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Analysis of Electromagnetic Force Ripple on the Rotor of a Bearingless Synchronous Reluctance Motor

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Abstract

This paper presents the analysis of electromagnetic forces on the rotor of a synchronous reluctance motor under self-levitation operation. Due to the presence of flux barriers, the ripple content in the torque and levitation force brings a major concern. Different schemes of torque ripple reduction have been taken as a reference and their effects on the levitation forces are investigated. The paper explores the advantages and disadvantages of rotor skewing, stator winding chording and asymmetric flux barrier design on the levitation forces. Finite element analysis has been used with current source, and the computations are performed by the angular sweep of the rotor varying with time. Skewing helps to damp the slot harmonic when the rotor is skewed for one slot pitch. Multi-slice model has been used to determine the skewing effect. A significant improvement in the reduction of levitation force ripple has been observed when the rotor is skewed. The chording slightly reduces the levitation force ripple. The asymmetric flux barrier design shows improvement in the reduction of torque ripple, however the levitation force has additional harmonics due to the asymmetry which is not a good option when used for the bearingless motor operation.

Keywords : Bearingless, Synchronous reluctance motor, Levitation force, Ripple analysis, Skewing, Chording, Asymmetric rotor

1. Introduction

Synchronous reluctance motors (SynRM) are considered as an effective, robust, and economical solution for high speed applications. However, due to the rotor anisotropy, torque ripple appears as a major problem in the operation of SynRM. There are different methods to reduce the torque ripple of a motor such as skewing of stator and rotor, chording of stator winding and using asymmetric flux barrier design.

Skewing the rotor for 1 slot pitch has been found as an effective solution to mitigate the ripple as reported in (Vagati, et al., 1998). In (Koshi, et al., 2011), a bearingless surface mounted permanent magnet motor is skewed, and the torque ripple was reduced successfully. There was, however no significant improvement in the force ripple characteristics. In (Chiba & Asama, 2012), the problem of skewing in bearingless operation of induction motor has been investigated. Due to the induced rotor currents, which travel in a skewed path, axial forces have been observed especially during high acceleration and retardation. Some possible solutions for this problem have been presented in (Chiba & Asama, 2012) and (Wang, et al., 2015). In (Bomela & Kamper, 1999), the chording of different combination has been tested on a SynRM and the effect on torque ripple has been studied. Chording helps to reduce the torque ripple as more sinusoidal waveform of flux linkage around the airgap is developed compared with winding without chording. Using asymmetric rotor has been presented in (Bianchi, et al., 2009), where in the first case, two laminations with different type of flux barriers have been used and put radially one after another in the stack, and in the second case, different flux barrier have been designed

in one lamination. In (Howard, et al., 2015), the flux barriers have been designed asymmetric under one pole. Both studies showed the effectiveness of using asymmetric rotor in the torque ripple reduction. The basic idea is that the higher order rotor harmonics in the torque ripple can compensate each other because of the asymmetry.
Bearingless operation of a SynRM can be performed by using 4 pole - 2 pole winding combination as presented in (Chiba, et al., 1991). However, the multiple flux barriers cause considerable ripple in the levitation force. To the best knowledge of the authors, no study has been conducted so far about the effect of skewing, chording and asymmetric rotor design of a reluctance motor on the electromagnetic forces during the bearingless operation. In this paper, the bearingless operation of a SynRM with rotor skewing, stator winding chording and asymmetric rotor design are analyzed and compared.

2. Effects of Skewing on the Forces

In this analysis we supply the winding with sinusoidal current waveform at the fundamental frequency only, so that all the harmonics analyzed in this paper refer to space harmonics. The bearingless SynRM has a traditional 4 pole winding which generate the torque, and a 2 pole winding which in interaction with the 4 pole winding generates the suspension force for the bearingless operation (Mukherjee, et. al, 2015). The machine design parameters are presented below in Table 1.

Table 1 Machine design parameters.

Power	5.4 kW
Main winding current	32 A
Additional winding current	1 A
Length of the motor	195 mm
Power factor	0.56
Frequency , Connection	50 Hz , Star
Number of pole pairs	2
Stator outer diameter	235 mm
Stator inner diameter	145 mm
Airgap	1 mm
Number of slots	36
Parallel branches	2

The skewing of the rotor is done by using multi-slice techniques. All the 2 D electromagnetic finite element (FE) analysis in this paper have been carried out using COMSOL Multiphysics 5.2 by angular sweep of the rotor varying with time. Both main and additional winding are supplied with current source. For n slices, to skew the rotor for an angle α, each slice is made by rotating the rotor by α/(n+ 1), and the skewing effect is calculated by averaging the forces from 1st slice to n slices at each time step (Urresty, et al., 2010). As the eddy current passing through the rotor is negligible, there will be no effect on axial forces due to skewing. So, a multi-slice model is sufficient to describe the skewing problem in this case. The rotor is skewed for 0.9, 1.0, and 1.1 slot pitch to compare the effects of different skewing strategies on the levitation force and disturbance force at no load condition as presented in Fig. 1.

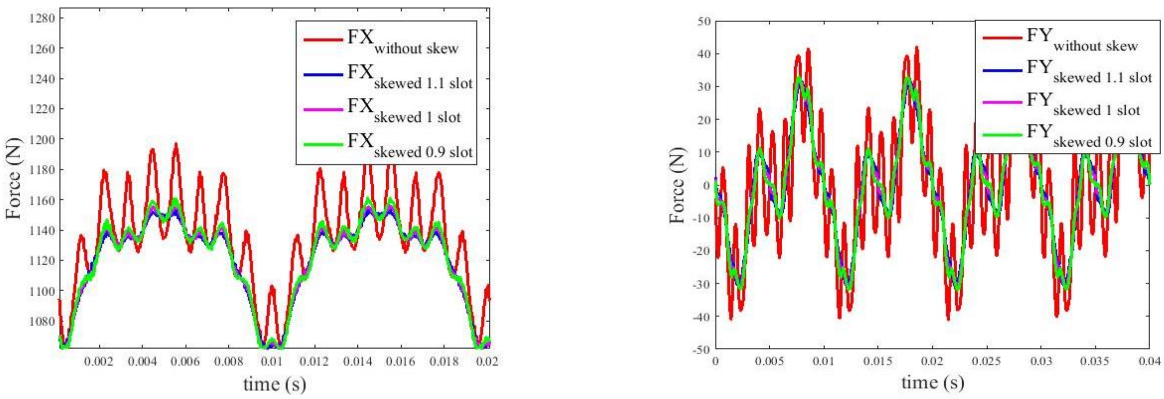

Fig. 1 Electromagnetic forces with and without skewing under sinusoidal current source at no-load operation.

These results are computed with 10 slices to model the continuous skewing at no-load. In this analysis, FX is the force in the direction of levitation and FY is the force perpendicular to the direction of levitation, which can be also considered as disturbance force. It can be seen that 0.9, 1 and 1.1 slot skewing reciprocate close result and it has reduced the ripple in the electromagnetic forces by reducing the space harmonics. The Fourier spectrum of the forces for continuous skewing at no-load operation are shown in Fig 2. All the Fourier transformations in this paper have been done by computing 10 time periods with 400 steps in each time period by angular sweep of the rotor varying with time. It can be observed that the harmonic order of 24, 32 and 36 has been reduced considerably after skewing. The average value of forces are 1122, 1124 N, 1118 N and 1120 for 1slot skewing, 1.1 slot skewing, 0.9 slot skewing and non-skewing cases respectively.

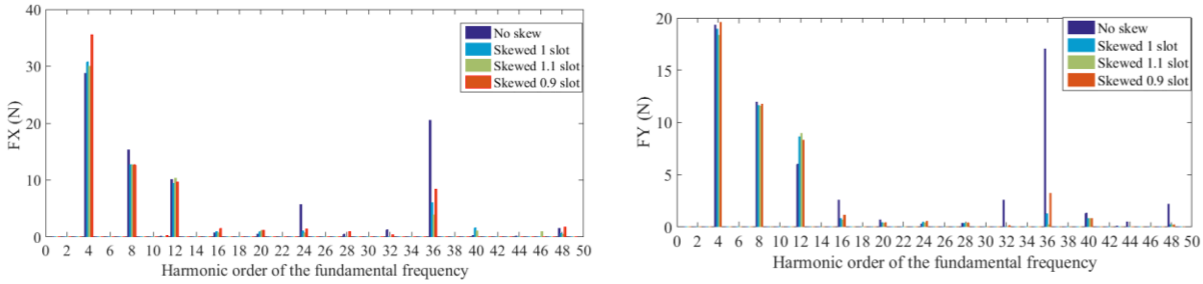

Fig. 2 Levitation force spectrum comparison for skewed and non-skewed rotor under sinusoidal current source at no-load operation.

3. Effects of Chording on the Forces

The main winding is chorded 8/9 to improve the magnetomotive waveform. The force ripple is 5.3 % without chording and 5.25 % with chording which means no significant improvement has been achieved by chording. The Fourier spectrum of the levitation forces for both cases at no-load operational point are shown in Fig. 3. Similar issue with torque ripple has been reported in (Bomela & Kamper, 2002) where chording brings no significant improvement in the reduction of torque ripple in a synchronous reluctance motor. A simple explanation is that the harmonics from the rotor flux barrier are so significant that the lower order harmonics of the flux are attenuated by the flux barrier. Hence, we cannot improve the force profile much by using chording. The average value of the forces are 1165 and 1120 for chorded and full pitch winding respectively.

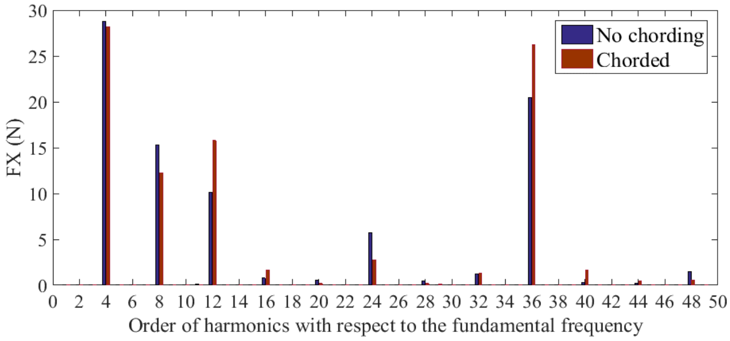

Fig. 3 Levitation force spectrum comparison for chorded and full pitch stator winding under sinusoidal current source at no-load operation.

4. Impact of Asymmetric Rotor on the Torque and Forces

Asymmetric rotor are designed to cancel certain harmonics in accordance with the designer's wish. As we have observed the slot harmonic plays a critical role, we wish to reduce the 36^{th} harmonic in the torque of the motor through introducing a suitable asymmetry in the flux barrier design. Also certain higher order harmonics in the torque waveform can be dampened by the asymmetry. In Fig. 4, a symmetric and an asymmetric rotor flux barriers are presented. These designs have been used for the comparison.

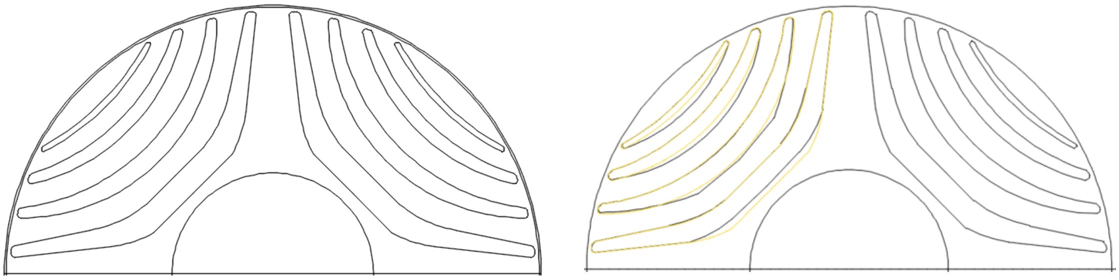

Fig. 4 From left, symmetric and asymmetric rotor ½ cross section under two pole of the motor. The other half of the cross-section of the rotor is identical with respect to the center line. In the asymmetric rotor cross section, the symmetric barriers are shown in yellow colour which are changed for the asymmetric design.

It can be observed that the flux barriers of one pole of the half of the cross-section of the asymmetric rotor is different than those of the other pole. The motor is loaded and the torque profiles of both designs are compared to ensure the objective of asymmetry are met. Results of this comparison is shown in Fig. 5. The torque ripple is 11 % for symmetric rotor and 10.3 % for asymmetric rotor. The average value of the torque are 35.2 Nm and 35.3 Nm for symmetric and asymmetric rotor respectively. Now, with this same design we compare the levitation forces on the rotor at no load. It can be clearly seen that asymmetry does not help. Instead it increases the force ripple with additional harmonics as shown in Fig. 6. This is due to the reason that in the torque computation most of the even space harmonics cancel each other where as in the force calculation the even space harmonics do not cancel each other during the global integration of the magnetic flux density over the airgap. Additional harmonic of the order of 2, 6, 10, 14 clearly substantiate the claim that additional space harmonics due to asymmetry arise in the levitation force waveform. The average value of the forces are 1120 N and 1124 N for the symmetric and asymmetric rotor respectively.

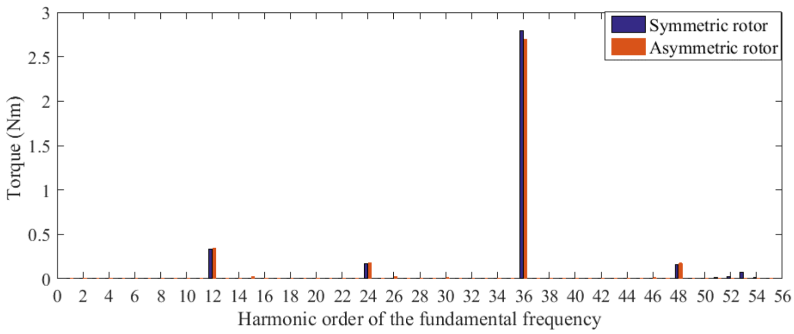

Fig. 5 Torque spectrum comparison for symmetric and asymmetric rotor under sinusoidal current source at rated load operation.

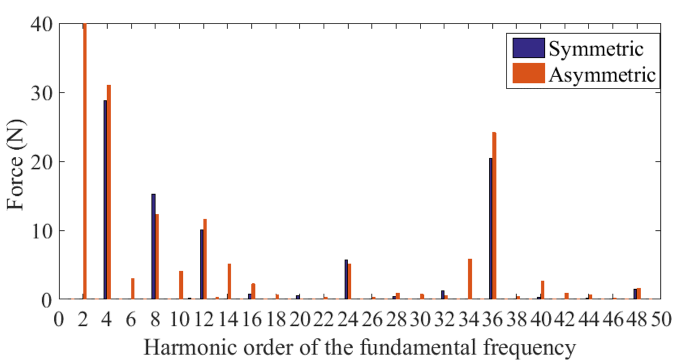

Fig. 6 Levitation force spectrum comparison for symmetric and asymmetric rotor under sinusoidal current source at no load operation.

5. Conclusion

From the above analysis, it can be observed that skewing is the most effective method to minimize the electromagnetic force ripple on the rotor in comparison to chording and asymmetric rotor. In this analysis skewing, chording and asymmetry are investigated separately, however the effect of skewing can be different under different chording scheme and asymmetry in the rotor. More simulations are needed to investigate if any harmonics can be minimized with some chording scheme. Since the harmonics from the flux barriers are so high, chording cannot help much to improve the force profile alone. With the asymmetric rotor, it has been observed that the same kind of asymmetry which improve torque profile does not necessarily improve the electromagnetic force profile on the rotor. However more investigation are needed on asymmetric rotor with different scheme of asymmetry to find if the force ripple can be minimized.

Acknowledgements

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References

Vagati, A., Pastorelli, M., Franceschini, G. and Petrache, S. C., Design of low-torque-ripple synchronous reluctance motors, IEEE Transactions on Industry Applications, Vol. 34, pp. 758-765, July/Aug. 1998.

Koshi, Y., Ooshima, M., Uddin, M. N. and Kitada, H., Improvement of Rotational Torque and Suspension Force by Winding Arrangement in a Bearingless Motor Drive for a Solid-Liquid Separator, IEEE International Electric Machines & Drives Conference (IEMDC), pp 1415-1420, 2011.

Chiba, A. and Asama, J., Influence of rotor skew in induction type bearingless motor, IEEE Transactions on Magnetics, Vol. 48, No. 11, pp 4646-4649, Nov 2012.

Wang, L., Bao, X., Di, C. and Li, J., Effects of novel skewed rotor in squirrel-cage induction motor on electromagnetic force, IEEE Trans. Mag., Vol. 51, No. 11, Nov 2015.

Bomela, X. B. and Kamper, M. J., Effect of stator chording and rotor skewing on average torque and torque ripple of reluctance synchronous machine, Africon, 1999 IEEE, Cape Town, 1999, Vol. 2, pp. 687-690.

Bianchi, N., Bolognani, S., Bon, D. and Dai Pre, M., Rotor flux-barrier design for torque ripple reduction in synchronous reluctance and PM-assisted synchronous reluctance motors, IEEE Transactions on Industry Applications, Vol. 45, No. 3, pp. 921-928, May-June 2009.

Howard, E., Kamper, M. J. and Gerber, S., Asymmetric flux barrier and skew design optimization of reluctance synchronous machines, IEEE Transactions on Industry Applications, Vol. 51, No. 5, pp. 3751-3760, Sept.-Oct. 2015.

Chiba, A., Rahman, M. and Fukao, T., Radial force in a bearingless reluctance motor, IEEE Trans. Mag., Vol. 27, No. 2, pp. 786-791, March 1991.

Mukherjee, V., Pippuri, J., Saarakkala, S. E., Belahcen, A., Hinkkanen, M. and Tammi, K., Finite element analysis for bearingless operation of a multi flux barrier synchronous reluctance motor, 18th International Conference on Electrical Machines and Systems (ICEMS), 2015, Pattaya, 2015, pp. 688-691.

Urresty, J. C., Riba, J. R., Romeral, L. and Garcia, A., A simple 2-D finite-element geometry for analyzing surface-mounted synchronous machines with skewed rotor magnets, IEEE Transactions on Magnetics, Vol. 46, No. 11, pp. 3948-3954, Nov. 2010.

Bomela, X. B. and Kamper, M. J., Effect of stator chording and rotor skewing on performance of reluctance synchronous machine, IEEE Transactions on Industry Applications, Vol. 38, No. 1, pp. 91-100, Jan/Feb 2002.