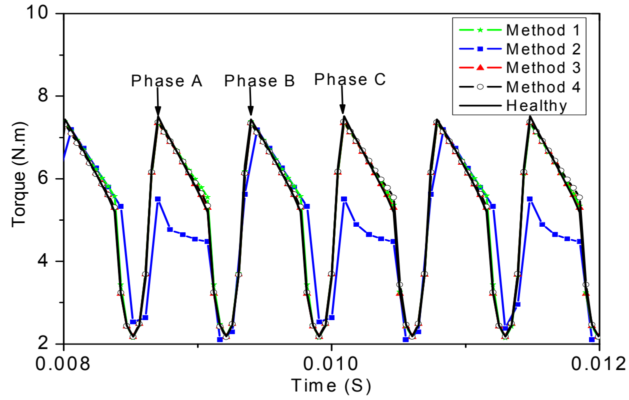


Fig. 6. Torque profiles of different winding methods and healthy motor.

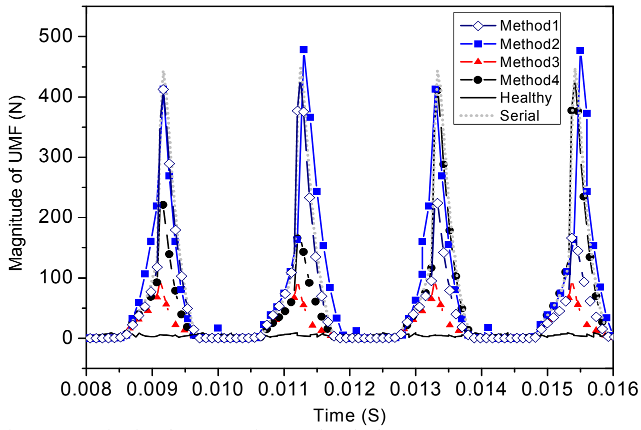


Fig. 7. Magnitude of UMF acting on the shaft.

4. Conclusion

In this paper, a 12/8 SRM with relative eccentricity between the stator and rotor axes is studied dynamically using a 2D FEA. Four parallel connections of coils were modeled in the external circuit. Current profiles of paralleling branches, torque profile and UMFs are obtained and compared. It is verified that proper parallel connection of coils can balance the currents in parallel branches and restrain torque ripple caused by eccentricity rotor while other method will make it worse. The proposed winding method which has two parallel branches with neighboring coils in series and an equalizer is found to effectively reduce the UMF on the rotor.

Acknowledgment

This work has been supported by Power Conversion System Center (2007-0192), which is funded by KETEP(Korea Institute of Energy And Resources Technology Evaluation And Planning).

Reference

[1] D.E. Cameron, J.H. Lang, S.D.Umans, "The origin and reduction of acoustic noise in doubly salient variable-reluctance motors", IEEE Transactions on Industry Applications, vol.28, no.6, pp.1250~1255, November/December, 1992.

[2] N.K. Sheth, K.R. Rajagopal, "Effects of nonuniform airgap on the torque characteristics of a switched reluctance motor", IEEE Transactions on Magnetics, vol 40, issue 4, part 2, pp.2032~2034, July, 2004.

[3] David G. Dorrell, I. Chindurza, and C. Cossar "Effects of rotor eccentricity on torque in switched reluctance Machines", IEEE Transactions on Magnetics, vol 41, Issue 10, pp.3961~3963, Oct. 2005.

[4] J. Faiz and S. Pakdelian, "Finite-Element Analysis of a Switched Reluctance Motor Under Static Eccentricity Fault", IEEE Transactions on Industry. Applications vol 42, Issue 8, pp.2004~2008, Aug. 2006.