Optimization and Thrust Force Calculation of Linear Generator in Starting Mode for Free-Piston Engine Applications

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Abstract—this paper provides a novel method to start the linear engine coupled linear generator from dead stop to its final steady state operation. This method depends mainly to use the linear generator mounted on the shaft of the linear engine to provide the required thrust force to move and oscillate the linear engine from bottom to top dead centers. It is a cost effective approach to start the internal linear combustion engine using its coupled tubular permanent magnet linear generator proposed here. This linear generator operates in this case in motoring mode, providing the required thrust force by feeding this linear generator phases with currents by using a three phase PWM inverter controlled by position feedback scheme. In order to provide the desired thrust force with specific value and direction, a position feedback is required to control the free piston engine motion through controlling the inverter switches using PWM control scheme.

I. INTRODUCTION

The linear machines are being employed increasingly in applications ranging from transportations, manufacturing, and office automation to material processing and generation systems [1]. For linear generators that are powered by internal combustion engine, the dual piston configuration has been suggested to be superior as it is more suitable for high-speed applications and avoids complexity on control [2-3].

In order to initiate the combustion process, a force is needed to move the translator assembly, to compress fuel in the combustion chamber and ignite it. The existence of the cogging force poses a problem for starting as it opposes the movement of the translator assembly wherever it travels from one side to the other. This cogging force results from the interaction between the iron-structure stator teeth and the permanent magnets mounted on the translator part of the linear generator.

Free Piston Engine (FPE) is used in hybrid electric vehicles for its compact volume, lower weight, higher efficiency than crankshaft rotating system counterpart [4]. The FPE consists of an internal Linear Combustion Engine (LCE) as a prime mover, coupled to a linear generator, which provides the auxiliary electrical power for the vehicle. In the normal operation of the FPE, the internal LCE is the prime mover for the linear generator. In starting stage, the LCE is at dead stop. Thus an external force is needed to accelerate the internal LCE for the first few cycles until steady state oscillating operation. One of the economic ways is to start the internal LCE using its coupled linear generator. The linear generator operates in this case in motoring mode, providing the required thrust force by feeding the linear generator phases with currents by using a controlled PWM inverter. In order to provide the desired thrust force with specific value and direction, a position feedback is required to control the FPE motion through controlling the inverter gate switches.

In this paper, the design part of the linear generator, the control circuit and feedback scheme are explained. An absolute analog sensor mounted on the moving part of the linear generator is used in the feedback signal processing circuit. According to the received position of the translator assembly, an appropriate three phase currents are fed to the linear generator windings, which provide thrust force to move the FPE in the starting stage of operation.

II. FREE PISTON ENGINE SYSTEM DESCRIPTION

The FPE consists of an internal LCE coupled with a linear generator as shown in Fig. 1. The internal LCE has two horizontally opposed pistons mounted on a common connecting rod (translator) that is allowed to oscillate between the two end-mounted cylinders. The two pistons will move simultaneously to compress or expand the fuel mixture in the cylinders. Combustion occurs alternately in each cylinder, forcing the piston assembly back and forth in an alternating fashion.

As the piston assembly moves in either direction, one cylinder will undergo the expansion process while the other undergoes compression, thus functioning as a non-linear spring. The resonant frequency can then be found by setting the sum of the forces acting on the pistons due to the in-cylinder pressures and the resultant electromagnetic force of the alternator equal to the mass of the piston assembly times the acceleration of the assembly. The second part of the FPE is the designed tubular permanent magnet (TPM) linear generator, mounted on piston rod.

The linear machine has various topologies and configurations. The TPM topologies are particularly attractive since they have a high thrust force density and a high efficiency, no end windings and zero net attractive radial force between stator and translator [5-7]. There are various tubular motor topologies [8-9], in which the armature may be either air-cored or iron-cored. The force density for slotted TPM topology is significantly higher than for slotless iron-cored. The slotted TPM linear generator is considered in this paper. In the current design of the TPM linear generator with PM magnetized in the radial direction is considered. The generator is axi-symmetric around z-axis (axial-axis) as shown in Fig. 1, thus the generated cogging force exists in the z-direction (motion) only, and the other radial forces cancel out. The main dimensions and other specifications for the studied TPM linear generator are listed in Table I.

The stator of the TPM linear generator consists of six slots for the ring coils placement. Thus, forming three phase winding, each phase consists of two coils connected in series. The primary or stator-fixed part of the TPM-LG consists of the stator core and coils. The core is assembled from 0.5 mm laminations of silicon steel material of grade 50H470 to reduce the eddy current loss and hence the total magnetic loss. These lamination discs are arranged in the r-direction.

Thus the flux goes through these laminations in a low reluctance path in stator teeth, while goes normal to the lamination discs in the stator back iron. The coil material is a rectangular copper conductor to maximize the winding fill factor and the load current value. These coils have a shape of circular cylinder placed in the stator iron core. The secondary (moving) part consists of a set of Nd-Fe-B material for the PMs which has high-energy product, translator back-iron and the translator shaft of non-magnetic material. The PMs are embedded on the linear generator shaft and magnetized radial direction and normal to the motion (axial) direction. The designed linear generator of a type of long translator (secondary) to let all the coils are active all time, and hence higher induced voltage.

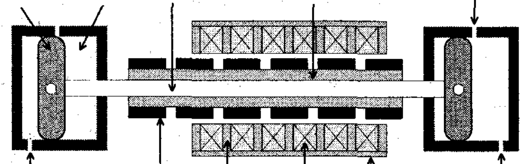

Fig. 1 The free piston engine system.

TABLE I
SPECIFICATIONS OF TPM LINEAR GENERATOR

Part	Item	Value	Unit
Stator	Stator length	144	mm
	Slot pitch	23	mm
	Slot depth	29	mm
	Tooth width	6	mm
	Stator inner radius	29	mm
	Stator outer radius	62	mm
	Coil fill factor	0.75	--
	Wire diameter	6.08	mm
	Coil turns	60	--
	Back-iron thickness	4	mm
Air gap	Air gap length	1	mm
Translator	Magnet length	30	mm
	PM thickness	4	mm
	PM retentivity, B_r	1.1	T
	PM coercivity, H_c	821.24	kA/m
	Pole pitch	34.5	mm
	Backiron thickness	14	mm
	Shaft radius	10	mm
	Stroke length	69	mm

III. TPM LINEAR GENERATOR OPTIMIZATION

The three-phase TPM linear generator dimensions can be optimized using Finite Element Method (FEM), so that the induced AC voltages are maximized and, at the same time, the undesired cogging force is kept as low as possible. This cogging force is developed from the magnetic attraction between the PMs mounted on the translator and the stator teeth.

The ripples of the cogging force produce both vibrations and noise. Thus, the cogging force should be minimized for a good design. A routine is chosen using Maxwell software to maximize the objective function, Γ. This objective function is proportional to the efficiency of the PM linear generator and at the same time, it is inversely proportional to the total volume of the generator. Hence the objective function can be represented by:

$$\Gamma = C_e\,(efficiency\,) + (1 - C_e)\frac{Gv^L}{Gv}$$

where, Gv^L is the maximum volume limit for the generator design, Gv is the current volume in the calculation routine and C_e is a factor and chosen on the basis of priority of the efficiency or the generator volume. Its value is normally greater than 0.5 and less than unity. If the generator efficiency is the critical factor, C_e is chosen near to unity.

The maximum volume limit of the generator, Gv, depends and chosen based on a specific application. Using this optimization routine, the induced AC voltages for a complete cycle and the cogging force are each time and compared to find the target values.

The magnetic (core) loss is calculated based on the manufacturer data sheet of the core material (Silicon Steel, 50H470). The data sheet provides core loss per kilogram with maximum flux density at different frequencies. The flux density in all iron parts are analyzed using FFT and at each harmonic, the corresponding core loss is evaluated, and hence the total core loss is found. The performance parameters of the designed TPM linear generator are listed in Table II.

TABLE II
TPM LINEAR GENERATOR PERFORMANCE PARAMETERS

Item	Value	Unit
rms induced voltages	80, 78,80	V
Rated current	22	A
Maximum cogging force	150	N
Stator weight	9.56	kg
Translator weight	4.38	kg
Total generator weight	13.92	kg
Phase resistance	0.093	Ω
Phase inductance	4.7	mH
Output power	4.85	kW
Core loss	16	W
Resistive loss	135	W
Total volume	1.967	L
Power/Weight ratio	348	W/kg

IV. POSITION FEEDBACK PWM CONTROL SCHEME

In the process of starting the internal LCE, there should be enough force to drive the piston assembly from a standstill state and also compress the fuel to achieve the required compression ratio at the top dead center. The initial force (or energy) is delivered by the interaction of the magnetic field of the permanent magnets attached to the translator and the field produced by the coils at the stator as high current is injected into them.

During starting operation for internal LCE, the PM linear generator works as a PM linear motor. The three-phase stator winding terminals are connected to the inverter. The inverter is a three-phase type as shown in Fig. 2, to control the linear motor phase's currents. Each leg of the inverter controls one phase of the generator winding. In controlling the phase currents, two phases only conduct at the same time as shown in Fig. 3.

To move the translator assembly from one side to the other, the thrust force generated from the applied currents must be in one direction for the whole stroke and in the opposite direction while the translator assembly goes back again. A routine was built to find the suitable phase current at each position of the translator assembly, to provide a thrust force in the proper direction.

The gate signals, required providing a thrust force in one direction over the forward stroke and an opposite one in the backward stroke. As it can be seen from Fig. 3, the starting operation includes twelve modes. In each mode only two switches from different bridge legs of the three-phase PWM inverter conduct.

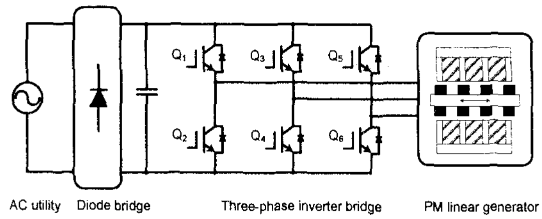

Fig. 2 The electrical part of the free-piston engine.

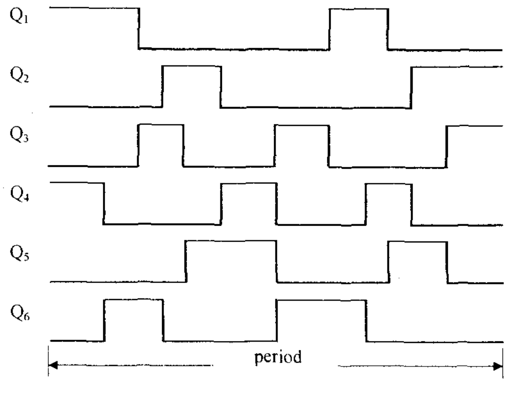

Fig. 3 Gate pulse signals of three-phase inverter switches during starting mode of operation.

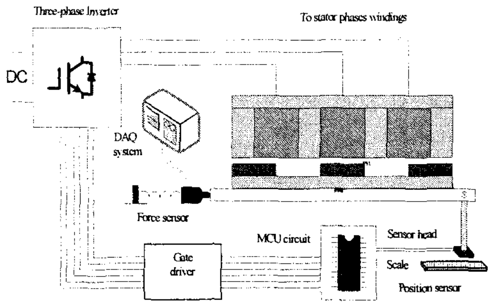

Fig. 4 Feedback control scheme for starting the free piston engine.

V. EXPERIMENTAL RESULTS AND DISCUSSIONS

To verify the validity of the FEM results; a prototype of the three-phase TPM linear generator is built together with the feedback control circuit as shown in Fig. 4. A position sensor feedback scheme is used to get the translator position at each instant of operation. The position sensor used here is an absolute analog type, thus there is no zero reference problems for new starting after stop. The position sensor magnet head is attached to the linear generator translator. The fixed part (scale) of the sensor is attached to the test bed.

The output of the position sensor is transferred to the Microcontroller (MCU) circuit to manipulate and calculate the correct corresponding PWM gate signals for the three-phase inverter, see Fig. 3. The thrust force is measured using another force sensor attached to the translator and its output is displayed on a data acquisition (DAQ) system.

The measured thrust force along the complete stroke length of the of the linear generator with the control scheme using d-q theory is shown in Fig. 5. The parameters in Fig. 5 are defined as follows: V applied voltage, k_v transformation factor, v linear velocity, x translator position, D damping coefficient, k_{rip} ripple coefficient, and k constant and other parameters are already defined. Applying the thrust control; the experimental and simulated thrust force is shown in Fig. 6 for different currents. It is clear that the experimental results agree to those obtained using Finite Element Method (FEM).

The existing ripples in the thrust force are due to the cogging force and should be minimum for critical applications. It can be noticed that the experimental thrust force values are compared well to those obtained using computer simulation based on FEM. It is worth to mention that the thrust force has value rather than zero at both ends of the stroke to provide the essential force to overcome the resisting forces of the internal LCE.

These resisting forces are friction and compression forces in addition to the cogging force of the three-phase TPM linear generator. The thrust force at both ends of the stroke will not damage the internal LCE cylinder or piston as the piston assembly moves in either direction, one cylinder will undergo the expansion process while the other undergoes compression, thus functioning as a non-linear spring. The TPM linear generator is designed to integrate with an internal LCE to form the FPE system.

The FPE system is suitable for many industrial, military, hybrid electric vehicle and space applications to provide electrical energy. It is found that the thrust force value Fe is in direct proportion to the applied current. The thrust force for the backward return stroke is the negative of the shown values in Fig. 6.

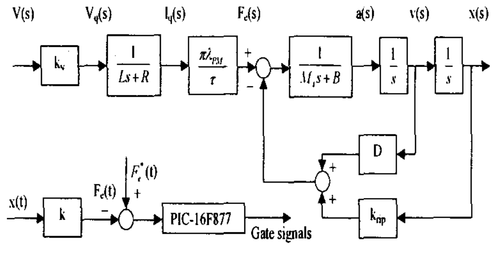

Fig. 5 Thrust force control scheme for starting a linear engine.

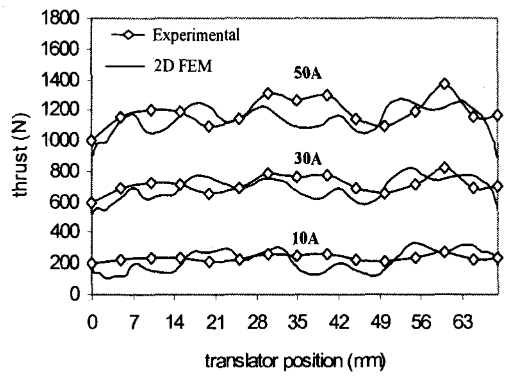

Fig. 6 Thrust force at different applied current values.

VI. CONCLUSIONS

A tubular permanent magnet three-phase linear generator was designed and optimized using 2D finite element method software. The designed targets of the proposed three-phase linear generator were to maximize its output power by increasing the induced AC internal voltage in generator mode of operation and to minimize its undesired cogging force. The performance parameters, power losses and output power were evaluated and demonstrated. A position feedback controlled three-phase PWM inverter-starting method for the linear engine coupled linear generator system was demonstrated and evaluated. The linear generator was used as a prime mover for the internal linear combustion engine to provide the essential thrust force to compress the fuel mixture and ignite the internal linear combustion engine for a few starting cycles until it comes to the oscillating steady state operation.

To provide a thrust force in a specific direction a control system was built using position and force sensors. According to the translator position an appropriate gate signals were forward to the inverter gate driver. The experimental thrust force values agreed well to those obtained using computer simulation software. It was found that the thrust force was directly proportional to the applied current from the three-phase PWM inverter output. The designed free piston engine system is suitable for many industrial, military, hybrid electric vehicle and space applications to provide electrical energy.

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