Research on the Electromagnetic Performance of an Axial Flux Permanent-Magnet Linear Synchronous Machine

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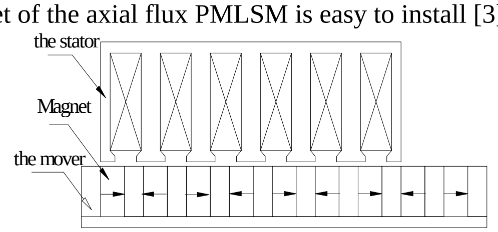
Abstract — A 1kW tubular axial flux permanent-magnet linear synchronous machine (PMLSM) used in Stirling generator system is investigated by the finite-element method (FEM) in this paper. The effect of current density and slot shoulder is analyzed. In order to fulfill the requirement of the temperature, the working temperature is simulated with the software Ansys. Besides, the out performances of the non-uniform velocity compared with those of the uniform velocity, and then we can find that the simulation of the non-uniform velocity is more useful. Moreover, a prototype has been manufactured, and the no-load experiments and load experiments about the prototype have been tested.

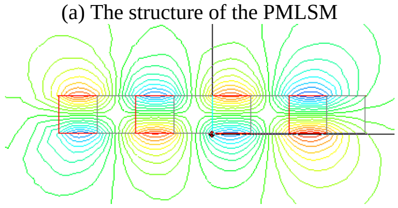
I. INTRODUCTION

This paper focuses on a 3-phase tubular axial-flux permanent-magnet linear synchronous machine (PMLSM) integrated with a free-piston Stirling engine. Compared with the commonly used internal combustion engine, Stirling engine can make use of more energy sources, such as solid fuels, thermal energy from nuclear and solar power. Besides, due to its small tremors, low noise, long life, insusceptible power output and efficiency, Stirling engines are widely considered for space applications[1]-[2].

Electricity is generated by the PMLSM in a Stirling system. The structure and flux distribution of the proposed PMLSM are shown in Fig. 1. The mover is made up of axial-flux permanent magnets. Compared with the radial flux structure, the mover back is abandoned, and the mover magnet of the axial flux PMLSM is easy to install [3]-[5].



(a) The structure of the PMLSM



(b) The flux distribution of the PMLSM

Fig 1.the structure and flux distribution of the PMLSM

In reference [6], a high power density axial-flux PMLSM has been designed, and some key parameters including the inner diameter of the airgap, the width and the thickness of the permanent-magnet rings have been analyzed. In this paper, the effect of the current density and the slot shoulder to the power density is further analyzed.

II. OPTIMIZATION OF THE POWER DENSITY

A. The effect of the current density to the power density

With constant dimensional parameters of the magnets and airgap, the current density is changed from 6A/mm^2 to 7.701 A/mm^2. The performance of the PMLSM with different current densities is shown in Table I.

Table I.Performance comparison of the PMLSM with different current densities

Current density(A/mm^2)	6	7	7.701
Total weight(kg)	3.02	2.925	2.83
Electromagnet power(W)	1186	1136	1006
Copper loss(W)	91.309	110.19	119.955
Efficiency	86.6	86.6	86.5
Power density(kW/kg)	0.303	0.351	0.377

The inner airgap increases with higher current density, and larger power density is achieved. But the current density can not be increased unboundedly due to the limitation of working temperature.

B. The effect of the slot-shoulder to the power density

The comparison of the structures with and without slot shoulder is shown in Table II. By the addition of slot shoulder, the total weight, electromagnet power and power density are increased by 0.92%, 9.7%, and 10.08% respectively.

Table II.The comparison of structures with and without slot shoulder

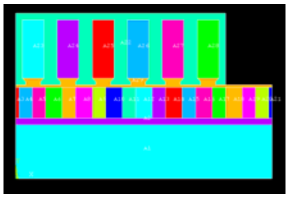
	with slot shoulder	without slot shoulder
Total weight(kg)	2.83	2.804
Electromagnet power(W)	1186	1071
Efficiency	86.5	85.2
Power density(kW/kg)	0.377	0.339

III. THERMAL ANALYSIS OF THE PMLSM

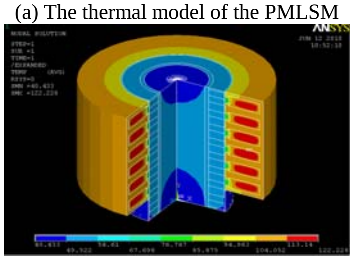
As the PMLSM may work under 70℃ and the maximum allowed temperature is 140℃, this section mainly discuss the thermal performance of the PMLSM.

The power loss of the machine is mainly made up of the copper loss in stator windings, the core loss in stator and mover. Theoretically, the highest temperature occurs in stator windings, as the copper loss is more than the others.

The thermal model and simulation result are shown in Fig. 2. It is found that the highest temperature in the stator windings is 122.3℃ which is still acceptable.



(a) The thermal model of the PMLSM



(b) Simulation result

Fig. 2. The thermal model and simulation result of the PMLSM

IV. THE OUTPUT PERFORMANCE UNDER UNIFORM AND NON-UNIFORM VELOCITIES

To simulate the non-uniform velocity, a rotating machine with crank-link is introduced as prime mover.

The actual velocity can be calculated by

$$v = R\omega \sin\varphi + \frac{1}{2} R\omega\lambda \sin 2\varphi \qquad (1)$$

where the R is crank radius, ω is the angular velocity of the crankshaft, φ is the crankshaft angle, λ is the connecting rod ratio.

With the parameters of the crank-link mechanism, the actual velocity can be described as

$$v = 1400\pi \sin(\varphi) + 49\pi \sin(2\varphi) \qquad (2)$$

And the comparison between the non-uniform velocities described by the equation and the uniform velocity is shown in Fig. 3.

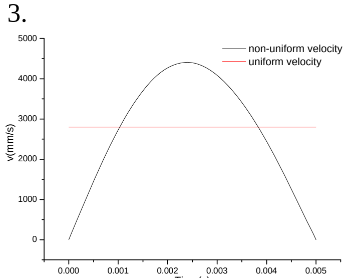
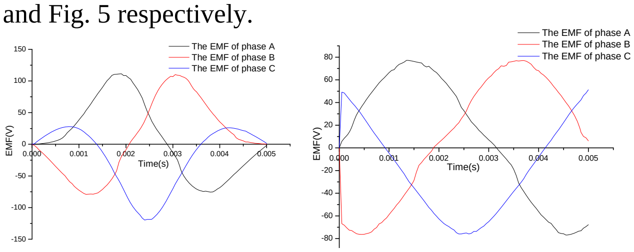
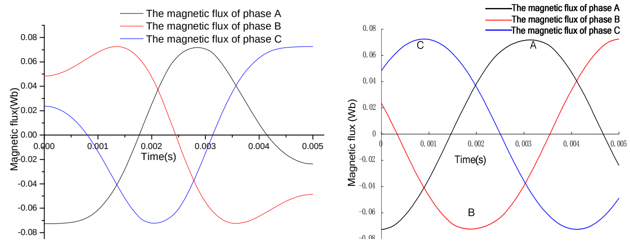


Fig. 3. the comparison of non-uniform and uniform velocities

The performances of both non-uniform and uniform velocities under no load and rated load are shown in Fig. 4 and Fig. 5 respectively.



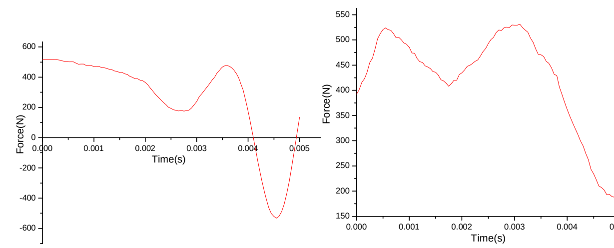
(a) The EMF of non-uniform velocity (b) The EMF of uniform velocity



(c) Magnetic flux of non-uniform velocity (d) Magnetic flux of uniform velocity

Fig. 4. The EMF and magnetic flux under no load

The EMF of the windings is not only related to air-gap magnetic field, but also the waveform of velocity. Therefore the EMF harmonic distortion of non-uniform velocity is larger than that of uniform velocity and so is the magnetic flux. Moreover, the peak value of the non-uniform velocity is larger than that of the uniform velocity, which is more useful for the generator. The frequency of the current in windings is changing because of the non-uniform velocity of the mover, so the force distribution becomes wave shape as is shown in Fig. 5(a).



(a) The force distribution of non-uniform velocity (b) The force distribution of uniform velocity

Fig. 5. The force distribution under rated load

V. PROMOTYPE

A prototype is manufactured, and then the no-load and load experiments of the prototype are carried out. In load experiments, resistance and batteries are used, and high power density and satisfactory electromagnetic performance of the proposed machine are proved.

VI. REFERENCES

[1] Jose A, Riofrio, Khalid Al-Dakkan, Mark E. Hofacker. Control Based Design of Free-Piston Stirling Engines. *American Control Conference*. vol.6, no.11, pp. 1533-1538, 2008.

[2] Vinod Kumar Gopal, Dr. Richard Duke, Dr. Don Clucas. Active Stirling Engine. *IEEE Region 10 Conference TENCON*. 2009, pp. 1-6.

[3] Z.Q.Zhu, X.Chen, D.Howe. Electromagnetic Modeling of a Novel Linear scillating Actuator. *IEEE Transactions on Magnetics*, vol.44, no.11, pp. 3855-3858, 2008.

[4] S.Taghipour Boroujeni, J.Milimonfared, M.Ashabani. Design, Prototyping, and Analysis of a Novel Tubular Permanent-Magnet Linear Machine. *IEEE Transactions on Magnetics*, vol.45, no.12, pp. 5405-5413, 2007.

[5] Yaow-Ming Chen, Shu-Yuan Fan, Wen-Shin Lu. Performance Analysis of Linear Permanent-Magnet Motors With Finite-Element Analysis. *IEEE Transactions on Magnetics*, vol.46, no.4, pp. 377-385, 2010.

[6] Ping Zheng, xuhui Gan, Lin Li. Analysis and Design of a High Power Density Axial Flux Permanent Magnet Linear Synchronous Machine Used for Stirling System. *International Conference on Pervasive Computing*. 2010, pp. 398-400.