An Integrated PM Magnetic-geared Machine for Hybrid Electric Vehicles

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Abstract

The free-piston generators have the advantages of simple structure, high power density and high efficiency, so they are proposed for applying in the series hybrid electric vehicles (HEV). In this paper, a novel PM linear magnetic-geared machine serving as the free-piston generator is proposed. The machine consists of a linear permanent magnet synchronous machine (PMSM) and a linear magnetic gear (LMG), which are integrated together. The proposed machine adopts a structure that the high-speed mover of the LMG and the translator of the linear PMSM share the same moving part. There are four main parts in the machine topology, including the low-speed mover with PMs, the ferromagnetic pole pieces, the high-speed mover with PMs and the stator with three-phase windings. In order to improve the speed of the PMSM translator, the magnetic-geared topology is adopted, such that the designed machine can generate the high-voltage electricity and have the high power density. In the magnetic-geared machine, the tubular stator is designed as a 12-slot structure with concentrated windings. In order to integrate the machine and the magnetic gear magnetically and mechanically together, the high-speed mover of the magnetic gear is designed as the translator of the machine. The tubular machine translator consists of one row of PMs. And the low-speed mover of the magnetic gear consists of a tubular iron core and PMs mounted on the inner face of the core. The PMs of both low-speed mover and machine translator are radial magnetized. Between the low-speed mover and the high-speed mover of the magnetic gear, the ferromagnetic pole pieces are fixed there to modulate the magnetic fields. Since the LMG has the advantage of high force density inherently, the proposed novel PM linear magnetic-geared machine can obtain the high power density, high efficiency and weight reduction by comparing with the conventional linear machines. This work is performed and verified by using the finite element analysis (FEA) method.

Keywords: Hybrid electric vehicle, free-piston generator, linear magnetic-geared machine, finite element analysis

1 Introduction

Nowadays, with increasing environmental concerns, the hybrid electric vehicles (HEVs) have drawn more and more attention [1]-[6]. HEVs are divided into four categories: series hybrid vehicle, parallel hybrid vehicle, series-parallel hybrid vehicle and complex hybrid vehicle [7]-[9]. As the key part of HEV, the propulsion system attracts more and more attention [10]-[12]. The structure that crankshafts and connecting rods are directly connected to the rotating electric machine is adopted in the traditional HEVs. In the internal combustion engine (ICE) pistons, it is indispensable to process the linear-to-rotational motion conversion since the linear motion of ICE pistons [13]-[16]. In comparison with the traditional HEVs, the linear free-piston generator can overcome the above problems, and improve the system energy conversion efficiency and power density of the machine.

Magnetic gears have the advantages of physical isolation, silent operation and inherently overload protection [17]-[21]. Thus, a variety of magnetic gears have been proposed. And the magnetic gear can be combined with the electrical machine as an integrated machine. Many linear magnetic-geared machines are proposed and discussed in [22]-[25]. In [26]-[27], the tubular PM synchronous machine is proposed. The power density and force density of this machine is high, but the fluctuation of its thrust force is high. Another configuration of magnetic-geared linear machine is the linear transverse-flux machine (TFM). This structure has higher power density and higher force density, which makes it suitable as the free-piston generator [28]. However, due to the inherent disadvantages, such as the low power factor and complex configuration, the application of TFM is limited. In [29]-[30], another kind of linear tubular machine integrated with a linear tubular magnetic gear is presented. The thrust force is high and the total harmonic distortion of no-load EMF is low enough for HEV application, but its structure is complex.

Due to the benefits of high efficiency, high power density and the simple structure, the free-piston generators are often applied in the series HEVs. As shown in Fig. 1, the free-piston generator adopts the topology that the ICE and magnetic-geared linear machine are integrated artfully. Namely, the free-piston is directly coupled with the high-speed mover of the magnetic-geared machine. The topology can eliminate the energy loss of linear-to-rotational motion.

The purpose of this paper is to design an appropriate linear machine for electricity generation. The idea is to use the magnetic-geared machine as the free-piston generator so that the ICE power can be directly converted as the electrical energy.

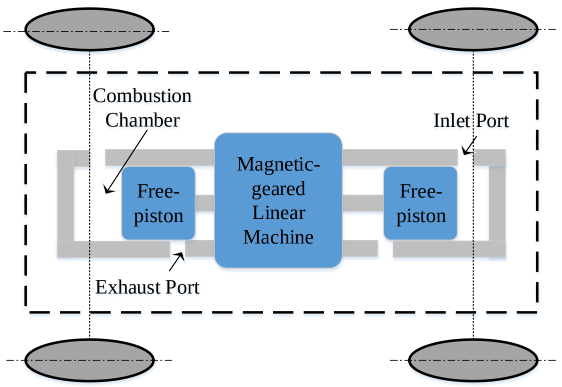


Fig. 1 Schematic of the free-piston generator

2 Machine Design

2.1 Machine Configuration

In this paper, a novel PM linear magnetic-geared machine serving as the free-piston generator is proposed. The machine consists of a linear permanent magnet synchronous machine (PMSM) and a linear magnetic gear (LMG), which are integrated together. Compared to the flat machine structure, the leakage flux of the proposed machine with tubular structure is much smaller. As shown in Fig. 2, the proposed machine adopts a structure that the high-speed mover of the LMG and the translator of the linear PMSM share the same moving part. There are four main parts in the machine topology, including the low-speed mover with PMs, the ferromagnetic pole pieces, the high-speed mover with PMs and the stator with three-phase windings. In order to improve the speed of the PMSM translator, the magnetic-geared topology is adopted, such that the designed machine can generate the high-voltage electricity and have the high power density.

In the magnetic-geared machine, the tubular stator is designed as a 12-slot structure with concentrated windings. In order to integrate the machine and the magnetic gear magnetically and mechanically together, the high-speed mover of the magnetic gear is designed as the translator of the machine. The tubular machine translator consists of one row of PMs. And the low-speed mover of the magnetic gear consists of a tubular iron core and PMs mounted on the inner face of the core. The PMs of both low-speed mover and machine translator are radial magnetized. Between the low-speed mover and the high-speed mover of the magnetic gear, the ferromagnetic pole pieces are fixed there to modulate the magnetic fields.

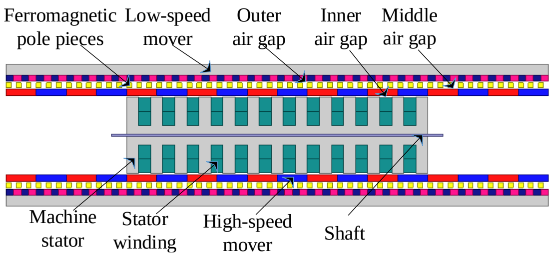


Fig. 2 Schematic of the linear magnetic-geared machine

Since the LMG has the advantage of inherently high force density, the proposed novel PM linear machine can obtain the high power density, high efficiency and weight reduction by comparing with the conventional linear machines. This work is performed and verified by using the finite element analysis method.

2.2 Machine Design

The operational principle of the magnetic gear is to use the ferromagnetic pole pieces to modulate the air-gap magnetic fields. And the air-gap fields consist of the magnetic field generated by PMs of the gear low-speed mover and the magnetic field generated by PMs of the gear high-speed mover. Based on the operational principle, the following equations are listed [31]:

$$n_s = p_l - p_h \tag{1}$$

$$G_r = p_l/p_h = v_h/v_l \tag{2}$$

$$G_r = F_l/F_h \tag{3}$$

where G_r is the gear ratio of the LMG, v_l is the velocity of the low-speed mover, and v_h is the velocity of the high-speed mover. These equations show that the machine parameter relationships are as follows: the active number of ferromagnetic pole-pieces n_s equals to the active pole-pair number of the low-speed mover p_l minus the active pole-pair number of the high-speed mover p_h.

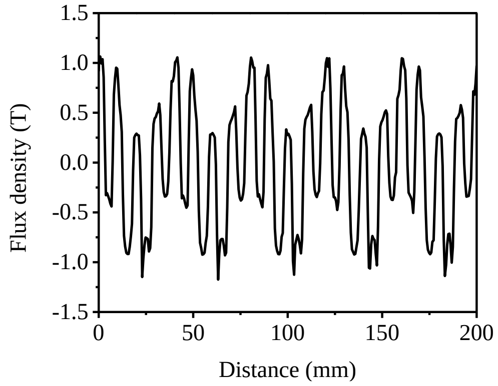
In this design, the stator and translator pole numbers of the magnetic-geared machine are set as 12 and 10, respectively. There are 54 active ferromagnetic pole pieces, 72 active permanent magnet poles in the low-speed mover, and 18 active permanent magnet poles in the high-speed mover. The designed PM linear magnetic-geared machine has high thrust force. And the gear ratio of the magnetic gear is 1/4, which works as transmitting the velocity or force from the low-speed mover to the high-speed mover. And the speed direction of low-speed mover is the same as that of the high-speed mover. The air gap has three parts, including the outer air gap, the middle air gap and the inner air gap. Based on the above design data, the 3-phase 12/10-pole magnetic-geared PMSM is designed. And the key parameters of the proposed machine are listed in Table 1.

Table. 1 Parameters of magnetic-geared machine

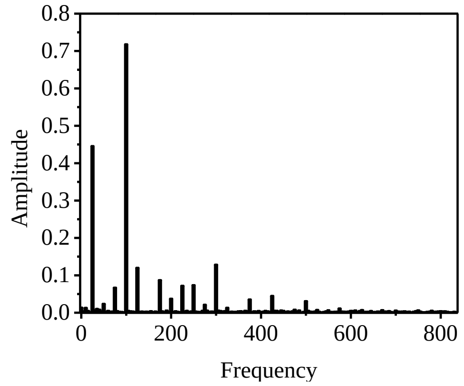
Pitch of stator	16 mm
Number of stator slots	12
Winding turns per coil	40
Pole pitch of low-speed mover	5 mm
Active pole number of low-speed mover	72
Inside radius of low-speed mover	36 mm
Outside radius of low-speed mover	47 mm
Pole pitch of high-speed mover	20 mm
Active pole number of high-speed mover	18
Inside radius of high-speed mover	26.5 mm
Outside radius of high-speed mover	30.5 mm
Modulation ring length	6.67 mm
Active ferromagnetic pole pieces	54
Outside radius of stator	25.5 mm
Rated velocity of low-speed mover	2 m/s
Rated velocity of high-speed mover	8 m/s
Gear ratio	1:4
Air gap length	1 mm

3 Finite Element Analysis

In this study, the 2D FEA method is adopted. And the electromagnetic performances of the proposed machine are simulated and analyzed. In Figure 3, the waveform of the outer air-gap radial flux density and the corresponding spectrum is shown. The Figure 4 shows the waveform of the middle air-gap radial flux density and the corresponding spectrum. And Figure 5 shows the waveform of the inner air-gap radial flux density and the corresponding spectrum.

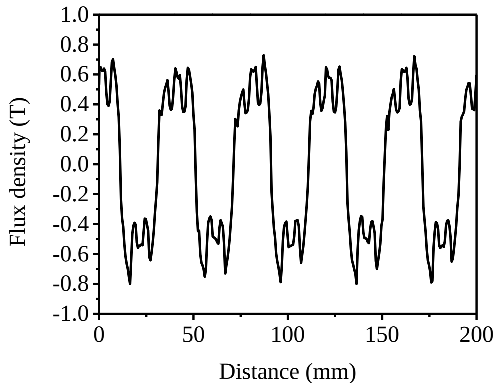


(a) Flux density waveform

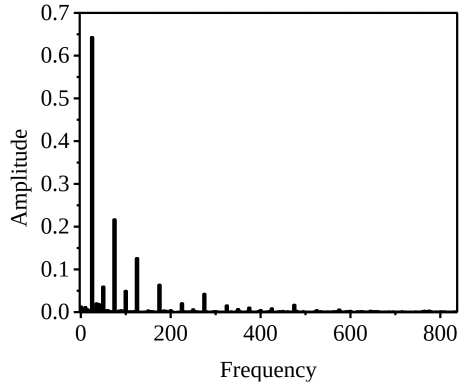


(b) Flux density spectrum

Fig. 3 Flux density waveform of the outer air gap



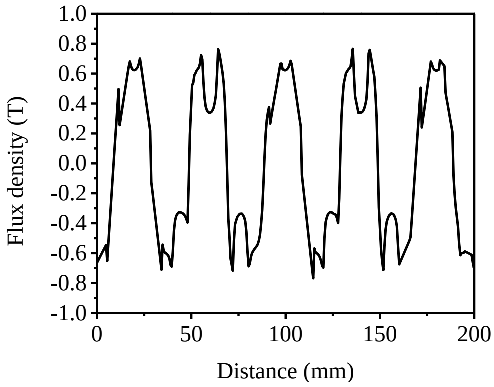
(a) Flux density waveform



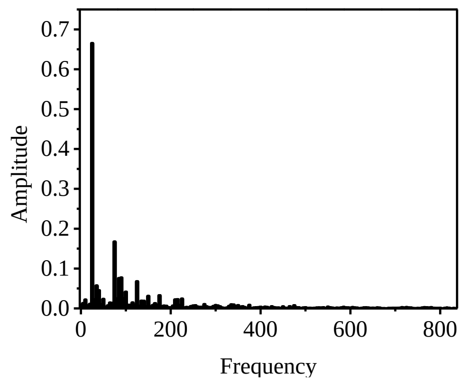
(b) Flux density spectrum

Fig. 4 Flux density waveform of the middle air gap

From the Figure 3 to Figure 5, it can be seen that the amplitudes of the harmonic components attenuate as the frequency increases. And the ferromagnetic pole pieces function as the modulation rings in the designed machine.



(a) Flux density waveform



(b) Flux density spectrum

Fig. 5 Flux density waveform of the inner air gap

Figure 6 shows the flux linkage of the proposed machine, which confirms that the machine can generate three-phase voltage with 1.13 Wb. However, the maximum value of the flux linkage of phase A is 1.38 Wb. The optimization problem of the proposed machine needs to be simulated and analysed in the following research.

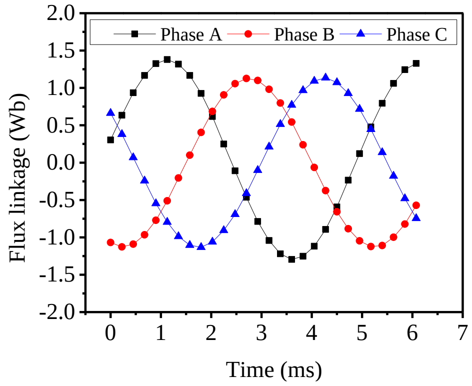


Fig. 6 Flux linkage waveforms

4 Conclusions

In this study, a novel linear magnetic-geared PMSM has been proposed for free-piston generator applied in HEV. The machine configuration and design criteria have been discussed. By using the FEA method, the proposed machine has been simulated and analysed. It can downsize the whole free-piston generator and amplify the translator velocity of the linear magnetic-geared PMSM machine. Thus, the proposed machine has promising application for free-piston generator in HEVs.

5 Acknowledgement

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