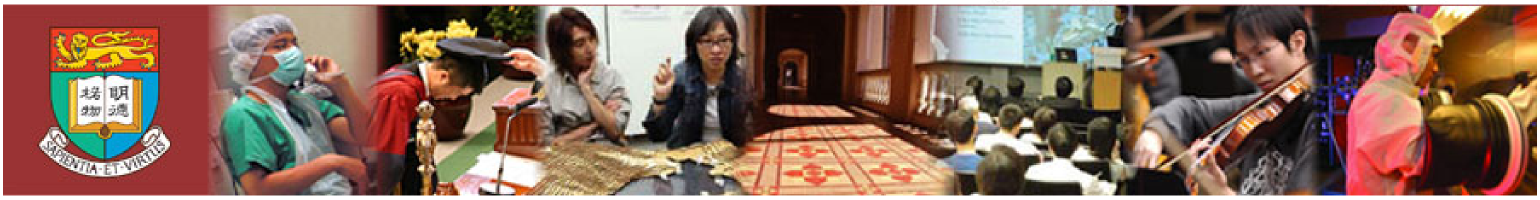

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Design and Analysis of a Flux-Controllable Linear Variable Reluctance Machine

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***Abstract*—This paper proposes a linear variable machine equipped with a set of field winding which is capable for adjusting the air-gap flux. As conventional variable reluctance machines, the proposed machine has a doubly salient structure and no permanent magnets or windings on the mover. The distinct feature of the proposed machine is that there are both the ac armature winding and the dc field winding in the stator. By inviting the dc field winding, the proposed machine not only has the flux control capability, but also realizes the bipolar operation. In this paper, the proposed machine design and its operating principle are presented and discussed. Then, a two-phase machine in modular design is dimensioned. By using the three-dimensional finite element analysis, both the steady and transient performances are quantitatively analyzed and evaluated.**

***Index Terms*—Bipolar operation, flux control, linear machine, variable reluctance machine.**

I. Introduction

VARIABLE reluctance machines are doubly salient machines that possess the excitation windings on the stator. The rotor only consists of iron lamination; hence its reliability and robustness is superb. The torque or thrust is developed by the tendency of the moving part aligning with the stationary part to maximize the corresponding flux linkage. However, due to the singly excitation nature, especially in the generating mode, the so-called excitation penalty is suffered which degrades its power density and efficiency. For solving this problem, permanent magnets (PMs) are equipped in the stator, so the doubly-salient permanent magnet (DSPM) machines, flux-reversal permanent magnet machines (FRPM) and flux-switching permanent magnet (FSPM) machines are proposed respectively [1]–[3]. Nevertheless, as other PM machines, the utilization of PMs results in uncontrollable air-gap flux and a limited constant-power operation range [4].

The purpose of this paper is to present a linear variable reluctance machine which is doubly excited by both armature winding and field winding. Therefore, the excitation penalty existing in traditional variable reluctance machines can be avoided. Furthermore, by using dc field winding for excitation, the air-gap flux is controlled flexibly thus extending the constant-power range.

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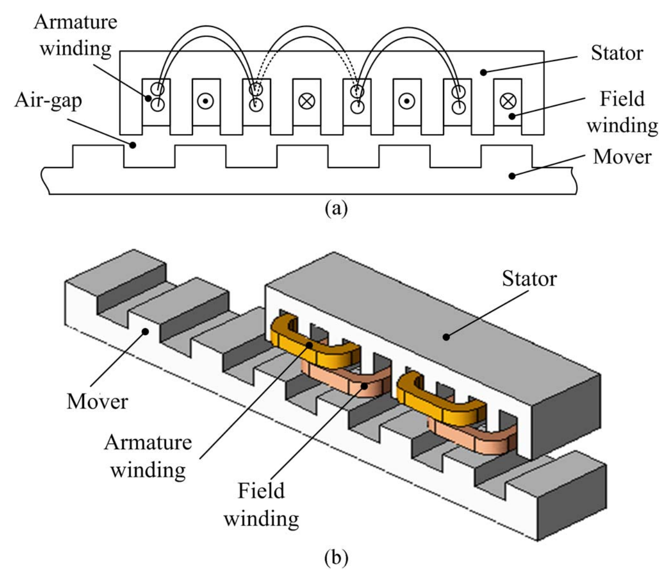

Fig. 1. One phase of the proposed linear variable reluctance machine. (a) 2-D topology. (b) 3-D topology.

II. Machine Design

A. Machine Configuration

The single phase configuration of the proposed linear variable reluctance machine is shown in Fig. 1. It consists of a passive salient-pole mover and a salient-pole stator equipped with windings. Its structure is very similar to the conventional switched reluctance machine (SRM). The mover is simply composed of iron core with no windings or PMs. This contributes a very low inertia and gives robustness for high speed operation. Other than one set of windings in the SRM, the proposed machine has both the armature winding and the field winding interleaving each other in the stator [5]. Also, compared with the concentrated winding in the SRM, the armature and field of the proposed machine adopt full-pitch distributed winding where the coil span is equal to slot pitch of the mover. The armature winding and the field winding are fed with trapezoidal ac current and continuous dc current respectively. By deploying the dc field winding, the air-gap flux can be adjusted without changing the firing angles and the excitation penalty in the SRM is also eliminated.

Although its topology is doubly salient, the relationship of the stator pole number and the rotor pole number is different from that of the SRM. In the proposed machine, the slot number is adopted here instead of the pole number. Due to the invitation of the field winding and the location of two windings, the stator slot number N_s and the mover slot number N_m is governed by:

$$\begin{cases} N_s = 4k \\ N_m = \frac{N_s}{2} = 2k \end{cases} \tag{1}$$

where k is a positive integer. The adoption of more slots, namely a large number of mover and stator poles can result in a smooth thrust force which is similar to that of the SRM. In this paper $k = 2$ is chosen for one phase, hence, resulting in a 16/8-slot two-phase linear machine.

B. Operating Principle

As with other variable reluctance machines, the developed thrust of the proposed machine is also generated by the variation of air-gap reluctance. However, because of the full-pitch arrangement of the armature winding and the field winding in the proposed machine, the variations of their self-inductances are negligible, and the variation of their mutual-inductance is significant. This makes a distinct difference between the SRM and the proposed machine.

The flux linkage of the armature winding and the filed winding are given by:

$$\psi_a = L_a i_a + M_{af} i_f \tag{2}$$

$$\psi_f = L_f i_f + M_{af} i_a. \tag{3}$$

The magnetic co-energy W_{co} due to the two excitation windings can be obtained by:

$$W_{co} = \int (\psi_a + \psi_f)(di_a + di_f) = \frac{1}{2} L_a i_a^2 + \frac{1}{2} L_f i_f^2 + M_{af} i_a i_f. \tag{4}$$

Therefore, the electromagnetic force can be determined by differentiating the magnetic field co-energy:

$$\begin{aligned} F_{em} &= \frac{dW_{co}}{dx} = \frac{1}{2} i_a^2 \frac{dL_a}{dx} + \frac{1}{2} i_f^2 \frac{dL_f}{dx} + i_a i_f \frac{dM_{af}}{dx} \\ &= T_a + T_f + T_{af} \end{aligned} \tag{5}$$

where L_a, L_f and M_{af} are the armature winding self-inductance, the field winding self-inductance and the mutual-inductance of the two windings, respectively; i_a and i_f are the armature current and field current, respectively; T_a is the armature reluctance force component which is due to the variation of the armature self-inductance, T_f is the field reluctance force component which is due to the variation of the field self-inductance, and T_{af} is the mutual reluctance force component which is due to the variation of the mutual inductance of the two sets of windings.

Compared to the conventional SRM, the distinct feature of the proposed machine is that by special selection of slot numbers according to (1) and slot-pitches of the stator and mover, the armature winding self-inductance and the field winding self-inductance is kept unchanged along with the mover movement and only the mutual inductance varies periodically, therefore, only the last item in (5) contributes the electromagnetic thrust force generation. As shown in Fig. 2, the field winding is fed all the time, while the armature winding is fed with ac current according to the mutual-inductance variation. Due to the bipolar operation, all the windings are energized for torque production simultaneously, hence fully utilizing the copper.

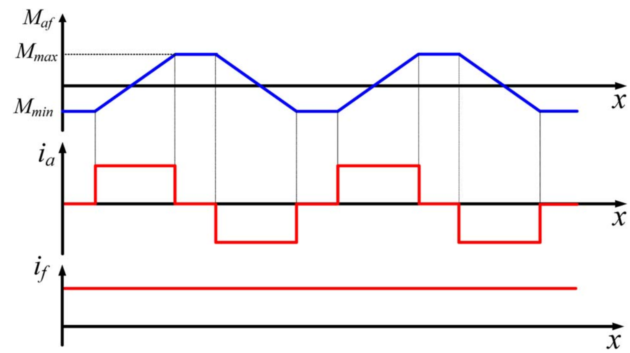

Fig. 2. Proposed machine operating principle.

TABLE I
KEY DESIGN DATA

Rated power	1.5 kW
Phase No.	2
Rated voltage (RMS)	50 V
Rated current (RMS)	15 A
Stator length	305.0 mm
Area per stator slot	218.3 mm^2
Stack length	300.0 mm
Mover pole-pitch	18.0 mm
Mover slot depth	10.0 mm
No. of turns per armature coil	50
No. of turns per field coil	100

For generating mode operation, the proposed machine operates simply as other PMAC machines [6] which do not need to control firing angles as the SRM do. Therefore, the excitation penalty in the SRM can be eliminated and the power generation efficiency is improved. According to (2), the generated voltage of the armature winding is determined by:

$$e = \frac{d\psi_a}{dt} = i_f \frac{dM_{af}}{dx} \frac{dx}{dt} = i_f U_m \frac{dM_{af}}{dx} \tag{6}$$

where U_m is the mechanical speed of the mover. According to (6), the amplitude of the induced voltage can be controlled by adjusting the fed field current, hence the output voltage can be maintained under different operating speeds and the operation range can be extended simply by flux weakening.

III. Machine Analysis

Since each phase operates independently, the proposed machine is very suitable for modular design which may greatly simplify the machine fabrication. In this paper, a two-phase linear machine is dimensioned and its key design data is shown in Table I. For assessing its steady and transient performances in both motoring and generating modes, the 3-D finite element method (FEM) is engaged for the magnetic field calculation.

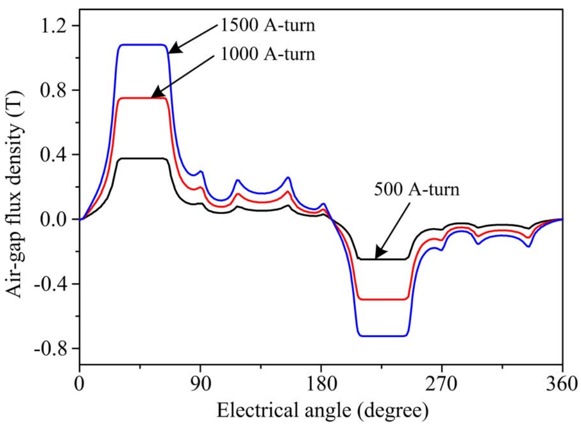

Fig. 3. No-load air-gap flux density under different MMFs of the field winding.

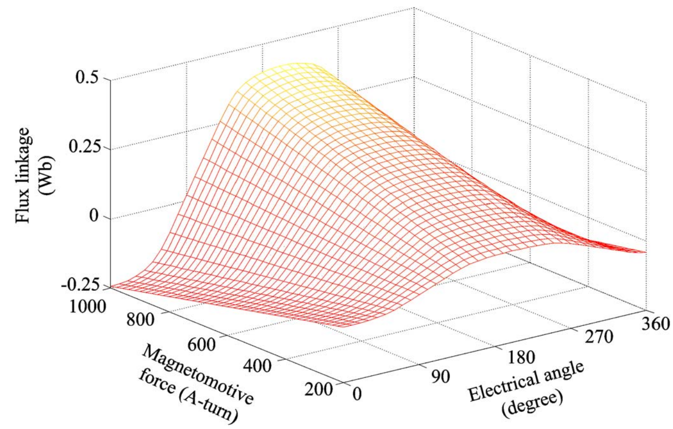

Fig. 5. Flux linkages of the field winding when phase A is excited under different MMF levels.

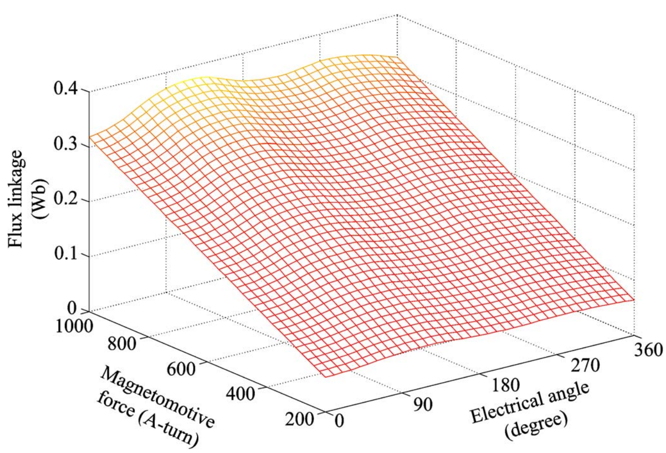

Fig. 4. Flux linkages of phase A when phase A is excited under different MMF levels.

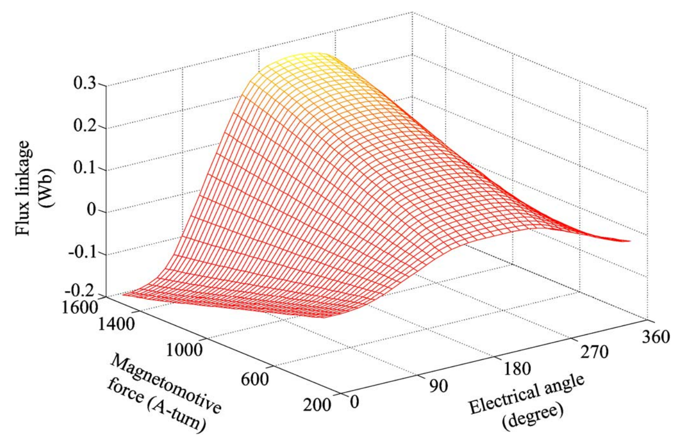

Fig. 6. Flux linkages of phase A when the field winding is excited under different MMF levels.

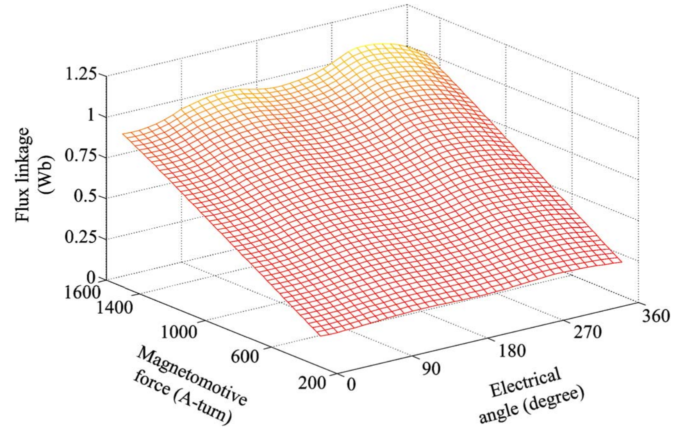

Fig. 7. Flux linkages of the field winding when the field winding is excited under different MMF levels.

Fig. 3 shows the no-load air-gap flux density under different magnetomotive forces (MMFs) of the field winding. It can be found that the air-gap flux density is proportional to the field current. Therefore, for the high-speed operation, the flux weakening control can be easily attained without tuning the firing angles. When only phase A is excited under different MMF levels and the mover travels a pole-pitch length, the flux linkages of phase A and field winding are shown in Figs. 4 and 5 respectively. Similarly, when only the field winding is excited under different MMF levels and the mover travels a pole-pitch length, the flux linkages of phase A and the field winding are shown in Figs. 6 and 7, respectively. It confirms that the armature winding self-inductance L_a and the field winding self-inductance L_f vary little whereas their mutual-inductance M_{af} has a distinct variation along with the mover motion which is the key for the machine operation. When the armature winding is fed with appropriate ac current, the constant thrust can be generated. Fig. 8 shows the developed thrust due to each phase and their resultant thrust force waveform at 1 m/s. Due to the bipolar operation, the thrust ripple of the proposed machine is satisfactory compared to the SRM at the same condition. According to (1), when the two sets of windings are fed at different current densities, the force density of the proposed machine can be computed as shown in Fig. 9. It can be observed that when the field winding is with the current density of 10 A/mm^2 and the armature winding is with the current density of 8 A/mm^2, a force density up to 50 kN/m^2 can be achieved.

Due to the field excitation, the proposed machine does not need to change the firing angle as the SRMs do when running as

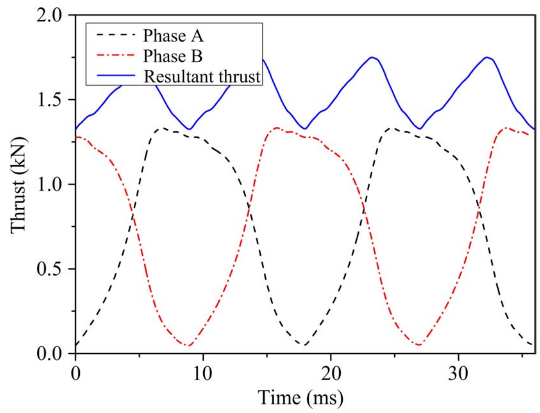

Fig. 8. Developed thrust force under rated condition.

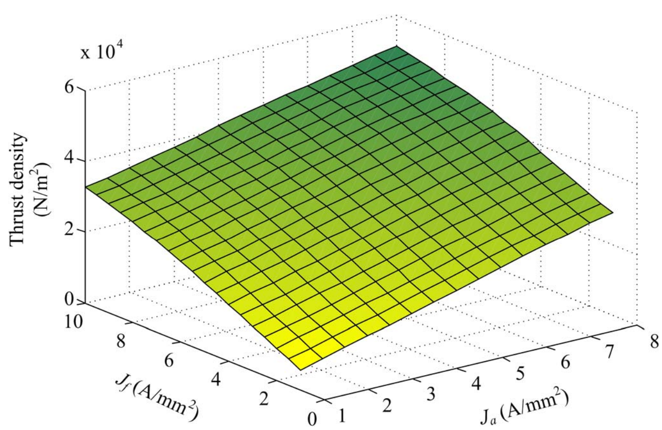

Fig. 9. Thrust density versus armature and field current densities.

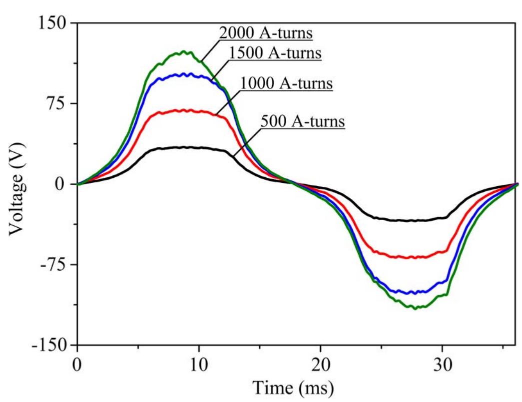

Fig. 10. Induced voltage waveforms at 1 m/s under different MMF levels of the field winding.

a generator, therefore, the excitation penalty and its additional losses can be totally eliminated. Fig. 10 shows the induced voltage waveforms of phase A at 1 m/s under different MMF levels of the field winding. According to (6), the amplitudes of the voltage are proportional to the field current. Since it is easy for adjusting injected current into the field winding, the proposed machine has a high degree freedom of flux control capability which is very similar to hybrid excitation machines [7] and memory machines [8], [9]. Fig. 11 shows the induced voltage waveforms at different speeds. By using

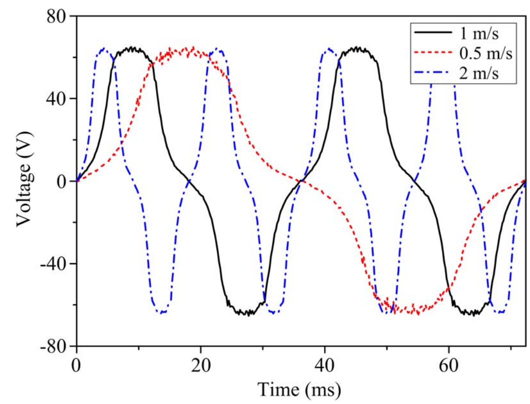

Fig. 11. Induced voltage waveforms at different speeds.

flux control, constant amplitudes of the output voltage can be maintained irrespective of mover speed variation. This feature is very promising for application in renewable power generation because of the fluctuation nature of the renewable energies.

IV. Conclusion

A two-phase flux-controllable linear variable reluctance machine has been proposed and analyzed. The proposed machine has a doubly salient structure which is similar to the conventional SRMs. The stator houses both the full-pitch field winding and the full-pitch armature winding. The mover consists of simple laminated iron core. Due to its salient nature and full-pitch winding configuration, the thrust force is generated due to the variation of the mutual-inductance of two windings. By adjusting the field current, the air-gap flux control can be attained. Therefore, the constant-power range can be extended accordingly. Furthermore, due to the modular design, the proposed machine is very easy to manufacture and assemble.

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