Paper: #81

Research on a Tubular Longitudinal Flux PM Linear Generator Used for Free-Piston Energy Converter

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Abstract—The free-piston energy converter (FPEC) is used for a series hybrid electric vehicle (HEV) scheme, which may have the advantages of high efficiency, compact structure and reliable operation. The linear generator is an important part in the FPEC, and a tubular longitudinal flux permanent-magnet (PM) linear generator scheme is investigated in this paper. The electromagnetic and thermal properties of the generator are analyzed with commercial software *Flux 2D*. The generator is optimized from the aspects of material selection and structure optimization. Rare-earth PM material VACODYM 655HR is selected for the permanent magnets, and low-performance low-loss material M235-35A is chosen for the stator lamination. The pole number and machine size are optimized, and the optimum scheme with efficiency of 0.935 and specific power of 1.49kW/kg is obtained, which meets the requirements of FPEC application.

Index terms—Hybrid electric vehicle (HEV), free-piston energy converter (FPEC), linear generator, finite-element method (FEM).

I. INTRODUCTION

Hybrid electric vehicle (HEV) is a good solution to the problems of energy crisis and environmental pollution considering the limit of the energy density of batteries today [1]-[3]. The free-piston energy converter (FPEC) integrates the functions of a

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Project 50577011 supported by National Natural Science Foundation of China.

combustion engine, the crankshaft, the connecting rod, and the rotating electrical generator used in conventional hybrid schemes into a single unit, which may have the advantages of high efficiency, compact structure and reliable operation [4]-[6]. It has promising applications in series hybrid vehicles and in distributed generation units.

The schematic diagram of the FPEC is shown in Fig. 1. The two ends of the translator of a linear generator are connected to the two pistons of two oppositely placed combustion chambers, respectively. The reciprocating ignition and compression processes in the two chambers drive the translator of the linear generator to move backwards and forwards, and thus electric energy is produced in the generator, which will be supplied to a motor, after rectification and inverting, to drive the vehicle. The linear generator is an important part in the FPEC [7]-[11], and in this paper a tubular longitudinal flux permanent-magnet (PM) linear generator scheme is investigated [12], [13].

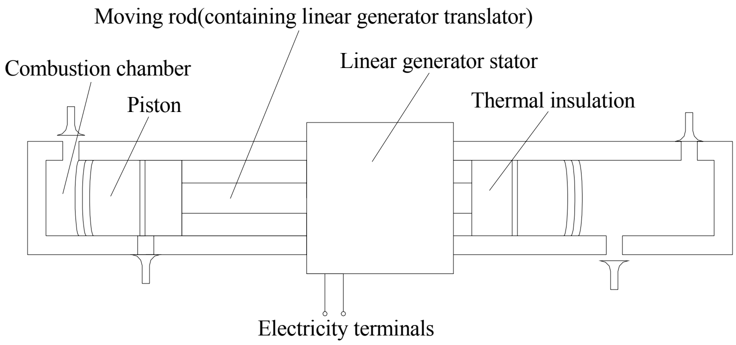

Fig. 1. Schematic diagram of the FPEC.

II. STRUCTURE OF THE TUBULAR LONGITUDINAL FLUX PM LINEAR GENERATOR USED FOR FPEC

The axial cross section diagram of the linear generator is shown in Fig. 2. It has two parts: stator and translator. The stator is composed of the stator lamination and winding, and the translator consists of axially magnetized permanent magnets, iron segments, and titanium. The titanium is a supporting part of the translator, and the iron segments are sandwiched between the permanent magnets to get better magnetic performance. To decrease the total weight and increase the specific power, the long translator structure is adopted in this paper.

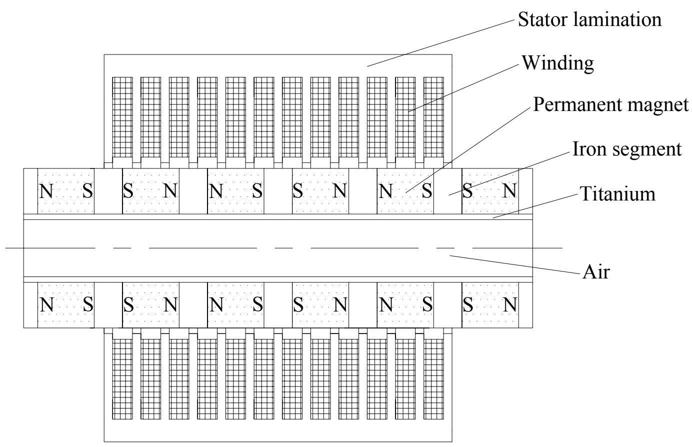

Fig. 2. Axial cross section diagram of the tubular longitudinal flux PM linear generator used for FPEC.

III. FEM MODEL

The electromagnetic and thermal properties of the tubular longitudinal flux PM linear generator are investigated with commercial software *Flux 2D*.

For the electromagnetic field analysis, due to the comparatively long axial length and big stator pole number, the end effect is neglected. To simplify the analyzing model and save on the calculating work, one pole region, which is shown in Fig. 3, is analyzed with 2D finite-element method (FEM). It is an axisymmetric problem, and lines ***ab*** and ***cd*** are set as Dirichlet boundaries, and lines ***ac*** and ***bd*** are set as antiperiodic boundaries.

For the thermal field analysis, the 2D FEM model shown in Fig. 3 is also used. Accounting for the influence of water-cooling system on the stator outer surface, Dirichlet condition of constant temperature 60°C is imposed on the boundary ***cd***; considering the heat from the combustions, Dirichlet condition of constant temperature 120°C is imposed on boundaries ***ae*** and ***bf***; boundaries ***ab***, ***ce*** and ***df*** are set as Neumann condition.

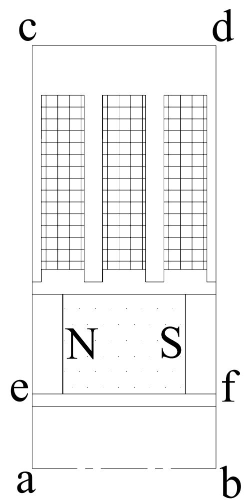

Fig. 3. 2D FEM model.

IV. OPTIMIZATION RESULTS

Efficiency and specific power are the main specifications for the linear generator used for FPEC, and they are optimized in this paper from the aspects of material selection and structure optimization.

Material selection

The selection of PM material and stator lamination material has much influence on the machine performance.

For the PM material, it is found that high remanence (B_r) and high coercivity (H_c) material is beneficial to both efficiency and specific power, so rare-earth PM material VACODYM 655HR is selected, with B_r 1.28T, H_c 990kA/m, and maximum continuous temperature 150°C.

For the stator lamination material, normally high magnetic performance material corresponds to high iron loss. Calculations show that, for high-performance high-loss material, the improvement in the magnetic performance cannot compensate for the iron loss increasing with regard to the generator efficiency and specific power. For example, for a typical scheme, the adoption of low-performance low-loss material M235-35A (typical specific iron loss is 2.25W/kg at 1.5T) leads to 3% efficiency enhancement compared to the scheme with high-performance high-loss material M700-50A (typical specific iron loss is 6W/kg at 1.5T). So the low-performance low-loss material M235-35A is chosen as the stator lamination material.

Structure optimization

The outer diameter and maximum axial length of the stator lamination and translator are determined by the FPEC system requirements. The choosing of the pole number will influence the main loss proportion, and further more the efficiency and specific power. With the increase of the pole number, the operating frequency is increased since the translator moves at a fixed speed cycle. The increase of the operating frequency will bring the increase of the iron loss. On the other hand, with the increase of the frequency, the induced back electromotive force (BEMF) is increased, and the current is decreased for the same power, so copper loss is decreased. A balancing point of iron loss and copper loss corresponds to the best matching of efficiency and specific power. So the pole number is an important factor that needs to be determined.

For each fixed pole number, local generator sizes are also optimized to obtain high average torque, low torque ripple, and comparatively higher efficiency and specific power.

When the FEM calculation is performed, the schemes of 8, 10, 12 and 14 poles are compared, and for each pole number, the generator sizes have been optimized, and the optimum scheme is used for the comparison with other pole number schemes.

The comparison data of pole number 8, 10, 12 and 14 are shown in Table I. For this generator, the chosen insulation material class of the winding is class F, which has an allowable hot-spot temperature of 155°C and an allowable average temperature of 145°C. For safety considerations, an extra margin of 25°C is included. Thus the maximum winding temperature is limited and should be lower than 120°C. From Table I, the maximum winding temperature of pole number 8 is beyond the temperature limitation, and this scheme is excluded. For the schemes of pole number 10, 12 and 14, the specific powers are similar, and the scheme of pole number 10 has the highest efficiency, so this scheme is chosen as the final one.

Table I. Comparison Data Of Different Pole Number Schemes

Pole Number	8	10	12	14
Iron Loss Per Pole (W)	69	91	103	129
Copper Loss Per Pole (W)	303	225	183	171
Machine Efficiency	0.94	0.935	0.93	0.914
Specific Power (kW/kg)	1.46	1.49	1.49	1.51
Maximum Winding Temperature (°C)	138	120	118	119

V. CONCLUSIONS

A tubular longitudinal flux PM linear generator used for FPEC is investigated in this paper. The electromagnetic and thermal properties of the generator are analyzed with commercial software *Flux 2D*. To meet the requirements of FPEC, proper permanent magnet (VACODYM 655HR) and stator lamination (M235-35A) materials are selected, and the pole number and machine sizes are also optimized. A scheme with efficiency of 0.935, specific power of 1.49 kW/kg, and maximum winding temperature of 120°C is presented. This scheme can fulfill the demands of FPEC.

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