MODELING AND DETECTION OF ECCENTRICITY AND DEMAGNETIZATION FAULTS IN BRUSHLESS PERMANENT MAGNET DC MOTORS BY VIBROACOUSTIC BEHAVIOUR

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***Abstract**: Vibrations and noise in electrical machines are directly related to the characteristics of the radial forces on one hand, and mechanical behavior on the other [1,8]. The characteristics of these forces depend on the air gap flux density, and they are influenced by other factors such as stator slots and poles, saturation level, winding type and certain faults. The aim of this work is to investigate the effect of eccentricity and demagnetization faults on electromagnetic noise generated by the external surface of PM synchronous machine. For this purpose an analytical electromagnetic vibroacoustic model is developed. Many parts of the analytical model are validated using FEM simulations. The results confirm the effect of eccentricity and demagnetization fault in generating some low modes radial forces.*

***Key words:** rotor eccentricity, demagnetization, noise and vibration, radial magnetic force, mode of vibration, natural frequency, acoustic radiation efficiency, noise spectrum.*

1. Introduction

Brushless direct current (BLDC) motors are one of the motor types rapidly gaining popularity. As name implies, BLDC motors do not use brushes for commutation; instead, they are electronically commutated. BLDC motors have many advantages over brushed DC motors and induction Motors [5]. These motors are used in many applications such as traction with variable speeds in transportation. However, the operation of theses motors is accompanied by unavoidable production of noise especially in the presence of faults. Several works was published in last years about noise and vibration of PM motors [1,3,4]. However less research has been observed in vibroacoustic behaviour of these motors in relation with faults and specially demagnetization [2]. The major contribution of this research is the effect of rotor faults such as eccentricities and demagnetization rotor magnet which create fault signature in the motor sound power level spectrum. For this purpose an analytical electromagnetic vibroacoustic approach to calculate the sound power level radiated from the PM motor is presented. To investigate the effect of eccentricity and demagnetization faults on magnetic noise, we introduce the two phenomena in the calculation of magnetic flux density in the air gap. The effect of eccentricity is introduced through the expression of the relative permeance while the effect of demagnetization is introduced by modeling the field created by the rotor magnets in the presence of a partial demagnetization defect. Analytically the magnetic flux density in the air gap of PM brushless machine is the product of magnetic flux density generated by rotor magnet (or stator winding) and the relative permeance which take into account the effect of slots [6,7], After the model calculates also the natural frequency of the stator and frame, stator yoke and frame displacements corresponding to the frequency of forces, and noise in the surrounding medium. All parts of the analytical model are validated by FEM simulations, this allows us to adjust and improve the analytical model.

2. Air gap magnetic flux density and radial forces

Analytically the magnetic flux density in the air gap of PM brushless machine is the product of magnetic flux density generated by rotor magnet (or stator windings) and the relative permeance functions which take into account the effect of slots and eccentricity faults.

$$\begin{aligned} B(\theta,t) &= \left[B_{magnet}(\theta,t) + B_{w}(\theta,t)\right]\bar{\lambda}(\theta) \\ &= B_{open\_circuit}(\theta,t) + B_{ar}(\theta,t) \end{aligned} \qquad (1)$$

Where $B_{magnet}(\theta,t)$ and $B_{w}(\theta,t)$ are the open circuit field produced by magnet and stator windings respectively when the stator slotting is neglected. Both of $B_{magnet}(\theta,t)$ and $B_{w}(\theta,t)$ can be calculated analytically from 2-d models in polar coordinates. $\bar{\lambda}(\theta)$ is relative permeance which take into account the effect of slots [2]. In practice and for most PM brushless motor harmonics in open circuit magnetic field have dominant role in the noise of electromagnetic origin [1,2]. Open circuit field calculated for a 600 Watts, 4 poles, 24 slots brushless motors is performed by analytical model and validated using FEM simulations. The results are presented in figure (1).

In a typical machine with unsaturated conditions, the flux lines are perpendicular to the iron surface. Therefore the tangential component of flux density can be neglected. The radial pressure between stator and rotor surfaces can thus be written as [1,2,4]:

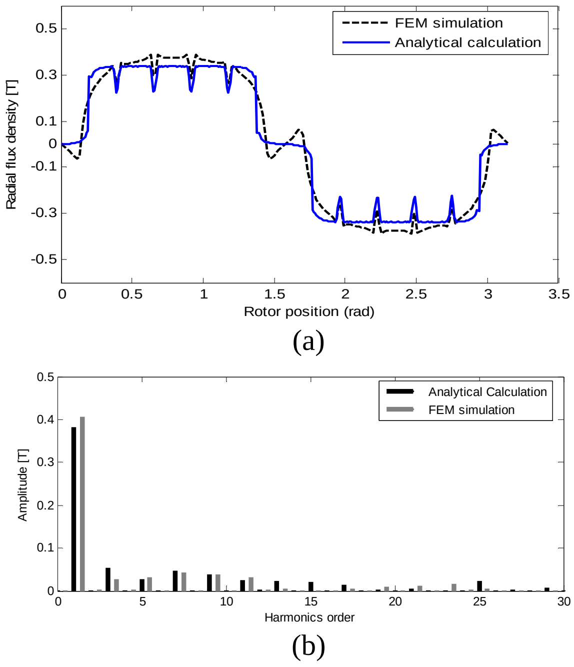
$$P_r = \frac{B^2(\theta,t)}{2\mu_0} \tag{2}$$

$$P_r = \frac{\left[B_{magnet}{}^2(\theta,t) + 2B_w(\theta,t)B_{magnet}(\theta,t) + B_w{}^2(\theta,t)\right]\ \bar{\lambda}(\theta)^2}{2\mu_0} \tag{3}$$

In equation (3) there are three group of infinite number of radial forces waves, each force wave can be expressed in the following general form

$$P_r(\theta,t) = P_{mr}\cos(r\theta - w_r t - \theta_r) \tag{4}$$

Where P_{mr} is amplitude of the magnetic pressure, wr is the angular frequency and r=0,1,2,3,4… are corresponding modes of radial magnetic force.



(a)

(b)

Fig. 1. Magnetic flux density in the air-gap of the motor (a) and its FFT decomposition (b)

By only considering the pure circumferential vibration modes of the stator core, the deflection of stator core is an inverse function of the fourth power of the force order r , so the most important from airborne noise point of view are low circumferential mode number. Faults such as eccentricity and demagnetization of permanent magnet in PM brushless DC motors contribute to generation of low mode vibration. The magnetic field calculated above in the case of faults contains additional harmonics giving rise to others harmonics forces waves.

3. Rotor eccentricity faults, definitions, causes and modeling

In ideal machine, the rotor is center-aligned with the stator bore, and the rotor's center of rotation is the same as the geometric center of the stator bore as shown in figure (2). A rotor eccentricity is a condition of unequal air gap that exists between the stator and the rotor. Air-gap eccentricity can occur in the form of static or dynamic eccentricity. In the case of a static eccentricity, the position of minimum radial air-gap length is fixed in space

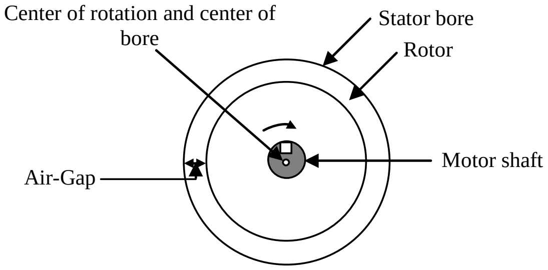


Fig. 2. Ideal motor (no-eccentric air-gap)

Typical cause of static eccentricity includes stator core ovality or incorrect positioning of the rotor or the stator at the commissioning stage. A dynamic eccentricity occurs when the center of the rotor is not at the center of rotation and minimum air gap revolves with the rotor. This means that a dynamic eccentricity is a function of space and time. A typical cause of a dynamic eccentricity includes bent shafts, mechanical resonances at critical speeds, and bearing wear. Figure (3) shows an illustration of how the rotor would rotate in the presence of each type of air-gap eccentricity.

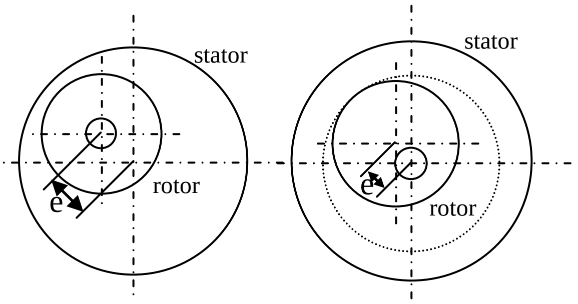


Fig. 3. Rotor eccentricity (a) static, (b) dynamic

Eccentricity faults in PM motors affect certain characteristic frequency components in the machine air-gap magnetic field and consequently vibration and sound power level spectrum radiated from the machine. The dynamic eccentricity causes magnetic flux density component at frequency given by:

$$f_{de} = f_1 + k\frac{f_e}{p} \tag{5}$$

Where f_{de} is the dynamic eccentricity frequency, f_1 is the fundamental frequency,
p is the pole pair number, and k is any integer.

The proof of equation (5) is based on the fact that the eccentricities cause change in the permeance. As indicated in equation (1) the flux density in the air-gap is given by the product of the field created by magnet (stator winding) and the relative air-gap permeance. Under the initial modelling assumption, the permeance is constant because of the uniform air gap. However, any change in the air-gap length causes a variation of the permeance which can be accounted for by additional harmonics in the permeance function and consequently in the air-gap magnetic field and radial magnetic forces.

In the mathematical model the effect of eccentricity is accounted by modifying the expression of the permeance function in the equation (1), which becoming variable not only in space but also in time:

$$\bar{\lambda}(\theta,t) = \bar{\lambda}_{sl}(\theta)\bar{\lambda}_{eccs}(\theta)\bar{\lambda}_{eccd}(\theta,t) \tag{6}$$

Where $\lambda_{sl}(\theta)$ is the relative permeance that includes the stator slots openings [1] , $\bar{\lambda}_{eccs}(\theta)$ and $\bar{\lambda}_{eccd}(\theta,t)$ is respectively the relative permeance that includes the static and dynamic eccentricity and which can be approximated by sinusoidal variation [1,2].

$$\bar{\lambda}_{eccs}(\theta) = \lambda_{eccs}\cos\theta \tag{7}$$

$$\bar{\lambda}_{eccs}(\theta) = \lambda_{eccd}\cos(w_{ec}t - \theta) \tag{8}$$

And $w_{ec} = w_r$ the angular rotor speed.

By using Fourier series decomposition, and after some mathematical operations we deduce the expression of the parameters λ_{eccs} and λ_{eccd}

$$\lambda_{eccs,d} = 2\frac{1-\sqrt{1-\varepsilon_{s,d}^2}}{\varepsilon\sqrt{1-\varepsilon_{s,d}^2}} \tag{9}$$

$$\varepsilon_{s,d} = \frac{e_{s,d}}{g} \tag{10}$$

e_s and e_d are the static and dynamic eccentricity respectively, g the air-gap length.

Including equation (6) for air-gap parmeance function instead of $\bar{\lambda}(\theta)$ in equation (1) we can obtain the magnetic flux density in the air gap of the machine with eccentricity effect taken into account. Figure (4) show the variation of magnetic flux density of 4 poles, 36 slots motors

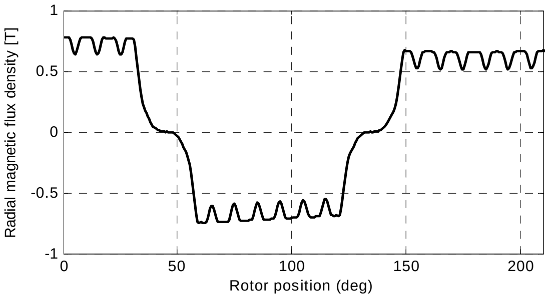


Fig. 4. Air-gap magnetic flux density with 25 % eccentricity

4. Rotor permanent magnet demagnetization faults

An air gap flux disturbance that results from some anomaly of permanent magnet is also an important fault that occurs frequently in BLDC motors. It is well known that some permanent magnet (Nd-Fe-B) corrode and can lead to disintegration, Cracks that form during manufacturing can lead to disintegration at high speeds. The flux disturbances can also be caused by partial demagnetization of the magnets which occurs for various reasons [5]. In this work we are particularly interesting to the partial demagnetization of permanent magnet. Unsymmetrical magnetization fault (or partial demagnetization) affects vibroacoustic behavior of PM machine by introducing even order harmonics in air gap magnetic flux density. To take into account the demagnetization effect in our model, the remanent induction is considered in the radial direction. So, the superposition theorem let us to consider the total induction of the permanent magnet containing a demagnetization phenomenon as composed with two signals: the first one Brpm represents the residual induction of the permanent magnet, and the second one Bd is the fault due to the demagnetization [9], see figure 5

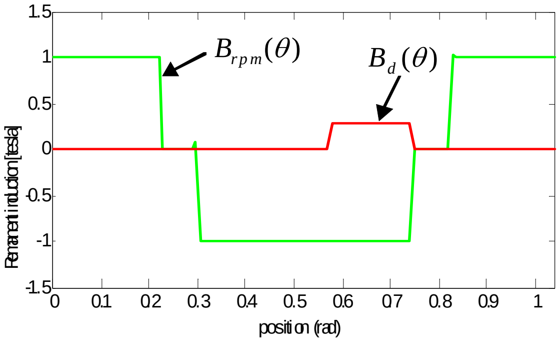


Fig.5. The two components of the studied permanent magnet (Brpmresidual induction; Bd : fault signal)

After decomposition in Fourier series of two signals, the model calculates the magnetic induction in the air gap of the machine in the presence of the defect by solving the electromagnetic equation.

In the case of defect one notices the appearance of the harmonics of even order in the space FFT of induction, particularly the harmonic of order 2 which gives rise to the mode of vibration 2 which is very dangerous from point of view vibroacoustic. After calculation of magnetic field with faults (eccentricity or demagnetization) in the air gap of PM motor and according to equation (3) and (4) we have an infinite number of radial magnetic forces waves in the air gap. These forces propagate in the air gap of the machine producing deflexion of the stator yoke in radial direction and consequently noise in the surrounding medium. An engineering approach to prediction of noise is presented in the next section.

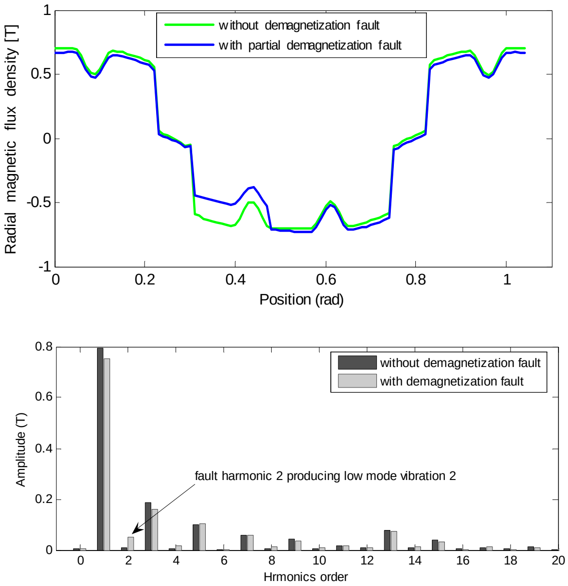


Fig. 6. Magnetic flux density in the air-gap with and without demagnetization (a) and its FFT decomposition (b)

5. Prediction of noise radiated from the stator system

The electromagnetic part of model described above allows us to have magnitudes, frequencies, and orders of radial magnetic forces. Noise and vibration of the motor structure are the direct responses of the excitation by these forces. For example if the radial magnetic force is close to one of the natural frequency of the stator system and the order *r* is the same as the circumferential vibrational mode *m* of the stator system, significant vibration and acoustic can be produced. The calculation of stator vibration which is considered in this case as 2D ring with free boundary condition is based on the theory of forced vibration with periodic excitation [11].

The vibration displacement of the machine of the mode number and frequency concerned can derived as:

$$Y_d^m = \frac{\pi D_{\&in} L_i P_{mr}}{K_m} \frac{1}{\sqrt{(1 - f_r^2 / f_m^2)^2 + 4\zeta_m^2 f_r^2 / f_m^2}} \qquad (11)$$

The vibration velocity of mode number m is then:

$$V_m = 2\pi f_r Y_d^m \qquad (12)$$

Where D1in is the stator core inner diameter, Li is the effective length of the stator core, Km is lumped stiffness of the stator, fm is the natural frequency of mode m , fr is the frequency of the force component of the order r and ζ_m is the modal damping ration. The natural frequency of the stator system can be approximately evaluated as [1]

$$f_{mn} = \frac{1}{2\pi} \sqrt{\frac{K_m^{(c)} + K_{mn}^{(f)} + K_m^{(w)}}{M_c + M_f + M_w}} \qquad (13)$$

Where $K_m^{(c)}$ is the lumped stiffness of the stator core for the mth circumferential mode, $K_{mn}^{(f)}$ is the lumped stiffness of the frame for mth circumferential and nth axial mode, $K_m^{(w)}$ is lumped stiffness of the stator winding of mth circumferential vibrational mode, Mc is the lumped mass of the stator core, Mf is the lumped mass of the stator core, and Mw is lumped mass stator winding. A numerical validation of analytical calculation of natural frequency was made by ANSYS software.

The vibrating structure of the machine produces sound waves in the ambient medium. Given the outside dimensions of a PM machine, the radiated acoustic power W corresponding to a specific vibration component can be calculated from the relative sound intensity $\sigma_m(f)$, since

$$W_m(f) = \frac{1}{2} \rho_0 c_0 S_c \sigma_m(f) V_m^2 \qquad (14)$$

Where S_c is the stator outer surface, ρ_0 the air density. Higher vibration levels mean higher radiated sound power. In many cases, however, it is not the absolute value, but $\sigma_m(f)$ which play the role of transfer function from the structural vibration to the acoustic response that is of greatest interest. σ_m is approximated using either its pulsating sphere expression , its finite or infinite cylindrical expression according to stator dimensions [10].

6. Simulation results of sound power level with rotor faults

6.A Eccentricity faults

Three simulations were made, for 4-poles, 36 slots PM synchronous motors at no load. The inner diameter is D1in=165mm, stator outer diameter D1out=232.5mm, effective length of stator 170mm, air-gap g=1mm. In first simulation, the rotor eccentricity was set at 0%, while the motor speed was set at 3500 rpm. In the second the rotor eccentricity was set at 25% and speed to 3500 rpm. In the last simulation the eccentricity was kept at 25 % but the rotation speed was increased to

4200 rpm to show the effect of rotating speed

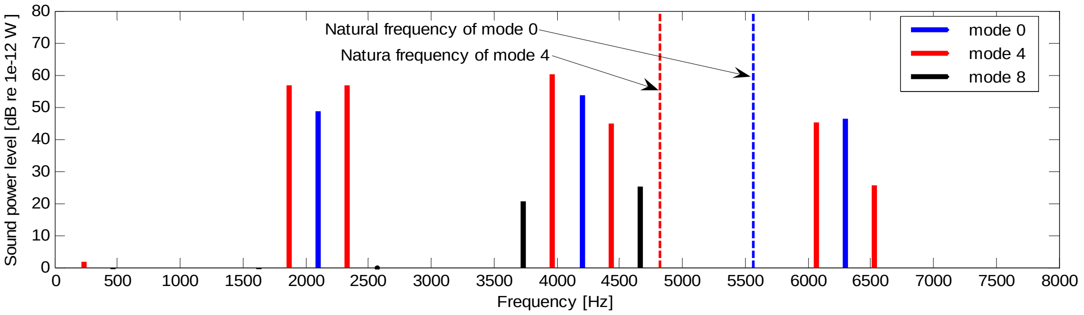


Fig. 7. Sound power level spectrum at 3500 rpm and without eccentricity (symmetric condition)

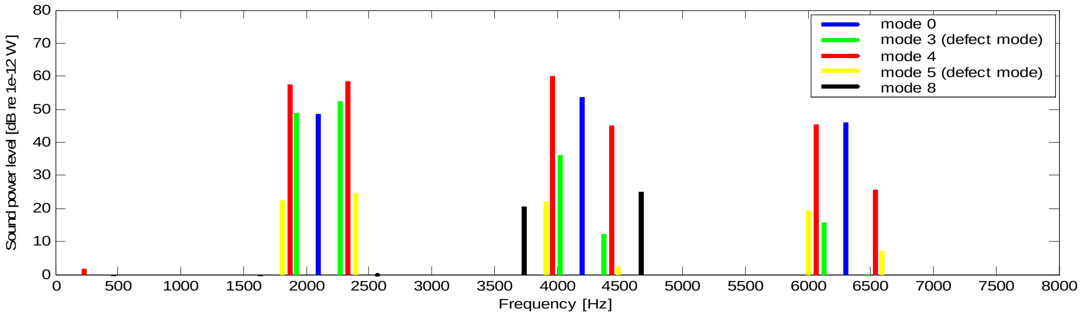


Fig. 8. Sound power level spectrum at 3500 rpm and with 25 % eccentricity

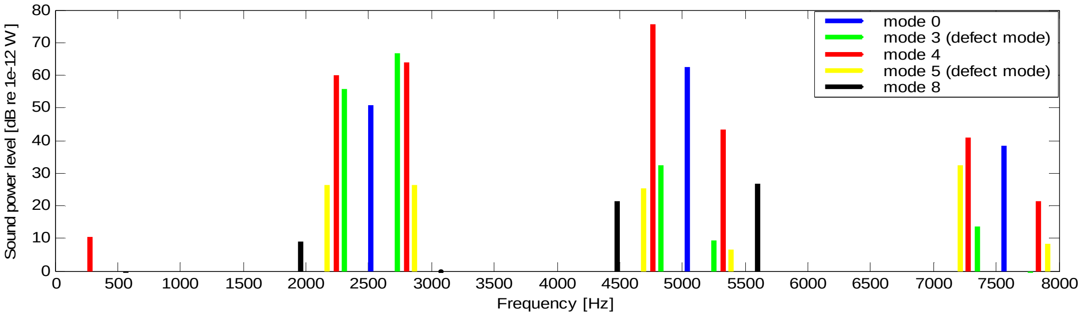


Fig. 9. Sound power level spectrum at 4200 rpm and with 25 % eccentricity

Note that the natural frequency of the stator system including stator teeth and frame calculated analytically and validated numerically are: 5566 Hz for circumferential mode 0, 991 circumferential mode 2, 2671 circumferential mode 3, 4819 circumferential mode 4. It noted that for a 0 % eccentricity (symmetric condition) there are only modes 0,4 and 8 . In the magnetic noise spectra for 25% eccentricity, we remark that some additional mode of vibration have been introduced, the new mode vibration included modes 3 and 5. We remark also that rotational speed affects both the frequencies and magnitudes of the sound power level. We remark also that the eccentricity fault may be very dangerous when the motor is used in variable speed applications, because the frequency of forces waves generated by eccentricity may become close to natural frequency of vibration mode 3 or 5 and the contribution of this mode to the global sound radiated by the machine become very important.

6.B Demagnetization faults

The demagnetization of magnet is introduced in analytical calculation of field by the method described above for the same machine. Figure (10) present the noise spectrum radiated from the external surface of the machine, when the machine is subject to partial demagnetization on one of its magnet.

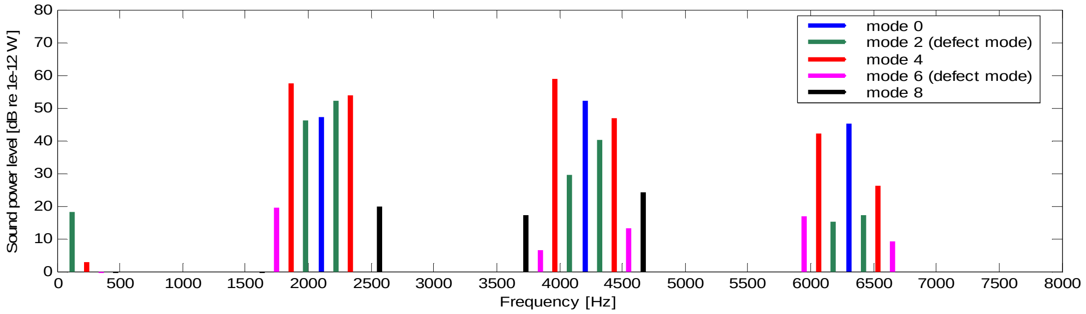


Fig. 10. Sound power level spectrum at 3500 rpm and with partial demagnetization rotor magnet

From figure and with comparison with symmetric case shown in figure (7), we can remark that partial demagnetization contribute to generation of low mode vibration and specially mode 2 which may be very dangerous from viewpoint vibroacoustic.

Conclusion

In this paper a noise predictive model of PM brushless motor was presented. The model takes into account effect of faults such as eccentricity and demagnetization. The demagnetization affects the open circuit magnetic field by introducing even order harmonics and especially harmonic 2 which creates in motors mode vibration 2 which very dangerous especially if the frequency of the generated force waves is near or close to the frequency of mode 2. The eccentricity faults affect the air gap magnetic field via permeance function, as a result the air gap magnetic field contains other harmonics contributes to the generation of low modes of vibration. The results are encouraging, so we will consider for the remainder of this work the use of the developed model in inverse problem for detecting these defects.

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