Design and Analysis of a Linear Wound Field Vernier Machine with Partitioned Stator

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Linear machines have been characterized as promising candidates for direct-drive applications such as wave energy conversion and railway traction. This is owing to the elimination of the rotary to linear mechanical interfaces which results in a very simple structure and reduced maintenance cost. In this paper, a novel partitioned stator (PS) linear wound field Vernier (LWFV) (PS-LWFV) machine is presented based on the concept of partitioned stator variable flux reluctance machine (PS-VFRM) and the magnetic gearing effect. The proposed PS-LWFV machine adopts an upper stator and a lower stator in which the armature and field windings are separately located respectively. Compared with the existing single stator LWFV machine, the proposed machine exhibits higher thrust force density and higher efficiency due to the more utilization of inner space and enlarged slot areas. The Genetic Algorithm (GA) is utilized to optimize the machine parameters for maximum thrust force based on a finite element analysis (FEA).

***Index Terms*—Linear machines, partitioned stator, Vernier, magnetic gear effect, wound field machine**

I. Introduction

Recently, linear permanent magnet (PM)Vernier machines incorporating the magnetic gearing effect have attracted extensive attention owing to their high force density, low cost, and high efficiency. In order to overcome the problems of mechanical integrity and thermal instability of the PMs locating in the mover, the linear primary PM Vernier (LPPMV) machine have been presented in which the PMs are located on surface of the stator teeth. Therefore, the mover is only made of iron which is very robust and desirable for high force operation [1], [2]. However, the PM machines have some disadvantages such as growing cost of the rare earth materials, limited working temperature and low field weakening capability. Hence, a low cost linear wound field Vernier (LWFV) machine is proposed in [3] which employs no magnets and offers high reliability. Moreover, this machine has the merit of wide speed range since the current in the field excitation windings can be controlled to adjust the air-gap flux density. However, LWFV machine suffers from geometric conflict between armature and field windings as both of them are located in one part. This paper presents a novel LWFV machine by considering the concept of partitioned stator variable flux reluctance machine (PS-VFRM) [4] and partitioned stator flux reversal PM (PS-FRPM) machine [5].

II. Machine Topology and Operating Principle

The topology of the proposed partitioned stator linear wound field Vernier (PS-LWFV) machine is illustrated in Fig. 1. It can be seen that there are no magnets in the structure and therefore high reliability and low cost can be obtained. The long mover is designed as a simple and robust iron core with modular structure while the armature and field excitation windings are mounted in separate upper and lower stators, respectively. Hence, in contrast to the existing LWFV machine [3], the electric loading and force density are not restricted. The non-overlapping concentrated windings are wound on both active stators which reduce the length of end windings and hence the copper loss. The operating principle of the machine is based on the magnetic gearing effect. The function of 11 translator teeth is to modulate the 9 pole pairs of the magnetic field produced by field winding on the lower stator. This modulation yields an effective air-gap flux distribution with two pole pairs. Thus, the pole pair number of 3-phase armature winding must be equal to two which leads to steady thrust force generation. The proposed PS-LWFV machine and the existing LWFV machine [3] are quantitatively compared in terms of their performance and configuration. By considering some fixed parameters for both machines, a fair comparison is carried out between them based on maximizing the average thrust force under fixed copper loss. The fixed and optimized parameters are listed in Table I.

III. Machine Performance and Comparison

Figs. 2a and 2b depict the waveforms and the harmonic spectra of the no load flux linkages of armature windings. The corresponding THD of flux linkage is 1.48% indicating purely sinusoidal and acceptable waveforms. However, there is a DC component in the flux linkages of phase A and phase C leading to slight asymmetries. This is owing to the longitudinal end effect being one of the intrinsic characteristics of linear machines. The back-EMF waveforms of the proposed machine at the rated speed of 1m/s and their spectra are illustrated in Fig. 3a and 3b. It is evident that the DC component of the flux linkages is eliminated. In addition, the back-EMFs are nearly sinusoidal and the THD is 3.86%. Fig. 4 compares the thrust force of the proposed PS-LWFV machine with the existing LWFV one when the copper loss is 60W and d-axis current is zero. The proposed machine offers 30.43% higher thrust force density compared with the existing one. This can be attributed to the larger slot areas for both armature and field windings which enables higher electric loading when the copper loss is constant but the inner space of the machine is highly utilized. Furthermore, the thrust force ripple of the proposed and the existing machines are 12.51% and 17.31% respectively. This is due to the fact that the proposed PS-LWFV machine benefits from almost symmetric 3-phase sinusoidal back-EMFs. Fig. 5 shows the detent force of the proposed machine. As illustrated in Fig. 5, the peak to peak value of the detent force is 3.08 N which is only 2% of the average thrust force and is acceptable. Fig. 6 depicts the average thrust force versus copper in both proposed and existing machines. It can be observed that the proposed PS-LWFV machine offers higher force density than the existing LWFV type over different values of copper loss and electric load.

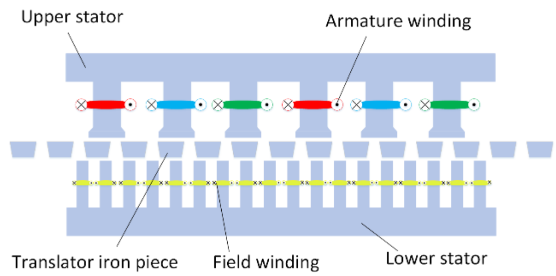
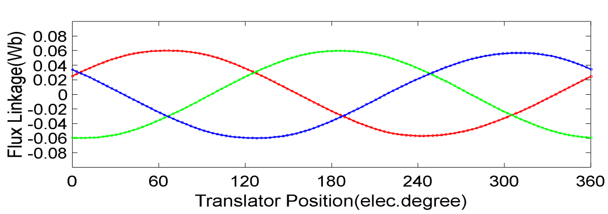


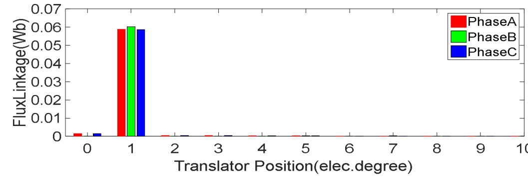
Fig. 1. Configuration of Proposed PS-LWFV machine.

TABLE I
DESIGN PARAMETERS AND PERFORMANCE COMPARISON OF THE PS-LWFV AND EXISTING LWFV MACHINES

Fixed Parameters	Unit	Proposed	Existing
Stator armature teeth number		6	6
Translator tooth number		11	11
Stator field tooth number		18	18
Stack length	mm	70	70
Total machine height	mm	120	120
Machine active width	mm	260	260
Air-gap 1 length	mm	0.5	0.5
Air-gap 2 length	mm	0.5	-
Stator pole shoe total height	mm	6.5	6.5
Armature winding copper loss	W	30	30
Field winding copper loss	W	30	30
Optimized Parameters	**Unit**	**Proposed**	**Existing**
Armature winding slot width	mm	26	19
Armature winding slot height	mm	27.5	19
Field winding slot width	mm	7.5	7.44
Field winding slot height	mm	36	30.5
Translator teeth height	mm	10	11
Translator teeth tip	mm	20	8.5
Translator teeth root	mm	11	9.5
Stator 1 yoke thickness	mm	21	27
Stator 2 yoke thickness	mm	18	-
Translator yoke thickness	mm	-	25
Pole shoe width	mm	26	35.88
Performance Comparison	**Unit**	**Proposed**	**Existing**
Average thrust force	N	150	115
Thrust force ripple	%	12.51	17.31
Iron loss	W	9	8.25
Output power	W	150	115
Efficiency	%	67.14	61

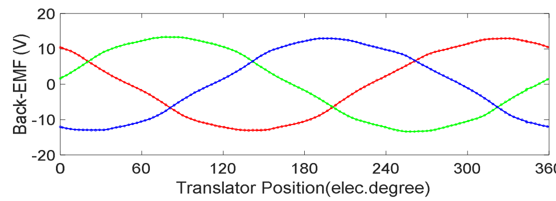


(a)

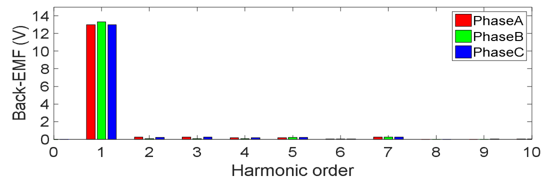


(b)

Fig. 2. Three-phase flux Linkages (a) Waveforms. (b) Harmonic Spectra.



(a)



(b)

Fig. 3. Three-phase back-EMFs (a) Waveforms. (b) Harmonic Spectra.

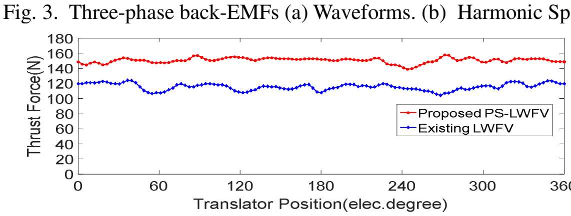


Fig. 4. Rated Thrust Force Waveforms

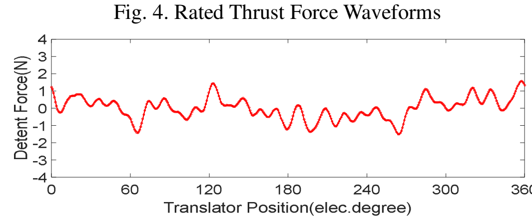


Fig. 5. Detent Force Waveform

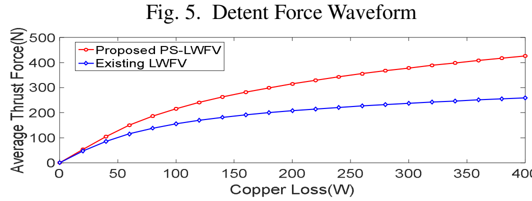


Fig. 6. Average thrust force versus different copper loss values

IV. REFERENCES

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