Abstract – The new bearingless doubly salient electro-magnetic machine (BDSEM) has advantages of robust structure, naturally decoupled characteristics of the torque and suspension control, and elimination of rotor angular position detection for the suspension control. However, due to the doubly salient pole structure, the instantaneous suspension force cannot be held constant with constant DC suspension current in different rotor position which has an impact on the suspension control. In this paper, the suspension force generation principle is analyzed, and the mechanism of instantaneous suspension force ripple is investigated in depth. The influence of rotor pole width on the suspension and generating performance of the BDSEM is analyzed by finite element method (FEM). Finally, the rotor pole width is optimized to reduce the force ripple and improve the generating performance.

Index Terms—Bearingless machine, doubly salient, reluctance, suspension force.

I. INTRODUCTION

THE bearingless switched reluctance machine (BSRM), free from mechanical bearings, has the robust structure without windings or permanent magnets (PMs) in the rotor, and is suitable for operating in the high speed and high temperature applications [1], [2]. However, the main windings of the BSRM are tightly coupled with the suspension windings, thus the regions of torque and suspension force cannot be fully used. Therefore the power density is reduced. Additionally, the rotor angular position detection is indispensable for suspension control and the suspension current should be regulated depending on it which reduces the system reliability especially for high speed and high frequency operation.

The consequent-pole bearingless permanent magnet (PM) machine [3]-[9], and homo-polar bearingless machine [10], [11], are proposed to improve the suspension performance, which have advantage of the DC suspension current regulation with elimination of the rotor angular position detection for suspension control. However, for the consequent-pole bearingless machine, the PM on the rotor limits the operation for the harsh environment application. The two-section structure of the homo-polar bearingless machine increases the axis length and reduces the power density. The hybrid stator pole structure of BSRMs have been proposed [12], [13]. The suspension force stator pole and torque stator pole are separated and the suspension force is independently controlled. However, the power density is relatively low and the torque ripple is higher due to only part of the stator poles are used for generating torque. The double stator BSRM [14], and BSRM with an axial magnetizing biased PM [15], also have the DC suspension winding on stator and the suspension force control is convenient.

The conventional doubly salient electro-magnetic machine (DSEM) has inherently simple and reliable structure like the switched reluctance machine (SRM) [16]. It has further advantages of simplified generating control since the rotor angular position detection is not required and the simple diode rectifier is used for generating operation [17]. With the suspension windings placed in the stator based on the magnetic field distribution characteristics of the DSEM, a new bearingless doubly salient electro-magnetic machine (BDSEM) is presented. The armature windings and suspension windings are naturally decoupled, due to the independent DC field winding in stator. The magnetic flux produced by the DC current in the field winding can be used for both torque and suspension force generation. The suspension force is generated by DC current in the suspension windings. The rotor angular position detection is eliminated for the suspension control.

However, the instantaneous suspension force cannot be held constant due to the salient pole structure of the BDSEM. The suspension force ripple has high frequency and is filtered by the mechanical inertial of the rotor at high speed. In contrast, at medium speed, the ripple could cause rotor radial position oscillation when the suspension current loop response is not fast.

In this paper, the rotor pole design is optimized to improve the suspension and generating performance of the proposed BDSEM. The suspension force ripple has high frequency and is filtered by the mechanical inertial of the rotor at high speed. In contrast, at medium speed, the ripple could cause rotor radial position oscillation when the suspension current loop response is not fast.

In this paper, the suspension and generating performance of the proposed BDSEM is studied. The suspension principle is introduced and the mechanism of suspension force ripple is investigated. It is found that with the reasonable rotor pole width, the suspension force ripple is reduced and the improved generating performance could be achieved.

II. CONFIGURATION AND OPERATION PRINCIPLE

A. Configuration

Fig. 1 shows the configuration of the new proposed BDSEM. It inherits the advantages of robust structure of SRM. The configurations of three phase armature windings and DC field winding are the same as the conventional DSEM. The field winding provides the magnetic flux which is used for both torque and suspension force generation. The
suspension windings $W_{sx}$ and $W_{sy}$ consist of two coils connected in series respectively, to provide suspension flux $\psi_{sx}$ and $\psi_{sy}$.

**B. Suspension Principle**

Fig. 2 (a) shows the principle of suspension force generation. The dominant field flux $\psi_f$ is generated by the DC current in the field winding. The suspension flux $\psi_{sy}$ generated by the suspension current $i_{sy}$ is superimposed on it. Then the air gap flux density at the angle of 90° is increased, while the flux density at the angle of 270° is decreased as shown in Fig. 3. Thus a suspension force is generated along the positive $Y$-axis when the rotor angle $\theta_r$ is 0°. When the rotor angle $\theta_r$ is 22.5°, the suspension force is also generated along the positive $Y$-axis, as shown in Fig. 2 (b).

**III. MECHANISM OF SUSPENSION FORCE RIPPLE**

Table I shows the key parameters of the BDSEM. Fig. 4 shows the $Y$-axis average suspension force of the BDSEM with different field current under no-load condition. It exhibits good linearity and decoupled characteristics between the orthogonal suspension windings. The suspension force is decreased due to the core saturation when the field current is increased as shown in Fig. 5.

However, the salient rotor pole structure results in the instantaneous suspension force ripple, which has an impact on the suspension control. Fig. 6 shows the $Y$-axis instantaneous suspension force when the field current $I_f$ is 2A. It can be seen that the suspension force is varying in different rotor position. Particularly, the force ripple is increased with the increase of suspension current $I_{sx}$.

When the suspension current $I_{sy}$ is zero, $I_{sx}$ is 1A, and rotor angle $\theta$ is 15°, the suspension force reaches its maximum along the negative $Y$-axis. Fig. 7 shows the normal component of air gap flux density at the rotor angle of 15°. Since the DC current is applied in the suspension winding $W_{sx}$, the normal flux density $B_{n2}$ and $B_{n4}$ are not equal, as shown in Fig. 7 and Fig. 8, while the normal component of...
flux density $B_{n1}$ and $B_{n3}$ are equal. Therefore, the $Y$-axis suspension force is generated at the rotor angle $15\,^\circ$ without suspension current $I_{sy}$.

IV. INFLUENCE OF ROTOR POLE WIDTH ON SUSPENSION PERFORMANCE

The influence of the rotor pole width on the suspension performance is investigated by finite element method (FEM). The rotor pole width coefficient $k$ is defined as

$$k = \frac{W_p}{W_sp}$$

where $W_p$ and $W_sp$ are the rotor pole width and stator pole width respectively.

When the rotor pole is broadened, the flux density $B_{n1}$ and $B_{n3}$ is increased as shown in Fig. 9 and Fig. 10, which contributes to increase of the $Y$-axis suspension force, as shown in Fig. 11(a). It is worth noting that the flux density $B_{n1}$ is decreased with the broadened rotor pole when the field current is increased as shown in Fig. 10. Therefore, when the field current is increased, the suspension force is decreased with the broadened rotor pole as shown in Fig. 11(b).

The suspension force ripple coefficient $\gamma$ is defined as
where $F_{\text{max}}$, $F_{\text{min}}$, and $F_{\text{avg}}$ are the maximum, minimum, and average suspension force during one period. The suspension force ripple is reduced with the broadened rotor pole as shown in Fig. 12.

The flat-top and sharp-bottom phase flux linkage appears
with the broadened rotor pole as shown in Fig. 13 (a). The peak to peak value of the phase flux linkage is a significant parameter for generating operation, since the induced phase voltage is expressed as

\[ e = -\frac{d\psi}{dt} = -\frac{d\psi}{d\theta} \cdot \omega. \]  

where \( \psi \) is the phase flux linkage, and \( \omega \) is the rotation speed. Therefore, the generating performance is improved when the rotor pole width coefficient \( k \) is 1.2.

V. CONCLUSION

In this paper, the mechanism of suspension force ripple of the new BDSEM is investigated, and the influence of rotor pole width on the suspension and generating performance is analyzed. The suspension force ripple is reduced with the broadened rotor pole. Meanwhile, the improved generating performance is achieved when the rotor pole width coefficient \( k \) is 1.2. The new BDSEM, with advantages of robust structure and simplified and decoupled control, is a promising option for operating in harsh environment and high speed application, such as the internal starter/generator system for the next generation more electric aircraft.

VI. REFERENCES


Li Yu (S’15) received the B.S. degree in electrical engineering from Nanjing University of Technology, Nanjing, China, in 2011 and the M.S. degree in electrical engineering from Nanjing University of Aeronautics and Astronautics, Nanjing, in 2014. He is currently working toward the Ph.D. degree in electrical engineering at the Center for More-Electric-Aircraft Power System, Nanjing University of Aeronautics and Astronautics. His main research interests include design and control of new reluctance machines for aircraft power and electric vehicles, and renewable energy generation systems.

Zhuoran Zhang (M’09–SM’12) received the B.S. degree in measurement engineering and the M.S. and Ph.D. degrees in electrical engineering from Nanjing University of Aeronautics and Astronautics (NUAA), Nanjing, China, in 2000, 2003, and 2009, respectively. Since 2003, he has been a member of the faculty of the Department of Electrical Engineering, NUAA, where he is currently a Professor and the Vice Director of the Jiangsu
Provincial Key Laboratory of New Energy Generation and Power Conversion. From February 2012 to June 2013, he was a Visiting Professor at the Wisconsin Electric Machines and Power Electronics Consortium, University of Wisconsin–Madison, Madison, WI, USA. His research interests include design and control of permanent-magnet machines, hybrid excitation electric machines, and doubly salient electric machines for aircraft power, electric vehicles, and renewable energy generation. He has authored or coauthored more than 80 technical papers and one book, and is the holder of 25 issued patents in these areas.

Wenjing Lu received the B.S. degree in electrical engineering from Nanjing University of Aeronautics and Astronautics, Nanjing, China, in 2015. She is currently working toward the M.S. degree in electrical engineering at Nanjing University of Aeronautics and Astronautics. Her main research interests include design and control of bearingless doubly salient machine.

Yuke Shi is currently working toward the B.S. degree in electrical engineering from Nanjing University of Aeronautics and Astronautics, Nanjing, China. His main research interests include electric machine.