Using an Appropriate Controller for Independent Current Control for Motoring of Force Windings of Bearing less Induction Motor

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Abstract

A bearingless induction machine has combined characteristics of induction motor and magnetic bearings. Therefore, the advantages are small size and low-cost. In the magnetic suspension of the bearingless motors, suspension forces are generated based on the feedback signals of displacement sensors detecting the movement of the rotor shaft. The suspension forces are generated taking an advantage of the strong flux distribution of a revolving magnetic field in the air gap between the stator and rotor. Thus, information of the instantaneous orientation and amplitude of the revolving magnetic field is required in a controller of the bearingless motor. Therefore, vector control methods are necessary for transient conditions. For control improvement of vector control, a PID controller can be used in horizontal and vertical force paths. Radial positions x and y are detected by displacement sensors.

Keywords: bearingless induction, suspension, flux distribution, sensors, control improvement.

1- Introduction

The magnetic clamping system is a newly arising technology that is used instead of the mechanical bearings and other accessories like windings, and it has gained significant attention nowadays. Since there is no mechanical friction, the motors that use this kind of system, can rotate with higher speed and they could be used in the industries with high-speed applications. Today, almost every electrical motor such as induction, synchronous, and switched reluctance is made bearingless, and each has been used in certain applications [24,25]. The overall structure of the bearingless motor and the procedure of generating force is almost identical in all kinds of these motors, which has been shown in different references and for different structures [2-5]. In [2], a method has been introduced which guarantees the stable performance of the motor under different load conditions. In the conventional and common method, the size and the path of the clamping force changes due to load that has been solved by the proposed method. The discussed motors have especially combined characteristics of an induction motor and magnetic bearings. In this paper, optimal flux path has been defined, and it frees the generation of the clamping forces from one another. In some motors, known as disc motors, the rotor is in disc shape and a stator is placed in each side of it. In [8], the proposed control system has the ability to control the axial displacement of the rotor and prevents any malfunction in motors' operations in different operational conditions. Generally, controlling methods can be divided into two categories; with sensors and sensorless. In order to reduce the manufacturing costs, and to shorten the motor shaft, it is common to use sensorless control methods. In [9,10], a new method was introduced to calculate and estimate rotor displacement. This method works based on the induction current detection through mutual inductance as a function of rotor displacement and deviation from the center of the stator. In [11,12], a comprehensive analysis has been done over clamping forces in bearingless induction motors with cage rotor. The force, the inductance and the linkage fluxes have obtained a new controlling system proposed that also considers the clamping force error path. In some cases, in particular motors and controllers, regardless of the precise control of clamping forces, the existence load causes oscillations on the motor shaft that should be eliminated. Some research has been done in this field that offer new methods to eliminate these oscillations. In some cases, harmonic oscillations have also been detected that methods have used to overcome this problem. In these methods clamping forces have been used to reduce the undesired effects, [13,14]. Similar to conventional induction motors, there are different structures for inverter supplying these motors, a particular kind of this have been studied in [15].

In this paper, two kinds of voltage source convertor have been compared and investigated for two-phase bearingless induction motors. In [16], a new structure of BLIM and controller has been offered. This motor has cage rotor with two-piece winding. Since radial forces are derived from magnetic energy, the modeling and the speed controlling of this system has been done in the reference frame of the air gap flux. Furthermore, due to angle difference between the stator current and the reference flux, an additional part has been added to the controller that sets the direction of the reference frame automatically. Intelligent methods like artificial intelligence, neural and fuzzy networks can also be used to control these kinds of motors, just like the other motors. To reduce the effect of the speed detection over stability and the accuracy of the bearingless induction motor, reference [17] has proposed a new estimation method that uses neural networks to increase the speed. Therefore, a sensorless controller has been obtained to control the speed of the motors that had acceptable results compared to other previous methods. As it was discussed in previous references, different analyses have been done over BLIMs and each of them covers a different perspective of these motors. Like previous studies, in [18-23] this work has been done with other similar methods that result in new equations that are necessary in developing control systems. Specifically, in [19], a method has been shown to control the radial position of the rotor in a two-pole cage BLIM which has a set of four-pole winding to generate clamping force. Using this controller, the performance of the machine becomes more stable, the vibration has been eliminated due to unbalanced weight and rotation, and the vertical force has been provided to clamp the motor shaft. This controlling system has the ability to perform in a wide area of speed and torque. Meanwhile, the consumed powers to generate force and the effect of it on the overall efficiency of the machine have been investigated in this paper.

In this paper, software analysis of the vector control of a bearingless induction motor is considered. Relevant mathematical studies and analysis are done over a particular motor, and related equations are extracted. Using these equations, a model has been shown for the motor through which necessary investigations are done over this motor. The vector control has been held over these motors and the undesired effects of this controller in the force generation system has been studied and then controlling the system has been modified that fixes this problem and it has been shown that the bearingless induction motor operates fine with proposed vector control.

2- Bearing less Induction Motor

One of the existence methods for usage in high-speed applications is to eliminate mechanical connections and using magnetic bearings. These kinds of motors can generate motor torque to do mechanical works, and additionally they can generate clamping force, which holds the rotor steady in the center of the stator. Due to the research have done, each AC electronic motor that has the ability to change the reference frame and equivalent circuit of the DC motor, can be manufactured without bearing.

In these motors, the M-pole main winding (with m even pole) is placed in a combination of a bunch of N-pole winding (with n even pole), named clamping winding. The placement of the windings are in a way that the interference between the magnetic fields of the two sets of the windings, led to radial force which is necessary in order to hold the rotor suspended. There exists an especial equation between the numbers of the poles of the two sets of the windings, which always needs to be considered. This equation can be written as the mathematic equation as $M - n = \pm 2$ or $m - n = \pm 1$. This indicates that the clamping forces do not generate in any condition, but the numbers of the motor's poles should obey the above equation in order to produce the force needed.

Specifically, in [2] a method has been represented to control the radial position of the rotor in a two-pole cage BLIM, which has a set of four pole windings in order to produce the clamping force. With this controller, the performance of the machine become more stable, the vibration due to misalignment of weight and rotation eliminated and the vertical force needed to hold the motor's shaft provided. This control system has the ability to function in a wide range of speed and torque.

The Magnetomotive force (MMF) related to the two-pole winding is expressed as a sinus function and with a proper approximation to the main components. The permeability changes caused by the changes in the air gap length caused by the rotor's radial relocation from the center of the stator have been studied and the changes in inductance and radial force have been shown. In these studies, it has been assumed that:

1. The spatial distribution of the MMF is equivalent and decomposed into main components
2. No magnetic saturation exists
3. Air gap permeability distribution is smooth. The harmonic of the stator slot is negligible and the rotor and the stator's surface are smooth and perfectly cylindrical.
4. The magnetic permeability of the iron core is infinite and the iron core magnetic reluctance is insignificant.
5. The radial relocation of the rotor to the air gap length and especially to the length of the rotor is small.

Bearingless motors have also several types of vector control [3]. The first type is indirect rotor flux vector control in which each of the two sets of windings is aligned with the M-pole rotor flux vector. By powering the force coils, the force will be generated in x and y-axis paths. In order to make sure that the F_x force generates only when it is needed, all the parameters of the two-pole winding should be transferred to the M-pole air gap flux reference frame. Hence, another vector control method is indirect vector control in the air gap flux reference frame. The main drawback with this approach is the lack of appropriate control over generated torque. There exist other structures of the vector control in which the reference frame could be selected as inertial or rotating. In the inertial reference frame, all the parameters are transferred to the coordinate system which is still and steady to stator. In a rotating reference frame, parameters are transferred to the coordinate system which can be aligned with stator flux, rotor and air gap flux. The BLIMs have attracted much attention due to their privileges, some of which are as follows:

1. Relatively simple and solid structure of the rotor
2. Providing steady rotation speed
3. Less torque vibration
4. Low costs in open loop applications

The main point in BLIMs is that in these motors, N-pole force winding have magnetic fields in comparison to stator rotates in a same synchronous speed with the field speed of the M-pole winding [5]. Then, the filed rotating electrical angle of the N-pole winding can be defined as:

$$\theta_r^N = \theta_r^M \tag{1}$$

Hence, in order to implement vector control on both N and M pole windings, the electrical sliding velocity of the N-pole windings, ω_{sl}^N , is needed. Both M and N pole field rotate with the same electrical angular velocity, ω_e so the rotor will rotate with a speed of

$$\omega_{r\ mech} = \frac{\omega_e - \omega_{sl}^M}{m} \tag{2}$$

Electrical sliding velocity between N-pole field and rotor is equal to:

$$\omega_{sl}^N = n[\frac{\omega_e}{n} - \omega_{r\ \mathrm{mech}}] \tag{3}$$

The generated filed by the N-pole force winding, follows the rotor with a relatively large slip. In other words, there exists a speed difference between the magnetic field generated by the N-pole winding and the rotor, which causes induced current in the rotor. Due to the structure of the vector control in the reference frame of the rotor flux, the i_{sq}^{N} component in $0=\frac{R_r}{L_r}\psi_{rd}+\frac{d}{dt}\psi_{rd}-\frac{L_0}{L_r}R_r i_{sd}$ equation should exist. It can be written as follows:

$$i_{sq-orient}^{N}=\omega_{sl}^{M}.\tau_r^{N}\,i_{mrd}^{N} \tag{4}$$

This component of the q-axis current indicates the $i_{sq-orient}^{N}$ parameter as the synchronization of the M and N pole magnetic field. To define the force sidelong the x, current component i_{sq}^{N} is required as i_{sq-con}^{N}. In this case:

$$i_{sq}^{N}=i_{sq-orient}^{N}+i_{sq-con}^{N} \tag{5}$$

The i_{sq}^{N} current will produce N-pole torque, which will be combined with the torque of the main winding.

$$T^{N}=k^{N}i_{sd}^{N}i_{sq}^{N} \tag{6}$$

In these equations, $k^{N}=3n\frac{L_0^{N^2}}{L_r^{N}}$ and $\sqrt{i_{sd}^{N^2}+i_{sq}^{N^2}}$ are equal to the root mean square of the N-pole stator winding current.

The forces along the x and y which apply to the motor, are controlled by the peak values of the air gap flux density related to the N-pole winding in two paths, B_{Fx}^{N} and B_{Fy}^{N}. These flux density values are related with the air gap hybrid flux vector ψ_0^{N}. Fig.1 indicates the overall scheme of the vector control in the reference frame of the rotor flux in a BLIM

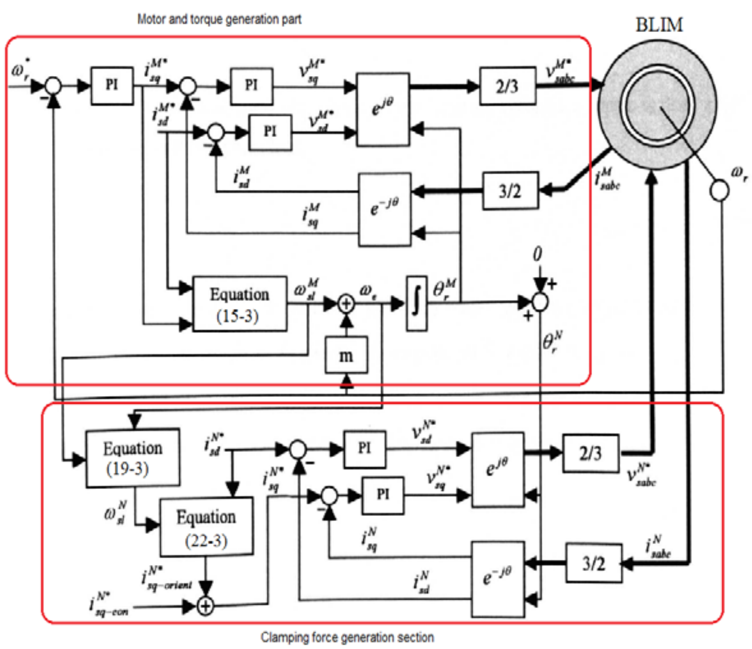

Fig. 1. Overall scheme of the vector control of the BLIM

Reference currents of the N-pole stator winding, $i_{sq-con}^{N^*}$ and $i_{sd}^{N^*}$, are conducted from feedback control ψ_{0d}^{N} and ψ_{0q}^{N}, based on the relevant reference values in which these reference values are obtained from, F_x^* and F_y^*

If it was necessary, in a BLIM, the vertical and horizontal deviation values of the rotor from the center of the stator, can produce F_x^* and F_y^* signals, respectively, through position feedback, which based on the deviation scale the necessary force will be produced to overcome that. To simplify calculations and do some simple studies, the reference values of the forces in both paths can be assumed constant.

3- Motor Winding Parameters

In this section the equivalent circuit of the cage induction motor for modeling and performance studying of it will be obtained. Three-phase cage induction motor is two-pole with triangle connection. Stator resistance value (R_s) and rotor resistance (R_r') are .24 ohm and 1.37 ohm, respectively.

Table .1.Two-pole winding parameters of the torque in BLIM

Rotor winding resistance	R_s^M	.19 ohm
Equivalent resistance of the rotor winding	$R_s^{M'}$	3.3 ohm
Self-inductance of the stator winding	L_s^M	22.2 mH
Self-inductance of the rotor winding	L_r^M	22.2 mH
Leakage inductance of the rotor winding	L_0^M	3.5 mH

The inductances of the equivalent circuit of the motor are obtained through loadless tests and with the locked rotor test. Resistance and parameters of the cage motor are represented in Table.1.

4- Force Winding Parameters

The constant amount of force needed to suspend the rotor of the induction motor, can be achieved through magnetic field interference of the M-pole and N-pole windings. In the desired motor for this purpose, beside the main two pole windings, four-pole force windings are also wrapped up around the stator. The amount of effective induced electromotive force for each phase of the force winding is equal to:

$$E_{rms} = \frac{2\pi}{\sqrt{2}} f k_w N_t \frac{2B_0 r l_z}{P} \quad (7)$$

And the stator phase resistance (R_s), can be calculated as:

$$R_s = \frac{4.19q\, N_s^2 L_{ts}}{1\times 10^6 C_s} \quad (8)$$

In which, q is the number of rotor phases and N_s is the number of the force winding turns in each phase, which are series together. In equation (8), L_{ts} and C_s are the equivalent values of L_{tr} and C_r relevant to the stator winding. In cage induction motors, the currents of the four poles force winding also are induced in the rotor. The resistance of this motor can be calculated as:

$$R_r' = \frac{4.19q\, k_{ws}^2 N_s^2}{1\times 10^6} \times a \quad (9)$$

Through which a is a constant factor that depends on the size of cage rotor. Given that there are two sets of three-phase winding with two and four-pole on the stator (q=3), the resistance of the relevant rotor with four pole winding is also connected with two-pole rotor resistance through following equation:

$$R_r^{N\,'} = \frac{k_{ws}^{N\ 2} N_{ts}^{N\ 2}}{k_{ws}^{M\ 2} N_{ts}^{M\ 2}} \times a \qquad (10)$$

Assuming that $k_{ws}^N = .956$, $N_{ts}^N = 50$ and using the other necessary values, $R_r^{N\,'}$ can be obtained. Through calculations, the values of the force winding parameters are shown in table. 2.

Table .2. The parameters of the four-pole force winding in BLIM

Stator winding resistance	R_s^N	.24 ohm
Equivalent resistance of the rotor winding	$R_s^{N\,'}$	1.37 ohm
Self-inductance of the stator winding	L_s^N	3.41 mH
Self-inductance of the rotor winding	L_r^N	3.41 mH
Leakage inductance of the rotor winding	L_0^N	3.5 mH

5- Simulation

Simulations have been done over a bearingless induction motor with the given specifications and a common control system has been implemented initially. Considering the mentioned block diagram and equations, vector control has also been implemented over the motor and the simulations have done in a Simulink environment. In the end, in order to compensate the undesired effects of vector control on the performance of the clamping system and generated forces, two PID controls have been used on each force and results have been compared with the two previous methods under the same operating conditions. All the values are conducted through trial and error methods and are indicated with approximation.

It's assumed that the motor operates in a normal mode. Currents in the motor windings are constant three-phase that produce torque. In t=.05s, a deviation will be happen over x axis, though the force windings should be controlled such that it can generate this force immediately and return the rotor to its center position. It should be mentioned that there exists a constant force in Y path, which must always be preserved, and in case the rotor deviates in this path, an additional force needs to be added in this direction. The generated forces in X path can be shown in Fig.2 with three controlling systems as; conventional, vector control, and PID control.

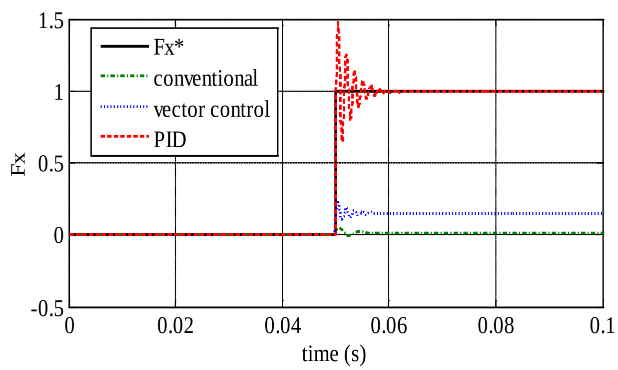

Fig.2. The generated forces in X path

Due to the loadless rotating of the motor, a small torque does exist that spends to rotate the motor itself. Therefore, the two pole torque winding has current, whereas the force winding has no current initially and after t=.05s the force has been generated, and thus, current has been established in the windings. This can be seen in Figs. (3-4) for three-phase. In conventional controlling strategy, proper control is not done over the force, which means the desired force has not been generated. Therefore, there is no sufficient current in relevant windings. For this reason, in the conventional vector control method the four pole current is also scant. This current has its higher value in the PID controlling approach, as it can be seen in Fig.3.

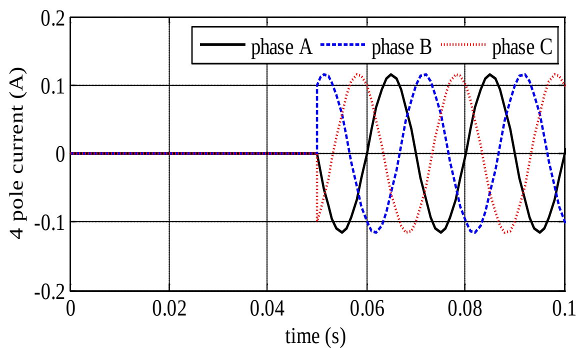

Fig. 2. Conventional control of BLIM

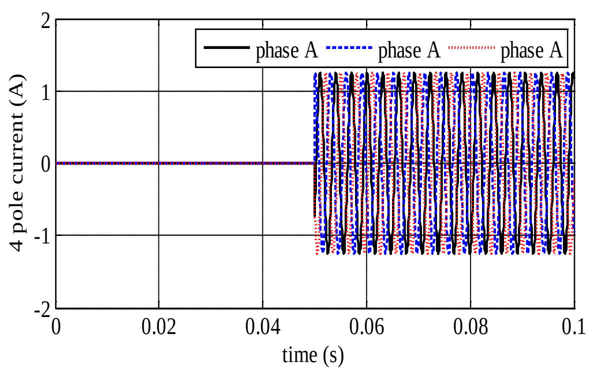

Fig. 3. Vector Control

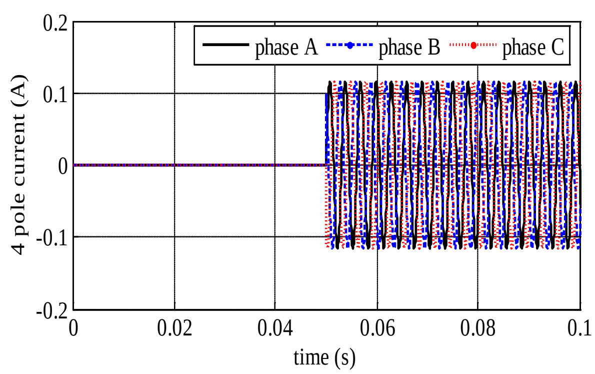

Fig. 4. PID compenstator vector control

6- Conclusion

In this research, it has been shown that the vector control of bearingless induction motor faces severe issues in generating forces, as the true values of the forces are not able to track the reference values properly. By using the conventional PID controller on each force, the steady state response of the forces is compensated largely. There are different methods that can be used to improve the transient response so real forces reach their final values in less time. It is obvious that the faster the response reaches its final value, the better the performance of the machine will be. Furthermore, vector control has oscillations that can be eliminated through methods like adaptive control.

7- Future Works

To enhance the steady state and transient response of the clamping forces, a variety of approaches can be used. Different controlling systems have been offered to control induction motors that have improved steady state and transient response. These methods can be expanded to bearingless motors and using approaches like intelligent procedures, they can be transformed to bearingless motors in a proper way. One of the conventional methods of controlling induction motors is the torque direct control that has faster response than vector control. This method can also be applied to bearingless motor and by improving the probable issues, the performance of the bearingless motors can be enhanced.

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