Design of a Linear Magnetic-geared Free-piston Generator for Series Hybrid Electric Vehicles

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***Abstract*—The free-piston generator is an energy conversion device which integrates a combustion engine and a linear electrical generator into a single unit. Due to its benefits in simple structure, high efficiency and robustness, the free-piston generator is very suitable for application in series hybrid electric vehicles. This paper proposes a linear magnetic-geared machine for free-piston generator. It integrates a linear magnetic gear with a linear permanent magnet synchronous machine (PMSM), and can achieve a higher force density and power density than conventional linear machines. By using finite element method (FEM), the proposed machine is analyzed and verified.**

Keywords-Free-piston generator; linear magnetic gear; linear permanent magnet synchronous machine; finite element method.

I. INTRODUCTION

With increasing concerns on fossil fuel crisis and global environment deterioration, there is a fast growing interest in electric vehicles [1]-[21]. In terms of driving range and initial cost, the hybrid electric vehicle (HEV) is a practical solution for commercialization of low emission vehicles [22]-[25]. HEVs are classified into four kinds: series hybrid, parallel hybrid, series-parallel hybrid and complex hybrid. The series hybrid is the simplest kind of HEV. Its engine mechanical output is first converted into electricity using a generator. The converted electricity either charges a battery set or propels the wheels via an electric motor and mechanical transmission system.

As shown in Fig. 1, a free-piston generator is applied for electricity conversion which integrates an internal combustion engine and a linear electrical generator into a single unit [26]-[27]. Therefore, the crankshaft, the connecting rod and corresponding accessories are eliminated. As the moving parts of the engine are decreased, the efficiency, flexibility and controllability of the system are improved. Fig. 2 shows the schematic of a free-piston generator used in series HEVs. The main task on this research topic is to find an appropriate linear machine for electricity conversion. The free-piston generator requires a high specific power, high efficiency, and a low moving mass linear machine. A lot of linear machine configurations were proposed and investigated [28]-[32]. The linear transverse-flux machine (TFM) which has a high force density and high power density was reported as most suitable electrical machine for free-piston generator [33]. However, the TFM usually has a low power factor, a complex configuration and a high manufacturing cost which hinder its wide application. The purpose of this paper is to propose a novel linear machine which integrates a linear permanent magnet synchronous machine (PMSM) with a linear magnetic gear [34]-[38] as the generator. The force density of a linear magnetic gear is three to six times as high as that of a conventional linear machine [35], thus the power density of the integrated linear machine can be greatly improved.

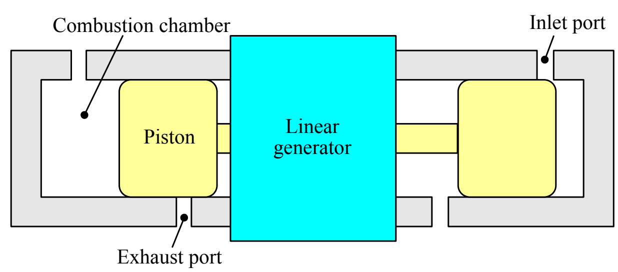

Figure 1. Schematic of a free-piston generator.

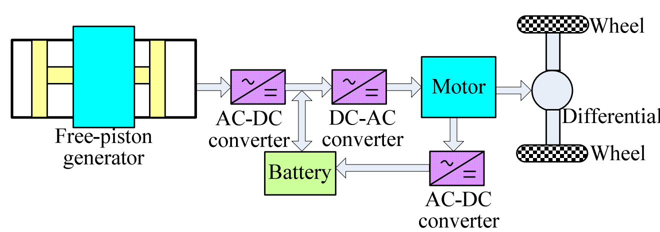

Figure 2. A free-piston generator in series hybrid electric vehicles.

II. MACHINE DESIGN

Fig. 3(a) shows the topology of the proposed linear machine for free-piston generator, in which a linear PMSM is artfully integrated into a linear magnetic gear to achieve compact construction. It consists of four parts: the linear PMSM stator, the linear PMSM translator which is also the high-speed mover of the gear, the stationary modulating ring of gear, and the low-speed mover of the gear. The low-speed

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mover of the gear is coupled to the pistons of the free-piston generator, and moves along with the pistons. Fig. 3 (b) gives a detailed configuration of proposed linear machine. The PMs of the moving parts are all surface-mounted to the back irons. The stationary rings and the stator of the linear generator are built of laminated ferromagnetic materials to reduce the eddy current loss. Epoxy is filled in the slots of the modulating rings to enforce the mechanical strength. The linear generator translator is designed with 6 active pole-pairs for high-speed operation, whereas the low-speed mover of the gear is designed with 15 active pole-pairs for low-speed operation. The modulating rings are sandwiched between the two PM movers incorporates with 21 active steel pole-pieces for modulating the air-gap field space harmonics.

The linear magnetic gear has a higher force density than the linear PMSM, thus by using the linear magnetic gear, the machine size can be reduced. Moreover, the speed of the generator translator can be improved which can produce a larger induced voltage.

The force transmission of the linear magnetic gear is based on the modulation of air-gap flux distribution. The linear magnetic gear is also a synchronous machine, and the synchronous speeds of the fields in two air-gaps are the same. Because of different poles-pair numbers at the two air-gaps, the different mechanical speed can be achieved. Like their rotational counterparts, linear magnetic gears also satisfy the following equations [39]-[43]:

$$n_s = p_{lm} + p_{hm} \tag{1}$$

$$G_r = -\frac{p_{lm}}{p_{hm}} = \frac{v_{hm}}{v_{lm}} \tag{2}$$

where p_{lm} is the number of active PM pole-pairs on the low-speed mover, p_{hm} is the number of active PM pole-pairs on the high-speed mover, n_s is the number of active stationary modulating ring pole-pieces, G_r is the gear ratio, v_{hm} is the velocity of high-speed mover, v_{lm} is the velocity of low-speed mover. In this design, p_{lm} is 15, p_{hm} is 6, and n_s is 21. Hence, G_r is −2.5, and the speed of high-speed mover is 2.5 times of that of low-speed mover.

When ignoring the power loss of linear magnetic gear, the constant power transmission satisfies:

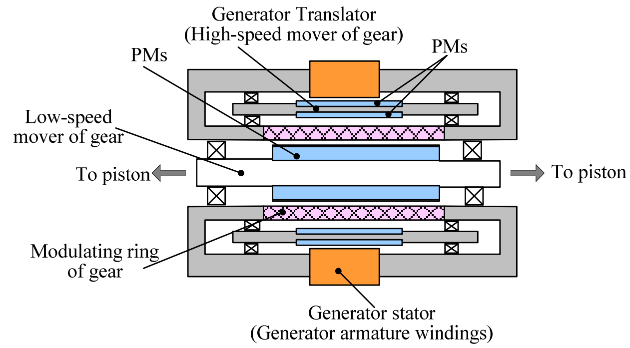
$$F_{lm}\ v_{lm} = F_{hm}\ v_{hm} \tag{3}$$

Thus, we have:

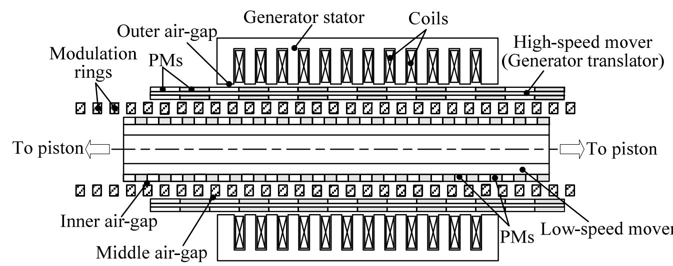
$$G_r = \frac{F_{lm}}{F_{hm}} \tag{4}$$

where F_{lm} is the thrust force acting on the low-speed mover, F_{hm} is the developed thrust force of the linear magnetic gear. Thus, by using magnetic gear effect, the developed thrust force will be two fifth of the force produced by combustion engine which may ease the linear generator design.

For the linear generator, the open-slot design is adopted for the stator, which may ease the fabrication and lamination of the stator iron core to lower the core loss. There are 12 ring-shaped windings for 3 phases which have no end connections.



(a)



(b)

Figure 3. Proposed machine. (a) Machine topology. (b) Cross section.

TABLE I. SEPCIFICATION OF PROPOSED MACHINE

Rated power	10 kW
Phase no.	3
Rated voltage	220 V
Gear ratio	−2.5
Axial length (active)	264 mm
Stroke length	17.6 mm
PM pole-pitch of low-speed mover	8.8 mm
PM pole-pitch of high-speed mover	22 mm
Pole-pitch of modulating rings	6.468 mm
PM remanence	1.2 T
PM coercivity	900 k A/m
Each air-gap length of 3 air-gaps	1.0 mm

III. MACHINE ANALYSIS

Since the proposed machine consists of two stationary parts, two moving parts, and three air-gaps, the finite element method (FEM) are used for machine performance calculation.

Fig. 4 shows the open-circuit field distribution. Fig. 5 shows the flux density waveform and its spectrum in each air-gap. It can be observed that the peak values of flux density in three air-gaps exceed 1.0 T which can confirm a high developed force. As Fig. 5 (a) shown, the largest asynchronous harmonic component in the inner air-gap is 15, and it interacts with the 4 pole-pair PMs on the high-speed mover to develop a thrust force because of the field modulation effect. With the modulating rings, pole-pair number of the flux spectrum in middle air-gap is 4 which is 15 in the inner air-gap, but the synchronous speeds in the three air-gaps are the same. Because of different PM pole-pair numbers on each moving parts, the different mechanical speeds of both movers can be achieved which satisfy (2). By fixing the high-speed mover, the static thrust force of low-speed mover can be obtained when low speed mover travels one pole-pitch. Fig. 6 shows the static force waveform of low-speed mover with a peak value of 2600 N. By relocating the relative position of the two movers when the static force of low-speed mover equals 2000 N, a continuous, steady force of the two movers can be achieved when the two movers travels at a speed satisfying (2). As shown in fig. 7, the thrust force of the low-speed mover is about 2000N, and the thrust force of the high-speed mover is about 900N. Thus, the gear ratio is about 2.22 which is slight lower than 2.5, and the result is due to the tubular structure which makes the high-speed mover a little larger surface area.

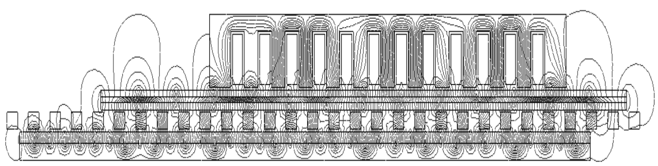
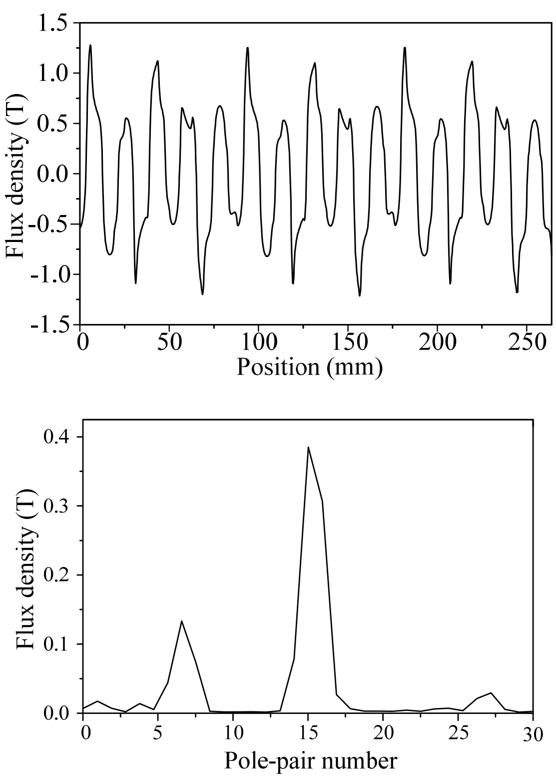
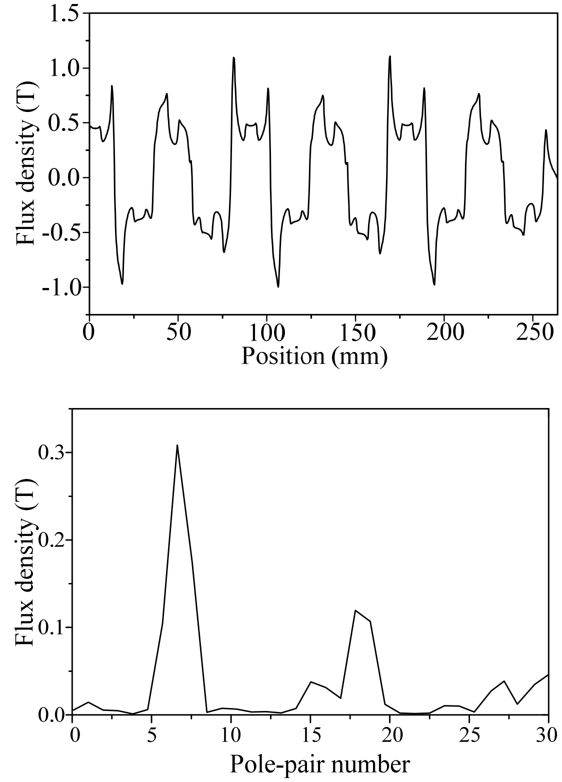


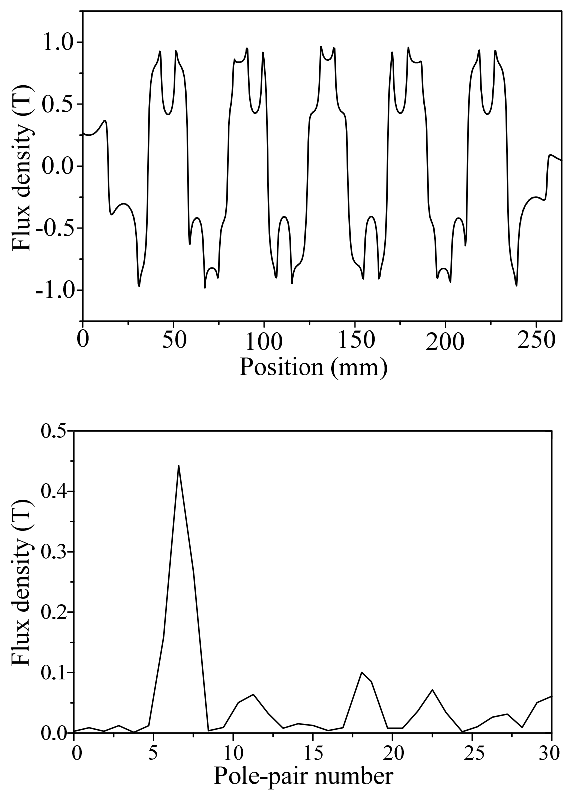
Figure 4. Field distribution of proposed machine.



(a)



(b)



(c)

Figure 5. Air-gap flux density waveform and its spectrum of proposed machine. (a) Inner air-gap. (b) Middle air-gap. (c) Outer air-gap.

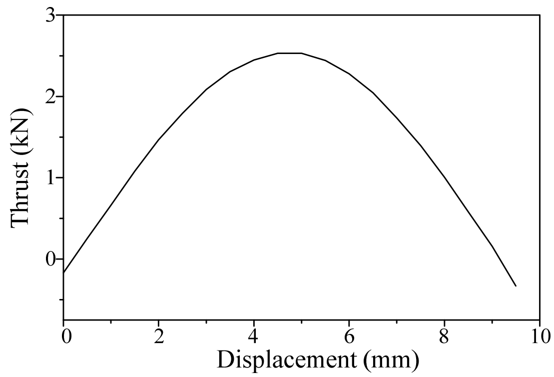


Figure 6. Static thrust force waveform of low-speed mover.

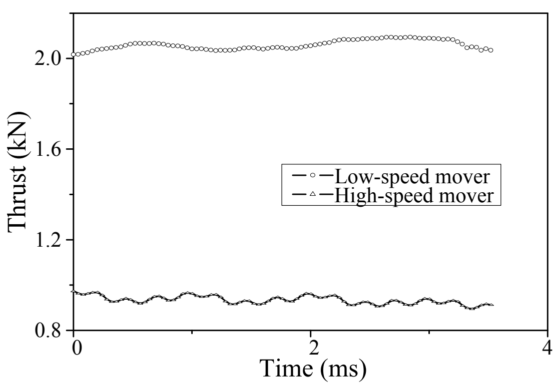


Figure 7. Force transmission capacity of the linear magnetic gear.

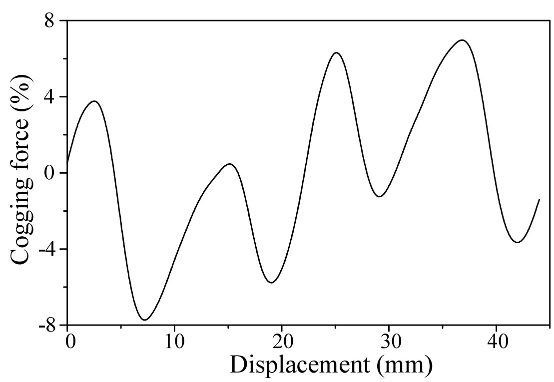


Figure 8. Linear generator cogging force.

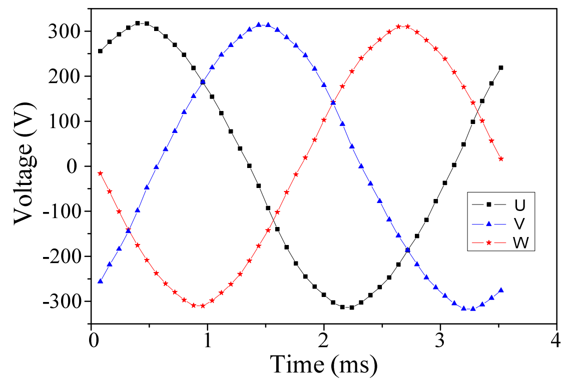


Figure 9. Induced EMF waveform.

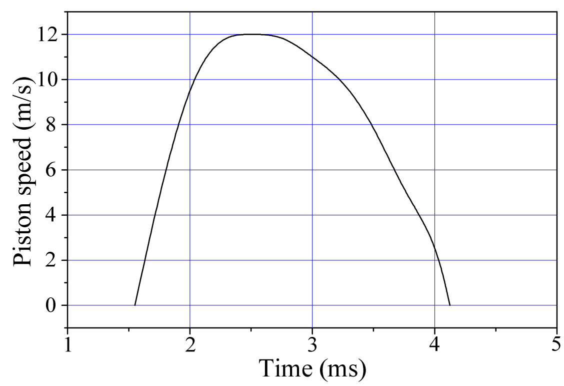


Figure 10. Piston speed for one stroke length.

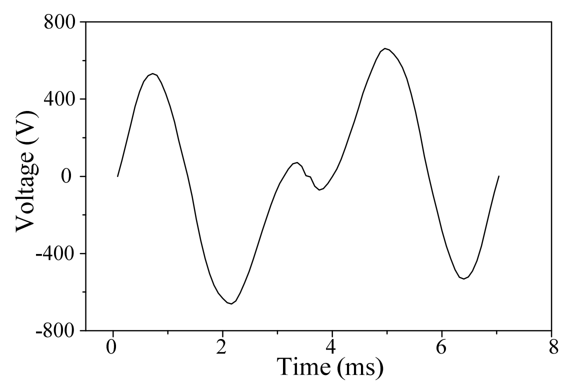


Figure 11. Induced EMF waveform of Phase U under variable speed.

When moves the translator of the linear generator one pole-pair pitch under open-circuit circumstance, the cogging force of the linear generator can be obtained as shown in fig. 8 which is within 8% of the high-speed mover thrust force. Fig.9 shows the induced electromotive force (EMF) of 3 phases when the linear generator translator travels at a constant speed of 5 m/s. According to [33], the piston speed of one stroke length is shown in fig.10. Fig.11 shows the induced EMF of phase U under this variable speed.

IV. Conclusion

A novel linear magnetic-geared machine for the free-piston generator is designed and analyzed. By using linear magnetic gear, the proposed machine can reduce the size of the linear generator, whereas keep the output power constant, thus the power density and efficiency are improved. This paper gives the machine structure and design details. By using FEM, the electromagnetic performance of the proposed machine is analyzed and simulated, which confirms that the proposed machine is feasible for the free-piston generator.

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