<table>
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<tr>
<th><strong>Title</strong></th>
<th>A novel flux-controllable vernier permanent-magnet machine</th>
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<td><strong>Citation</strong></td>
<td>The IEEE International Magnetic Conference (INTERMAG2011), Taipei, Taiwan, 25-29 April 2011. In IEEE Transactions on Magnetics, 2011, v. 47 n. 10, p. 4238-4241</td>
</tr>
<tr>
<td><strong>Issued Date</strong></td>
<td>2011</td>
</tr>
<tr>
<td><strong>URL</strong></td>
<td><a href="http://hdl.handle.net/10722/140224">http://hdl.handle.net/10722/140224</a></td>
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I. INTRODUCTION

HIGH speed operation with flux weakening control and low speed operation with high torque output are always two very attractive features for electric machine design. Recently, a new kind of flux-controllable permanent-magnet (PM) machines are presented, which can effectively offer the airgap flux control for wind power generation and electric vehicles [1]–[3]. Vernier machines also draw much attentions in recent years since they have the outstanding feature of providing low speed operation with high torque output [4], [5]. However, until now, there is no any report on the integration of these two distinct features into one machine design.

The purpose of this paper is to propose a novel flux-controllable vernier PM (FCVPM) machine, which artfully integrates these two merits for offering the low speed high torque output and providing the high speed flux weakening control. The key is to use the vernier structure for achieving the gear effect and hence obtaining the high torque output at low speed operation, and adopt the DC field winding for performing the flux weakening control for high speed operation. The detailed machine design and operation principle will be discussed and analyzed. Also, the time-stepping finite-element-method (TS-FEM) will be developed to verify the validity of the machine design.

II. MACHINE DESIGN

Fig. 1 shows the proposed FCVPM machine, which has 22 pole-pair PMs, 24 salient flux modulation poles in the inner stator, and 6 embedded large slots for accommodating the armature windings and DC field windings. The detailed machine configuration and characteristics are given as follow.

For the outer rotor, it is made of solid iron and locates 22 pole-pair PMs in the inner surface. Since the outer rotor is very simple, it is easily for manufacture and achieves the merits of robustness and reliability for intermittent operation. Also, the outer-rotor topology enables full utilization of the inner space for other machine components. For the inner stator, the salient-pole embedded-slot vernier structure is adopted for the machine design. Namely, the salient poles play the role of flux modulation, whereas the embedded slots accommodate the three-phase armature windings and the DC field windings. So, when the flux is first modulated by the salient poles in the stator and then goes through the PM poles in the rotor, the PM poles server as the teeth of regular gear. That is, a small movement of the rotor makes a large change in the flux, which results in a high torque output. This phenomenon is called the "magnetic gear effect" [4]. On the other hand, when the DC field current is added during high speed operation, the airgap flux density can be effectively weakened. Thus, this machine achieves the merits of low speed operation with high torque output and high speed operation with flux weakening control.

The vernier structure for the machine tooth-pole arrangement is governed by

\[ N_r = N_s - p_s \]  

(1)

where \( N_r \) is the number of rotor PM pole pairs, \( N_s \) is the number of flux-modulation salient poles, and \( p_s \) is the number of armature winding pole pairs [4]. Hence, the corresponding high-to-low speed ratio \( G_r \) is governed by

\[ G_r = \frac{|i p_s + j N_s|}{i p_s} \]  

(2)

where \( i = 1, 3, 5, \ldots \) and \( j = 0, \pm 1, \pm 2, \ldots \) [4], [5]. When \( i = 1 \) and \( j = -1 \), the largest space harmonic component is obtained.

Furthermore, the relationship between the \( N_s \) and the \( p_s \) can be given as

\[ N_s = m \times p_s \times k \]  

(3)
where \( m \) is the number of winding phases and \( k \) is the flux-modulation poles per phase per armature pole. Usually, it has \( k = 2, 3, 4, 5, \ldots \). So, in this machine design, the parameters are selected for \( m = 3, p_s = 2 \), and \( k = 4 \). Then, it has \( N_s = 24, N_r = 22 \), and \( G_c = 11 \). It means that the rotor speed is only 1/11 of that in stator for armature rotating field speed. Thus, when the rotor speed is 200 rpm, the speed of armature rotating magnetic field in stator is scaled up to 2200 rpm.

Therefore, with the outer-rotor topology, this FCVPM machine has the following distinct features and merits.

- The proposed FCVPM machine artfully integrates the vernier structure and the field windings together, which readily provides the high torque output at low speed operation and flux weakening control at high speed operation. Hence, it has the great potential for different applications, such as the direct-drive applications for wind power generation and electric vehicles.
- The outer-rotor nature can make the machine directly couple with the other rotating components, hence removing the mechanical transmission and improving the transmitted effectiveness. For instance, the outer-rotor topology enables the rotor directly coupling with the wind blades, hence constituting the direct-drive wind power generation system. Also, the outer-rotor structure allows the machine directly connect with the tire rim of EVs, hence easily forming the in-wheel motor drive system. In addition, the outer-rotor configuration inherently offers a large diameter to accommodate a large number of PM poles, which usually requires for vernier machines [4], [5].
- The inner stator adopts the salient modulation poles, which can effectively module the low harmonic components, namely fundamental space harmonics, to yield the high space harmonics in the airgap. Also, the embedded-slot vernier structure can not only fully use the stator space but also reduce the armature winding slot number and hence enlarge the slot area for more conductors. In addition, the multi-pole fractional-slot of the inner stator to rotor (24/22) can significantly reduce the cogging torque which usually occurs at conventional PM machines. Moreover, the concentrated winding structure can effectively reduce the phase shifting and hence increasing the power density.

III. MACHINE ANALYSIS

Since the proposed FCVPM machine has two sets of windings (the armature winding and DC field winding), its operation principle has some difference from the traditional PM brushless machines. Also, because of the unique structure and operation principle, the time-stepping finite-element method is employed for the machine performance analysis.

A. Operation Principle Analysis

In general, the PM brushless machines can operate in BLDC or BLAC mode according to the trapezoidal or sinusoidal shape of the no-load electromotive force (EMF) waveforms [6], [7]. But it should be noted that any PM brushless machine can operate at either BLDC or BLAC mode when it needs. For the proposed FCVPM machine, Fig. 2 shows the corresponding BLDC and BLAC operation modes. When it works in BLDC/BLAC mode, its conduction angle is 120 degree/180 degree.

The electromagnetic torque \( T_e \) of this machine consists of three components, namely the PM torque component \( T_{pm} \), its conduction angle is 120 degree/180 degree.

The electromagnetic torque \( T_e \) of this machine consists of three components, namely the PM torque component \( T_{pm} \), which is due to the interaction between the PM flux linkage \( \Psi_{pm} \) and the armature phase current \( i \). The DC field torque component \( T_f \) which is due to the interaction between the DC field flux linkage \( \Psi_f \) and \( i \), and the reluctance torque component \( T_r \) which is due to the variation of the winding inductance \( L \). Its mathematical expression is written by

\[
T_e = T_{pm} + T_f + T_r = i \frac{d\Psi_{pm}}{d\theta} + i \frac{d\Psi_f}{d\theta} + \frac{1}{2} L \frac{d^2 i}{d\theta^2}
\]  (4)

where \( \theta \) is the rotor position. It should be noted that the PM torque component essentially dominates the torque production, whereas the reluctance torque component is minor and pulsating with zero average value. So, when the flux linkage increases with the rotor position, a positive armature current is applied with the conduction angle 120 degree for BLDC mode or 180 degree for BLAC mode, resulting in a positive torque. When the flux linkage decreases with the rotor position, a negative armature current is applied, also resulting in a positive torque. Meanwhile, according to the machine working condition and operation speed, the DC field current is added to weaken the flux linkage, and hence the DC field torque component. Namely, when this machine operates for direct-drive application at low speed operation, no DC field current will be added, hence maintaining the high torque output. When the machine requires the flux weakening control at high speed operation, the DC field current will be added, hence effectively reducing the airgap flux density.

The basic control circuits of this FCVPM machine are similar with the conventional types of PM BLDC or BLAC machines [3], [7], except for the control circuit of the DC field winding. Fig. 3 shows the power circuit for the DC field current control, which is actually a typical H-bridge converter. Hence, both the magnitude and the direction of the DC field current can be easily regulated by adjusting the duty cycle of the selected conductive switches.
is the field solution region, the conductor/magnetic vector potential, the applied voltage, the damping coefficient, the remnant flux density. Second, the armature circuit equation of the machine during motoring is given as:

\[ \Omega : \frac{\partial}{\partial x} \left( v \frac{\partial A}{\partial x} \right) + \frac{\partial}{\partial y} \left( v \frac{\partial A}{\partial y} \right) = -J - v \left( \frac{\partial B_{xy}}{\partial x} - \frac{\partial B_{yx}}{\partial y} \right) + \sigma \frac{\partial A}{\partial t} \]

where \( \Omega \) is the field solution region, \( A \) the magnetic vector potential, \( J \) the current density, \( v \) the electrical conductivity, and \( B_{xy}, B_{yx} \) the remnant flux density. Second, the armature circuit equation of the machine during motoring is given as:

\[ u = R \dot{i} + L_e \frac{di}{dt} + \frac{1}{S} \int_{\Omega_e} \frac{\partial A}{\partial t} d\Omega \]

where \( u \) is the applied voltage, \( R \) the winding resistance, \( L_e \) the end winding inductance, \( i \) the axial length, \( S \) the conductor area of each turn of per phase winding, and \( \Omega_e \) the total cross-sectional area of conductors of each phase winding. Third, the motion equation of the machine is given by:

\[ J_m \frac{d\omega}{dt} = T_e - T_L - \lambda \omega \]

where \( J_m \) is the moment of inertia, \( \omega \) the mechanical speed, \( T_L \) the load torque, and \( \lambda \) the damping coefficient.

Consequently, after discretizing the equations of (5)–(7), the TS-FEM model can be deduced. Fig. 4 shows the no-load magnetic field distributions with and without filed currents. It can be seen that the flux lines are effectively modulated by the split poles on the stator teeth and go through the PM poles, hence verifying the desired flux modulation effect. Also, with the DC field current, the flux lines are effectively weakened in some modulation poles and leak in the winding slots.

**B. TS-FEM Analysis**

The TS-FEM is developed to analyze the machine performances. First, the electromagnetic field equation of the proposed machine is governed by [8]:

\[ \Omega : \frac{\partial}{\partial x} \left( v \frac{\partial A}{\partial x} \right) + \frac{\partial}{\partial y} \left( v \frac{\partial A}{\partial y} \right) = -J - v \left( \frac{\partial B_{xy}}{\partial x} - \frac{\partial B_{yx}}{\partial y} \right) + \sigma \frac{\partial A}{\partial t} \]

where \( \Omega \) is the field solution region, \( A \) the magnetic vector potential, \( J \) the current density, \( v \) the electrical conductivity, and \( B_{xy}, B_{yx} \) the remnant flux density. Second, the armature circuit equation of the machine during motoring is given as:

\[ u = R \dot{i} + L_e \frac{di}{dt} + \frac{1}{S} \int_{\Omega_e} \frac{\partial A}{\partial t} d\Omega \]

where \( u \) is the applied voltage, \( R \) the winding resistance, \( L_e \) the end winding inductance, \( i \) the axial length, \( S \) the conductor area of each turn of per phase winding, and \( \Omega_e \) the total cross-sectional area of conductors of each phase winding. Third, the motion equation of the machine is given by:

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**IV. PERFORMANCE ANALYSIS**

With the TS-FEM model, the machine basic characteristics, low speed and high speed operation performances are analyzed. The key design data is given in Table I.

First, the basic characteristics of the proposed FCVPM machine are given in Fig. 5 and Fig. 6. Fig. 5 shows that with the field current, the flux linkage can be effectively weakened. So, it tells that this machine can readily perform flux control. In addition, Fig. 6 shows that all flux density waveforms have 22 pole pairs in the airgap within 360 degree which corresponds to two pole pairs of the stator rotating field, hence verifying the principle of vernier structure. Also, it can be observed that although some parts of the flux density are strengthened by adding the field current, these parts are much less than those are weakened. Thus, the overall effect of the flux density is weakened when adding the field current. The corresponding harmonic spectra also tell that the 2nd, 22nd, 44th, 66th, and 110th have the prominent values due to the modulation effect. And the 22nd spectrum is effectively weakened by applying the DC field current.

Second, the low speed (rated speed of 200 rpm) operation performances of this machine are given in Fig. 7 and Fig. 8. From Fig. 7(a), it can be found that the no-load EMF waveform is more like trapezoidal than sinusoidal. It tells that the machine can usually operate in BLDC mode, but may work in BLAC mode when needed. As expected, from Fig. 7(b), it can be seen that the machine can offer a high torque output, which is up to 100 Nm. In addition, Fig. 8 shows the torque performances of the machine. It can be observed that the average steady torque is about 90.0 Nm. And the steady torque ripple is 11.8%, which is much lower than those of doubly-salient machines [6], [7]. Also, the cogging torque is very small, namely 3.4% of the steady torque, which verifies the design idea of the multi-pole fractional-slot structure.

**TABLE I**

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
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<tr>
<td>Rated power</td>
<td>2 kW</td>
</tr>
<tr>
<td>Rated torque</td>
<td>90 Nm</td>
</tr>
<tr>
<td>Speed range without field current</td>
<td>200 rpm</td>
</tr>
<tr>
<td>Number of phases</td>
<td>3</td>
</tr>
<tr>
<td>Number of rotor pole pairs</td>
<td>22</td>
</tr>
<tr>
<td>Number of flux modulation poles</td>
<td>24</td>
</tr>
<tr>
<td>Rotor outside diameter</td>
<td>246.0 mm</td>
</tr>
<tr>
<td>Number of DC winding poles</td>
<td>6</td>
</tr>
<tr>
<td>Rotor inside diameter</td>
<td>211.2 mm</td>
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<tr>
<td>Stator outside diameter</td>
<td>210.0 mm</td>
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<tr>
<td>Stator inside diameter</td>
<td>40.0 mm</td>
</tr>
<tr>
<td>Stack length</td>
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<tr>
<td>Resistance of phase winding</td>
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Fig. 6. Airgap flux density and its harmonic spectrum with different field currents. (a) 0 A/m². (b) 2 A/m². (c) 5 A/m².

Fig. 7. Low speed operation performances. (a) No-load EMF. (b) Torque-angle ability.

Fig. 8. Torque performances.

Third, the high speed (1000 rpm) operation performances are shown in Fig. 9. It can be seen that the EMFs obviously reduced with adding the field current, hence proving the validity of the flux control. Also, from Fig. 9(d), it can be found that the amplitudes of the EMFs nearly linearly decrease with the field current. It tells that the machine has the good flux control ability.

V. CONCLUSION

This paper presents a novel FCVPM machine for direct-drive applications. Since the machine adopts the vernier structure and introduces the field winding, it can readily achieve the high torque output at low speed operation and the flux weakening control at high speed operation. The machine characteristics and performances prove the validity of the machine design and the capability for both low speed and high speed operations.

ACKNOWLEDGMENT

This work was supported and funded by the grants of HKU Small Project Funding 201007176302 and HKU Strategic Research Theme and the University Development Funding (Initiative on Clean Energy & Environment, ICEE), Hong Kong Special Administrator Region, China.

REFERENCES