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Influence of Main Winding Connection on Vibration and Acoustic Noise of Bearingless Switched Reluctance Motors

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Abstract: Fundamental principle and control strategy of main winding square-wave current of bearingless switched reluctance motors are introduced. Since rotor eccentric exists when operation of BSRM, influence of eccentric on air-gap flux distribution with different main winding connections is analyzed. As pulsation of radial force is origin of vibration and noise of SRM, a radial force mathematic model is introduced considering magnetic saturation. Winding currents are different with different main winding connections even under the same load, thus radial forces of stator poles are different. Influence of main winding connections on vibration of stator is researched and the conclusion of all parallel of main winding coils is in favor of vibration reduction is draw.

Keywords: Bearingless Motor, Switched Reluctance Motors (SRM), Winding Connection, Magnetic Radial Force, Vibration and Acoustic Noise

Introduction

Switched reluctance motors (SRMs) have been already used in some special applications because of their superior performances such as fail safe, robustness, low inertia and the ability to operate in high temperatures. However, significant vibration and noise limit their application. Frequency domain analysis show that pulsation of magnetic radial force acting on stator poles is the source of vibration and noise of SRM, especially when the harmonic frequencies of radial force coincide with natural frequencies of stator, vibration and noise increased significantly [1].

Bearingless switched reluctance motors (BSRMs), as a special kind of SRM, also face vibration and noise problem. Moreover, large unbalanced magnetic attraction force acting on stator in radial direction, caused by rotor eccentric due to mechanical errors, worsens radial deformation of stator, therefore, vibration and noise becomes more serious. Especially at very high speed, magnetic attraction force will not only increase difficulty of controlling and lower suspension accuracy, but also intensify deformation of stator yoke and deteriorate vibration. Therefore, study of vibration and noise suppression is very important.

A magnetic radial force mathematic model of BSRM considering magnetic saturation is derived in paper [2]. Three load control strategies are researched, from the view of control of BSRM, to explore control strategy in favor of vibration suppression in paper [3]. A feed-forward compensator for vibration caused by rotor eccentric is proposed in paper [4], however, its method using to measure rotor magnetic center is more complicated. In this paper, influence of main winding connection ways on vibration caused by rotor eccentric is researched. The results are significant for quiet operation and stable suspension of BSRM.

Control Strategy and Magnetic Radial Force Model

Control Strategy. A three-phase 12/8 pole structure BSRM is taken as example to explain winding structure in this paper. BSRM uses concentrated windings and there are two sets of windings on each salient pole of stator composed of main winding and suspension winding. Take phase A as example, main winding N_{ma} consists of 4 coils on 4 stator poles connected in a certain serial-parallel way. Suspension winding N_{sa1}, N_{sa2} in α and β direction consists of 2 coils on 2 radial opposite stator poles connected in serial, respectively. Suppose only one phase conducts at any time, suspension force generated by phase A can be written as [5]:

$$F=\sqrt{K_{f0}^2(\theta)i_{ma}^2(i_{sa1}^2+i_{sa2}^2)} \tag{1}$$

And the average torque by phase A is:

$$T_{avg}=G_{tm1}(\theta_m)i_{ma}^2+G_{ts1}(\theta_m)\frac{F^2}{i_{ma}^2}\,. \tag{2}$$

Where, i_{ma}, i_{sa1} and i_{sa2} are currents of A-phase of main winding and suspension windings in α and β direction respectively, θ_m is advance angle, defined as the angle of winding current conduction region midpoint ahead of the stator and rotor axis aligned position, $K_{f\,0}(\theta)$, $G_{tm1}(\theta_m)$ and $G_{ts1}(\theta_m)$ are functions of motor size parameters and rotor position angle θ.

In the single-phase conduction control strategy, each phase winding current conduction width is a fixed 15deg, therefore, the turn-on angle is $\theta_{on}=-\pi/24-\theta_m$ and the turn-off angle is $\theta_{off}=\pi/24-\theta_m$. Thus, in case of determined structure parameters, the key to control the motor is to control winding currents and advance angle. However, by a given T_{avg} and F can not only determine i_{ma}, i_{sa} and θ_m three control parameters. Control strategy of main winding square-wave current use "seek the maximum advance angle θ_m" as constrains, aiming to reduce negative torque so as to minimize torque ripple, to determine the only identified control parameters.

Magnetic Radial Force. By combining Maxwell stress tensor method with magnetic circuit method, taking magnetic saturation into account, radial force of stator pole can be derived and expressed as:

$$\begin{aligned}F_{sr}=\frac{h\mu_0}{2}\Bigg\{&\frac{1}{l_0^2}\left[U(1-\frac{1}{2e_m})+\frac{l_mB_{sat}}{2\mu}-\sqrt{\frac{l_m^2B_{sat}^2}{4\mu^2}+U\frac{B_{sat}}{e_m\mu}(l-\frac{l_m}{2})+\frac{U^2}{4e_m^2}}\right]^2(\frac{\pi r}{12}-r|\theta|)\\&+\frac{1}{l_{f1}^2}\left[U(1-\frac{1}{2e_f})+\frac{l_fB_{sat}}{2\mu}-\sqrt{\frac{l_f^2B_{sat}^2}{4\mu^2}+U\frac{B_{sat}}{e_f\mu}(l-\frac{l_f}{2})+\frac{U^2}{4e_f^2}}\right]^2(l_0+2r|\theta|)\Bigg\}\,.\end{aligned} \tag{3}$$

Where, $U=N_mI_m+N_sI_s$, $\mu=\mu_0\mu_r$, $l=l_0+l_s+l_r$, $e_m=1+l_0/l$, $e_f=1+l_{f1}/l$, $l_m=l+\mu\cdot l_0/e_m/\mu_0$, $l_f=l+\mu\cdot l_{f1}/e_f/\mu_0$.

In the above equations, N_m, N_s are turns of main winding and suspension winding. I_m, I_s are currents of main winding and suspension winding. h is length of core, r is radius of rotor, μ_0 is air permeability, μ_r is differential permeability of core material, B_{sat} is the saturation magnetic flux density of core material, θ is angle of rotor pole deviation from stator pole, l_0 is average length of air-gap, l_s, l_r are heights of stator pole and rotor pole, respectively. l_{f1} is average length of edge flux path. Suppose the edge flux path is a circular trajectory, average length of edge flux path can be expressed as $l_{f1}=l_0+\pi r|\theta|/4$.

Theoretical Analysis

By selecting different numbers of serial-parallel branch of main winding coils, different connections can be formed. Take phase A as example, Fig.1~ Fig.3 show three typical kinds of main winding connections: all serial, all parallel and two-parallel-two-serial.

Ignoring mutual inductance of interphase, A-phase magnetic equivalent circuit of three kinds of connections can be expressed by Fig.4. Where, M_{a1}~ M_{a4} are magneto motives, P_{a1}~ P_{a4} are reluctances composed of air-gap reluctance, stator pole reluctance and rotor reluctance, Φ_{a1}~Φ_{a4} are air-gap flux.

Due to the air-gap is very small, electronic-magnetic force between stator and rotor can be approximately calculated by Maxwell formula:

$$F = \frac{1}{2\mu_0} B^2 S = \frac{1}{2\mu_0} \frac{\Phi^2}{S}. \tag{4}$$

Where, B is magnetic flux density, S is the effective cross-section area of magnetic path.

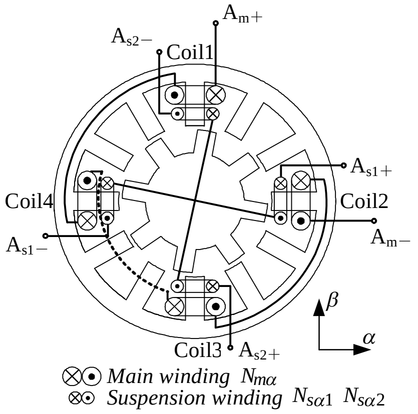


Fig.1 All serial

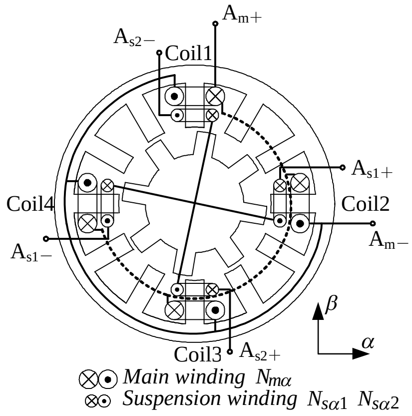


Fig.2 All parallel

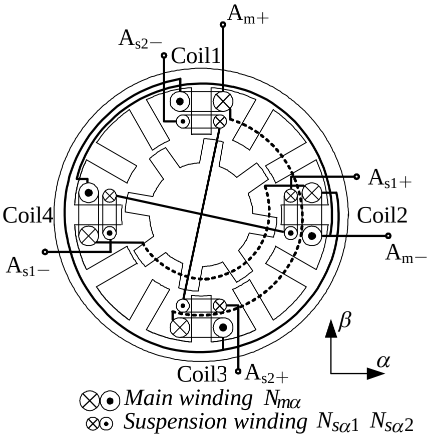


Fig.3 Two-parallel-two-serial

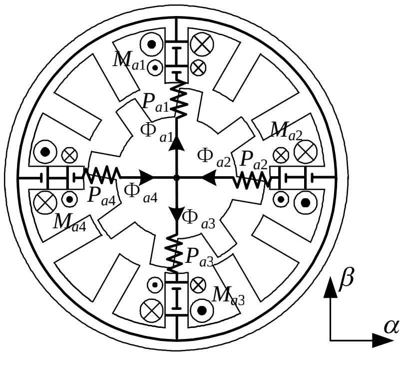


Fig.4 *A*-phase magnetic equivalent circuit

Given the radial load of BSRM is self-weight of rotor and is along the negative direction in β-axis, then 4 air-gap flux are:

$$\Phi_{a1} = (N_m i_{ma1} + N_s i_{sa1}) \cdot P_{a1}. \tag{5}$$

$$\Phi_{a2} = (N_m i_{ma2} + N_s i_{sa2}) \cdot P_{a2}. \tag{6}$$

$$\Phi_{a3} = (N_m i_{ma3} - N_s i_{sa3}) \cdot P_{a3}. \tag{7}$$

$$\Phi_{a4} = (N_m i_{ma4} - N_s i_{sa4}) \cdot P_{a4}. \tag{8}$$

Where, i_{ma1}~ i_{ma4}, i_{sa1}~i_{sa4} are currents of main winding and suspension winding, respectively. Due to serial of suspension winding coils in every direction, then

$$i_{sa1} = i_{sa3},\ i_{sa2} = i_{sa4}. \tag{9}$$

It is clear that $\Phi_{a1} > \Phi_{a3}$, $\Phi_{a2} = \Phi_{a4} (i_{sa2} = i_{sa4} = 0)$ and $F_{a1} > F_{a3}$, $F_{a2} = F_{a4}$ according to equation (4). Therefore, suspension force is produced in the positive β-axis.

Suppose that rotor has magnetic eccentric so that the mass center of rotor deviates from its geometric center. Use variable e representing rotor eccentricity and it is positive while towards the positive direction in β-axis, otherwise negative. Assume here e is positive and is small enough compared with air-gap length, then

$$P_{a1} > P_{a2} = P_{a4} > P_{a3}\,. \tag{10}$$

i) When main winding coils are all serial, $i_{ma1}=i_{ma2}=i_{ma3}=i_{ma4}$. From equations (4) ~ (10) it can be known that Φ_{a1} increases while Φ_{a3} decreases due to rotor eccentricity, therefore, F_{a1} increases while F_{a3} decreases. In this way, force acting on rotor is not only the active controlling suspension force, but also unbalance magnetic attraction force in the positive β-axis, which will make controlling more difficulty and imprecise. At the same time, upper and bottom stator poles suffer from great difference radial force because of interaction force, thus deformation and vibration of stator will increase.

ii) When main winding coils are all parallel, voltage of each coil is equal, that is

$$U_{ma1} = U_{ma2} = U_{ma3} = U_{ma4}\,. \tag{11}$$

Ignoring resistance of coils, voltage balance equation of any main winding coil is

$$U_{maj} = \frac{d\psi_{aj}}{dt} \text{ and thus } \psi_{a1} = \psi_{a2} = \psi_{a3} = \psi_{a4}\,. \tag{12}$$

$$\psi_{aj} = \int U_{maj} dt = N_m \Phi_{maj} \pm N_s \Phi_{smaj} = N_m^2 i_{maj} \cdot P_{aj} \pm N_s^2 i_{saj} \cdot P_{aj}\,. \tag{13}$$

Where, ψ_{aj}, Φ_{maj} and Φ_{smaj} are total flux linkage, self inductance flux and mutual inductance flux of main winding, respectively. From equations (9), (10) and (13) we could know that $\Phi_{sma1}>\Phi_{sma3}$, $\Phi_{ma1}<\Phi_{ma3}$, therefore

$$i_{ma1} < i_{ma3}\,,\ i_{ma2} = i_{ma4}\,. \tag{14}$$

It is clear that with resistance of main winding ignoring, currents in the 4 parallel main winding coils are not uniform when rotor has magnetic eccentric. Current of main winding coil along eccentric direction is smaller than the opposite one, so difference of radial force acting on this pair of stator poles decreases, thus resulting in vibration reduction of stator.

iii) When main winding coils are two-parallel-two-serial connection, that is, coils in one direction are parallel, then serial with coils in the other direction, voltage balance equations are

$$U_{m-coil1} = U_{m-coil3} = U_1\,,\ U_{m-coil2} = U_{m-coil4} = U_2\,. \tag{15}$$

Like the situation of all parallel, flux linkage of parallel coils is equal, therefore, unbalance magnetic attraction force and vibration due to eccentric could be reduced. It is worth noting that with rotor eccentric inductance of 4 main winding coils are different, which will result in $U_1 \neq U_2$, thus flux linkage of adjacent main winding coils and consequently radial force of adjacent stator poles are unequal.

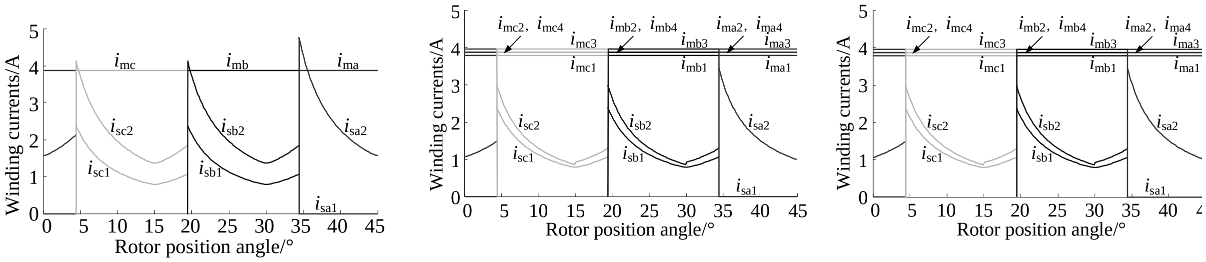
Simulation Analysis

Winding currents. Simulation is based on the above 12/8 pole structure BSRM and its parameters are: outer diameter of stator core is $D_1=120mm$, inner diameter of stator pole is $D_2=60.5mm$, outer diameter of rotor is $d=60mm$, axial length of core is $h=75mm$, average air-gap length is $l_0=0.25mm$, main winding turns is $N_m=14$, suspension winding turns is $N_s=17$, core material of stator and rotor is non-oriented steel sheet 35W250, its saturation flux density is $B_{sat}=1.77$T and relative permeability is $\mu_r=4100$.

Assumed rotor eccentricity is $e=0.01mm$ in β-axis, and the simulation conditions are: (1) three phases conduct by turns every 15deg, commutation is done instantaneously, (2) given torque is $T_{avg}=0.05N\cdot m$, (3) given suspension force is $F=49N$. Then wingding currents i_{ma}, i_{sa1} and i_{sa2} can be calculated based on control strategy of main winding square-wave current under different main winding connection. Simulation results are given in Fig.5.

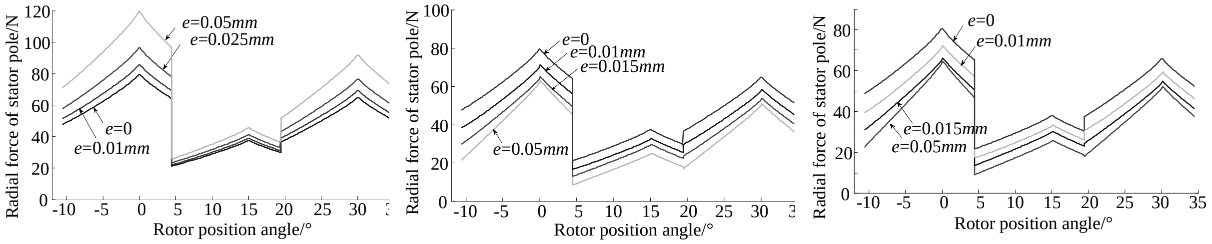
Radial force of stator. Radial force acting on stator can be obtained by substituting the above winding currents into equation (3). Fig.6 shows the radial forces in air-gap 1 with three different kinds of main winding connection ways.

It can be seen from Fig.5~ Fig.6 that under the same conditions of rotor eccentricity and output of BSRM, currents and radial force of upper stator pole are different with different main winding connection ways. Currents in coil1~coil4 are clearly equal when all serial and radial force of stator pole is the largest, so it will excite the largest vibration and noise of stator. While all parallel or two-parallel-two-serial, current in coil3 is smaller than coil1 and radial forces of stator pole are almost the same. Moreover, as rotor eccentricity increases, radial force increases when all serial while decreases when all parallel or two-parallel-two-serial. It is precisely because with rotor eccentric from magnetic centre, currents in the 4 main winding coils of A-phase are inconsistent when parallel, which results in the reduction of unbalance magnetic attraction force, thus vibration and noise will be smaller than that of all serial.



（a）all serial （b）all parallel （c）two-parallel-two-serial

Fig.5 Winding currents



（a）all serial （b）all parallel （c）two-parallel-two-serial

Fig.6 Radial force of stator pole

Summary

In this paper, magnetic radial force acting on stator pole is calculated under different main winding connection ways. The results show that under the same conditions of load, vibration and noise of BSRM is smaller when 4 main winding coils of one phase are all parallel or two-serial-two-parallel than when they are all serial. With 4 main winding coils of one phase all parallel or two-serial-two-parallel vibration and noise will be suppressed when there is rotor magnetic eccentricity. A disadvantage of main winding coils all parallel or two-serial-two-parallel is that suspension force is smaller than all serial which is not conducive to rotor shaft suspension. Thus they are suitable for the occasion of empty radial load or light radial load which requires the motor operation quietly.

References

[1] Cameron.D.E, Lang.J.H, Umas.S.D: The origin of acoustic noise in variable-reluctance motors. IEEE Industry Applications Society Annual Meeting, October 1989:108-115.

[2] Yang Yan, Deng Zhiquan, Cao Xin, et al. Magnetic Radial Force Model of Bearingless Switched Reluctance Motors. Electic machines and control, 2009,13 (3):377-382.

[3] Yang Yan, Deng Zhiquan, Zhang Qianying, et al. Effects of Control Strategies on Stator Vibration of Bearingless Switched Reluctance Motors. Acta Aeronautica ET Astronautica Sinica, accepted.

[4] Masatsugu Takemoto, Akira Chiba, Tadashi Fukao. A Feed-forward Compensation for Vibration Reduction considering Magnetic Attraction Force in Bearingless Switched Reluctance Motors. 7th Int. Symp. on Mag. Bearings, August 23-25, 2000, ETH Zurich.

[5] Yang Gang, Deng Zhiquan, Cao Xin, e1 al. Advanced Angle Calculating Method for Winding Currents in Bearingless Switched Reluctance Motor. Journal of Nanjing University of Aeronautics & Astronautics, 2009,41(2):159-164.