Analysis of Half-coiled Short-pitch Windings with Different Phase Belt for Multiphase Bearingless Motor

Bingnan Li*, Jin Huang† Wubin Kong* and Lihang Zhao*

Abstract – The analysis and comparation of the half-coiled short-pitch windings with different phase belt are presented in the paper. The half-coiled short-pitch windings can supply the odd and even harmonics simultaneously, which can be applied in multiphase bearingless motor (MBLM). The space harmonic distribution of the half-coiled short-pitch windings with two kinds of phase belt is studied with respect to different coil pitch, and the suitable coil pitch can be selected from the analysis results to reduce the additional radial force and torque pulse. The two kinds of half-coiled short-pitch windings are applied to the five- and six-phase bearingless motor, and the comparation from the Finite Element Method (FEM) results shows that the winding with $2\pi/m$ phase belt is fit for the five phase bearingless motor and the winding with $\pi/m$ phase belt is suitable for the six phase bearingless motor. Finally, a five phase surface-mounted permanent magnet (PM) bearingless motor is built and the experimental results are presented to verify the validity and feasibility of the analysis. The results presented in this paper will give useful guidelines for design optimization of the MBLM.

Keywords: Bearingless motor, Finite Element Method (FEM), Half-coiled short-pitch winding, Multiphase

1. Introduction

Various types of bearingless motors have been successfully applied to multiple areas, such as flywheel energy storage systems, semiconductor, pumps and mixers in medical industry, etc [1-4]. It is benefited from its advantages as like noncontact bearing capability and no mechanical friction and lubricants.

Based on the theory of the electromagnetic field, the nonuniform magnetic field in machine airgap produces the magnetic force, which can support the rotor shaft in the airgap. Hence, the uniform magnetic field in the airgap should be broke for the rotor levitation. So far, there are mainly two kinds of methods to work it out. One is that the additional set of conditional windings is wound on the stator core with the main windings [5-8]. It needs two sets of inverters to supply the currents to the torque- and suspension-winding respectively. This configuration is clear and easily control. However, this machine has larger size of outer diameter as compared to the conventional motor with mechanical bearings. The other one is that single set of multiphase windings is wound on the stator core with the main windings [9-11]. The flux density of only one side of airgap changes with the current injection, and the other side remains unchanged. Thus, the current requirement is low. However, the control system also requires two sets of three-phase inverters to build asymmetric fields.

An induction bearingless motor with six-phase half-coiled short-pitch windings powered by single six-phase inverter was proposed based on the conventional three phase induction motor [9-11]. The system can be implemented with a smaller airgap and consequently smaller steady state current. However, it is difficult to obtain better control performance. A bridge configured winding was proposed for multiphase bearingless motors (MBLM) in [12, 13]. It offers relatively low power loss and is possible to be extended to other multiphase machines. However, the isolated multiple single-phase inverters are required to provide the levitation currents. Additionally, a main motor winding structure with middle-point current injection was proposed in [14]. The flux density of only one side of airgap changes with the current injection, and the other side remains unchanged. Thus, the current requirement is low. However, the control system also requires two sets of three-phase inverters to build asymmetric fields.

The torque and suspension performance of the MBLM depend on the configuration of the half-coiled short-pitch winding, and it is necessary to study its characters for the design optimization of the MBLM. Following on the preliminary results in [17-19], the winding optimization for
the MBLM can maximize the winding utilization rate for the torque performance and reduce the additional radial force for the suspension performance.

The half-coiled short-pitch windings with $2\pi/m$- and $\pi/m$-phase-belt are investigated in the paper, which are applied to the five- and six-phase bearingless motor. The mathematical model of the half-coiled short-pitch winding with $2\pi/m$- and $\pi/m$-phase-belt is analyzed. Then the space harmonic distribution of the two types of windings with respect to different coil pitch is studied, and the analysis and comparison for the five- and six-phase bearingless motor by Finite Element Method (FEM) are provided. Finally, the static and dynamic experiment on a five phase surface-mounted permanent magnet (PM) bearingless motor is presented to verify the validity of the analysis.

2. Analysis of Half-coiled Short-pitch Windings with Different Phase Belt Applied in Five Phase Bearingless Motor

2.1 Mathematical model of half-coiled short-pitch winding with $2\pi/m$- and $\pi/m$-phase-belt

In the bearingless motor, it is necessary to obtain two magnetic fields with a difference of pole-pair numbers equal to one to generate suspension force [20]. It means that both odd and even fields are needed simultaneously. The half-coiled short-pitch winding, which is defined as the winding with the coils under half pole, can meet the requirement. The half-coiled short-pitch winding with $2\pi/m$ phase belt is shown in Fig. 1. There is only two phases in Fig. 1, which contains two coils respectively.

The winding function of the half-coiled short-pitch windings with single coil is shown in Fig. 2, which can be written as

$$N_a(\phi) = \sum_{\nu=1,2,3,\ldots}^{2N} \frac{N}{v\pi} \sin\left(\frac{\nu y_1\alpha_1}{2}\right) \cos(v\phi) = \sum_{\nu=1,2,3,\ldots} N_v \cos(v\phi)$$ (1)

where $\phi$ is the spatial angle, $v$ is the space harmonic order, $\alpha_1$ is the angle between the adjacent slots, $y_1$ is the coil pitch, $N$ is the number of turns per slot, $N_v$ is the magnitude of the $v$th space harmonic.

Hence, it is possible to plot the diagram of winding function of phase $a$ based on (1), which is shown in Fig. 3. And the general winding function can be written as (2).

$$N_a(\phi) = \sum_{\nu=1,2,3,\ldots}^{q_1} \sum_{\nu=1,2,3,\ldots} N_v \cos[v\phi - (q_1-1)\nu\alpha_1]$$ (2)

where $q_1$ is the number of coils per phase.

The half-coiled short-pitch winding with $\pi/m$ phase belt is shown in Fig. 4. Each phase winding is divided into two coil groups. They are embedded in the up- and down-side of the slot respectively, which forms two kinds of coil pitch $y_1$ and $y_2$.

The winding function of phase $a$ is shown in Fig. 5. And the general winding function of half-coiled short-pitch winding with $\pi/m$ phase belt can be written as (3).
Fig. 5. Winding function of half-coiled short-pitch winding with $\pi/m$ phase belt

$$N_d(\phi) = \sum_{q_2=1,2,3,...} \sum_{s=1,2,3,...} N_c \cos[v\phi - (q_2 - 1)v\alpha] + \sum_{q_2=1,2,3,...} \sum_{s=1,2,3,...} N_c \cos[v\phi - (y_2 - y_1 + q_2 - 1)v\alpha]$$

where $q_2$ is the number of coils per coil group.

### 2.2 $2\pi/m$ Phase Belt

A 30-slot five-phase bearingless motor with half-coiled short-pitch winding is shown in Fig. 6. The winding is $2\pi/m$ phase belt, which is 72° in this bearingless motor. The coil numbers of each phase $q_1$ is equal to six in the bearingless motor. All the phase windings are star connected.

![Fig. 6. Five phase winding with 72° phase belt](image)

**Fig. 6.** Five phase winding with 72° phase belt

The coil pitch $y_1$ is equal to ten in Fig. 6. The phase winding function is shown in Fig. 7(a) based on (2). In addition, the magnitude of each space harmonic can be obtained by FFT, which is shown in Fig. 7(b). It is seen that the magnitudes of the first and second space harmonic are larger than those of other space harmonics. Especially, the third space harmonic is almost zero.

Furthermore, the distribution of the magnitude of each space harmonic with respect to different coil pitch can be also acquired following on the same method as shown in Fig. 8. According to the analysis results in [18], the third space harmonic can generate the additional radial force, which should be reduced by adjusting the coil pitch. It is seen that each space harmonic changes periodically with respect to the coil pitch. When the coil pitch is equal to ten, the magnitude of the third space harmonic $N_3$ reaches the minimum value. At this point, the magnitude of the first space harmonic is equal to 3.10, which is $\sin(\pi/3)$ times of the maximum value of $N_1$ and the magnitude of the second space harmonic is equal to 1.27, which is $\sin(2\pi/3)$ times of the maximum value of $N_2$.

### 2.3 $\pi/m$ Phase Belt

The five phase bearingless motor with $\pi/m$ phase belt is shown in Fig. 9. The winding is 36° phase belt, and all of the windings are star connected. Each phase winding is divided into two coil groups, and coil number of each group $q_2$ is equal to three. The up- and down-side coil groups have the same coil pitch $y_1$, and the best choice for $y_1$ is $3q_2$, which is equal to nine in Fig. 9. In addition, the coil pitch $y_2$ is equal to fourteen in Fig. 9.

It is possible to generalize the winding function method to the five-phase winding with $\pi/m$ phase belt as shown in Fig. 10(a). The magnitude of each space harmonic can be obtained by FFT, which is shown in Fig. 10(b). It is seen that the magnitudes of the first and second space harmonic are larger than those of other space harmonics, and the third space harmonic reaches its minimal value. In addition, since the five-phase windings are symmetric, the fifth space harmonic will be cancelled out.
Since the coil pitch $y_1$ is constant, the space harmonic changes with respect to the coil pitch $y_2$ as shown in Fig. 11. When the coil pitch $y_2$ is equal to $3q_2$, which means that $y_2$ is the same with $y_1$, the space harmonics reach their maximum value simultaneously. Furthermore, when the coil pitch $y_2$ is equal to fourteen, the third space harmonic reaches the minimum value. In addition, the magnitudes of the first and second space harmonic are equal to 2.63 and 0.86 respectively at this point. Hence, the utilization rate of this winding is lower than that of the five phase bearingless motor with 72° phase belt.

2.4 FEM analysis for two types of five-phase bearingless motor

The analysis results are verified in a five-phase surface-mounted PM bearingless motor with the parameters shown in Table 1 by FEM.

The axes of the magnetic pole of permanent magnet and the phase winding are coincident, and the unit torque- and suspension-current with same phase angle are injected into the five phase winding. The airgap flux density of torque- and suspension-field are obtained as shown in Fig. 12. It is seen that the axes of the two torque fields are not coincident, and the phase difference is equal to $\pi/6$. The reason is that the axis of the winding with $\pi/m$ phase belt is compounded by two coil groups, the phase difference of which is $\pi/3$ in Fig. 9. Moreover, the axes of the two suspension fields are not coincident either, and the phase difference is equal to $\pi/3$. In addition, the magnitudes of the torque- and suspension-field of the winding with $2\pi/m$ phase belt are larger than that of the winding with $\pi/m$ phase belt because of the higher winding utilization rate of the former one.

The suspension force with respect to different suspension current values is analyzed by FEM as shown in Fig. 13. It is seen that the suspension force is proportional to the suspension current. In addition, the suspension force constants, which is defined as the suspension force with respect to unit current, are 42.68N/A and 29.20N/A respectively. It shows that the winding with $2\pi/m$ phase belt...
belt can produce larger suspension force than that of windings with \( \frac{\pi}{m} \) phase belt with same current value. Hence, the winding with \( 2\frac{\pi}{m} \) phase belt is more suitable for the five phase bearingless motor.

3. Six Phase Bearingless Motor with Different Phase Belt

3.1 \( 2\frac{\pi}{m} \) phase belt and \( \frac{\pi}{m} \) phase belt

For the convenience of comparison, the six phase bearingless motor possesses the same parameters with the former five-phase bearingless motor as shown in Table 1, except that the number of stator slot is equal to 36. The six phase bearingless motor with \( 60^0 \) and \( 30^0 \) phase belt is shown in Fig. 14. And all of the phase windings are star connected. Following on the same method in the previous section, the space harmonic distribution with respect to different coil pitch is presented as shown in Fig. 15.

Table 1. Parameters of a five-phase surface-mounted PM bearingless motor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Stator outer radius</td>
<td>87.5mm</td>
</tr>
<tr>
<td>Stator inner radius</td>
<td>49mm</td>
</tr>
<tr>
<td>Airgap length</td>
<td>2mm</td>
</tr>
<tr>
<td>Stack length</td>
<td>105mm</td>
</tr>
<tr>
<td>Magnetic retentivity</td>
<td>1.1T</td>
</tr>
<tr>
<td>Magnetic coercivity</td>
<td>-8.38e5A/m</td>
</tr>
</tbody>
</table>

According to the analysis results presented in [15], the fourth space harmonic can generate the additional radial force, which should be reduced by adjusting the coil pitch in the six-phase bearingless motor. In Fig. 15(a), when the coil pitch \( y_1 \) is equal to nine, the magnitude of the fourth space harmonic \( N_4 \) reaches the minimum value. Meanwhile, the magnitude of the first space harmonic is equal to 2.58, which is \( \sin(\pi/4) \) times of the maximum value of \( N_1 \). And the magnitude of the second space harmonic reaches the maximum value 1.59.

In Fig. 15(b), it is interesting to note that the magnitude of the fourth harmonic is eliminated with respect to any value of coil pitch \( y_2 \). Hence, when \( y_2 \) is equal to \( 3q_2 \), which means that it is the same with coil pitch \( y_1 \), the magnitudes of the first and second harmonics can reach the maximum value at the same time. And they are equal to 2.67 and 1.83 respectively. Since the winding distribution coefficient increases, the utilization rate of the winding is improved by 1.035 and 1.15 times than that of the six phase bearingless motor with \( 60^0 \) phase belt.

3.2 FEM analysis for two types of six-phase bearingless motor

The above two six-phase bearingless motors are analyzed by FEM as shown in Fig. 16. The results show that the axes of the two torque fields are coincident, which is same for the two suspension fields. In addition, the magnitudes of the torque- and suspension-field of the winding with \( \frac{\pi}{m} \) phase belt are a little larger than that of the winding with \( 2\frac{\pi}{m} \) phase belt.

(a) Torque field          (b) Suspension field

Fig. 16. Airgap flux density of the torque field and suspension field with unit current
Fig. 17. Suspension force of the two types of six phase bearingless motors

Table 2. Characters of the half-coiled short-pitch windings for five- and six-phase bearingless motor

<table>
<thead>
<tr>
<th></th>
<th>Five phase Bearing less motor</th>
<th>Six phase Bearing less motor</th>
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<tbody>
<tr>
<td></td>
<td>2(\pi/m)</td>
<td>(\pi/m)</td>
</tr>
<tr>
<td>(N_1)</td>
<td>3.10</td>
<td>2.63</td>
</tr>
<tr>
<td>(N_2)</td>
<td>1.27</td>
<td>0.86</td>
</tr>
<tr>
<td>Suspension force constant (N/A)</td>
<td>42.68</td>
<td>29.20</td>
</tr>
</tbody>
</table>

In addition, the suspension force with respect to different suspension current values is analyzed by FEM as shown in Fig. 17. The suspension force constants of the six phase winding with \(\pi/m\)- and \(2\pi/m\)-phase-belt are 42.17N/A and 48.45N/A respectively. It shows that the winding with \(\pi/m\) phase belt can produce larger suspension force than that of windings with \(2\pi/m\) phase belt under the same current value. Hence, the winding with \(\pi/m\) phase belt is more suitable for the six phase bearingless motor.

The characters of the four types of the half-coiled short-pitch windings are summarized in Table 2. It is seen that the half-coiled short-pitch winding with \(2\pi/m\) phase belt is fit for five-phase bearingless motor and the winding with \(\pi/m\) phase belt is suitable for six-phase bearingless motor. In addition, although the six phase bearingless motor with \(\pi/m\) phase belt has better suspension performance than that of the five phase bearingless motor, the five phase bearingless motor with \(2\pi/m\) phase belt has the advantages as more compact construction, better torque performance and less power devices, which is more suitable for industry application.

4. Prototype and Experimental

A five-phase surface-mounted PM bearingless motor prototype is shown in Fig. 18. The parameters of the structure are the same as those of the FEM model as shown in Table 1. And its winding configuration adopts the half-coiled short-pitch winding with \(2\pi/m\) phase belt as shown in Fig. 6. The bottom of the rotor shaft is held by the spherical roller bearing. And there is a gap of 0.3mm between the top shaft and auxiliary bearing for rotor suspension. There are two eddy-current-type gap sensors to measure the rotor displacement.

To verify the validity of the analysis results by FEM, it is necessary to measure the suspension force constant in the experiment. Firstly, the magnetic pole of PM is located on the \(\alpha\)-axis in the space by injecting little exciting current, and the rotor is maintained at standstill. Then the rotor is suspended by injecting the suspension currents. After that, the external force is applied on the \(\alpha\) - and \(\beta\)-axis of the rotor shaft respectively. And the corresponding suspension currents are changed by adjusting the values of the applied force as shown in Fig. 19. It is seen that the applied force is proportional to the suspension current. And the suspension force constant is equal to 32.21N/A in Figs. 19(a) and 33.67N/A in Fig. 19(b), which is in basic agreement with the FEM results in Fig. 13. The error between the analysis result and measurement could result from the manufacture errors, magnetization of the permanent magnet and so on, which is acceptable in the industry application.

Based on the measured suspension force constant, the suspension and acceleration experimental results are shown in Fig. 20. In the initial acceleration stage, the rotor rotates around the auxiliary bearing and the suspension currents stay in zero. After injecting the suspension current, the rotor moves to the center quickly and suspension currents \(i_{d2}\) and \(i_{q2}\) are in a shape adjusting to maintain the rotor radial displacement variations \(\alpha\) and \(\beta\) less than 50 \(\mu\)m.
which successfully certify the feasibility of the MBLM.

5. Conclusion

This paper analyzes the harmonic distribution of the half-coiled short-pitch windings with different phase belt and its application in the multiphase bearingless motor (MBLM). The selection of the coil pitch is very important to optimize the torque performance and reduce the harmful space harmonic for the stable suspension of the rotor shaft. Consequently, the analysis and comparation results by FEM show that the winding with $2\pi/m$ phase belt is fit for five phase bearingless motor and the winding with $\pi/m$ phase belt is proper for six phase bearingless motor. And the five phase half-coiled short-pitch winding with $2\pi/m$ phase belt is proved to be more suitable for the MBLM in the industry application. The results presented in this paper provide a theoretical foundation for the further study of the design optimization of the MBLM.

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References


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