



Design and Analysis of Tubular Type Linear Generator for Free Piston Engine

CHIT SU SU HLAING¹, ZAW HTET MYINT²

¹Dept of Electrical Power Engineering, Mandalay Technological University, Mandalay, Myanmar,
E-mail: goldleaf87@gmail.com.

²Dept of Electrical Power Engineering, Mandalay Technological University, Mandalay, Myanmar,
E-mail: zawhtetmyint528@gmail.com.

Abstract: As a response to the major climatic changes due to global warming and the foreseen oil shortages once the natural reserves will perish, most vehicle manufacturers began research programs on alternative fuel vehicles. The Hybrid Electric Vehicles, as an intermediate step to full electric vehicles, can incorporate Free Piston Engine –Linear Electric Generator systems to produce the required electric energy. Tubular-type linear generator for the free-piston engine is analyzed using finite element method and its characteristics are explained. Magnetic characteristics of the linear generator are calculated using the finite element method and various structures are considered to achieve the lowest detent force within the rated voltage. The path of the magnetic flux is constructed by the axially magnetized magnets and the iron pole, and the detent force is minimized by adjusting the width of the magnet pole.

Keywords: Linear Generator, Free-Piston Engine, Detent Force, Tubular-Type Linear Generator, Finite Element Method.

I. INTRODUCTION

The free-piston engine system has high efficiency and reliability in the energy conversion process because of the absence of the mechanical devices like a crankshaft, a connecting rod, etc. The linear generator plays a very important role in this free-piston engine system to realize high efficient system [1],[2]. In this research, the tubular-type linear generator for the free-piston engine is analyzed and designed. The tubular-type generator has higher efficiency and reliability than the flat-type one because of its structural merits. The amount of the leakage flux is small and the rotation of the piston does not affect the electric characteristics of the linear generator [3]-[6]. For the stable operation of the linear generator, the detent force should be minimized. The detent force is minimized by varying the magnetic pole pitch. This method can reduce the detent force and also improve the output waveform.

The modified pole pitch values are optimized and then the tubular-type linear generator is designed. The stroke, frequency, number of poles and phases are determined by the conditions of the free-piston engine and the machine controller. In this research, 1KW, 2-pole, 3-phase linear generator is analyzed and designed. The stroke of the machine is 72mm and the operating frequency is 30Hz. The finite element method is used to analyze the magnetic characteristics of the generator. The back-emf and detent force characteristics are simulated and the optimized design factors of the generator are derived from those results. Free Piston Engines. A combustion engine is referred to as a “Free

Piston” if the linear movement of the pistons is not transformed into rotational motion by using the crankshaft. There are two types of FPE: internal combustion engine, where the combustion takes place inside the cylinders and external combustion engines, where a working fluid is heated in an external source and then flows through the cylinder (such as the steam engine) [4]. The absence of a crankshaft brings the advantage of fewer moving parts and reduced friction between the piston and the cylinder walls, but also requires an additional device that would store the mechanical work produced by the piston during the power stroke and return some of that to prepare the system for a new cycle. Depending on the number of piston and their position there are several possible topologies.

A. Single Piston

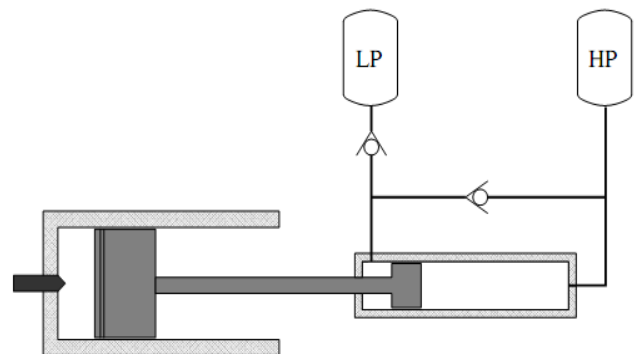


Figure1. Single piston

It uses only a combustion chamber and a rebound device to store part of the energy generated during the combustion stroke. Such a system is shown in Figure 1 where the rebound device is at the right. This device allows the control of the system frequency and stroke by controlling the low and high pressure valves.

B. Dual Piston

Dual piston eliminates the need of a rebound device during functioning because the combustion stroke of one piston coincides with the compression stroke of the second piston, Figure 2. An external force needs to be applied when starting the engine, a force that can be produced by the linear electrical machine. The high vibration levels produced by such a system can be eliminated by using two or more systems that would work in anti-phase, requiring precise control.

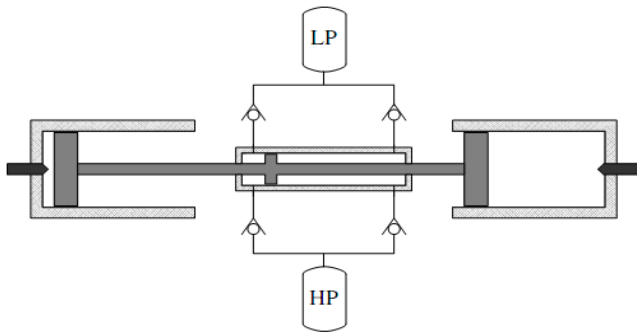


Figure2. Dual piston

C. Opposed Piston

The two pistons share the same combustion chamber and a mechanical synchronization part that assures that the pistons move simultaneously is needed, like the one shown in Figure 3. Each piston requires a rebound device on the free shaft end and the load may be mounted on each side [5].

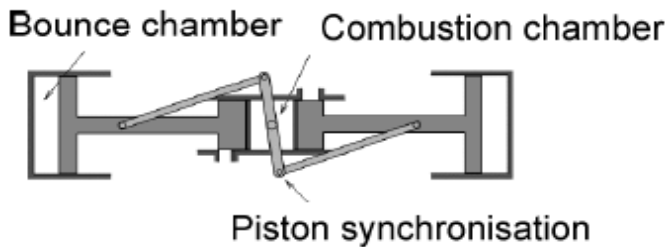


Figure3. Opposed piston

II. DESIGN OF THE LINEAR GENERATOR

A. Tubular-type Linear Generator

Figure 4 shows a cut-away view of the tubular-type linear generator. The machine of this research consists of the coil-wound stator and the permanent magnet mover. The ring magnets on the cylindrical mover are axially magnetized and the iron poles make the magnetic flux paths. The radial magnets or Halbach array magnets could be used, however, for simple structure in this research; the ring shaped iron pole is used instead of the magnet pole. The tubular-type linear generator has some better qualities than the flat-type one.

Because of the symmetric structure, the leakage is smaller than that of the flat-type one. Also, the amount of coil is less and there is no end coil, therefore the copper loss becomes less than that of flat type generator. The shaft is cylindrical and it can be easily connected with the rod of the engine piston without complex mechanical structure. Furthermore, the cylindrical mover can be rotated freely with the piston of the engine and there is no interference to the magnetic characteristics in this structure.

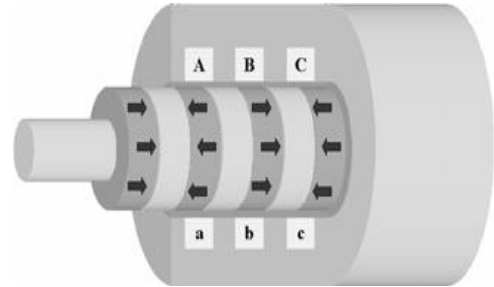


Figure4. Cut-away view of the tubular-type linear generator

B. Specification of the Linear Generator

Table 1 shows the specifications of the linear generator in this research. The rated output is 1kW and the stroke of the linear generator, 72mm, is limited by the free-piston engine stroke and the operation frequency, 30Hz, is that of the hydrogen engine. The maximum output voltage is 300V, which is limited by the control circuit elements. From the mechanical size of the free-piston engine, the proper size of the linear generator is selected. There are two modules of 2-pole mover and three modules of 3-phase stator coil.

TABLE I. SPECIFICATION OF LINEAR GENERATOR

Output, KW	1
Pole/phase	2 pole/3phase
Stroke, mm	72
Frequency, Hz	30
Maximum Output Voltage, V	300

C. Back-EMF Analysis

The stroke of the linear generator is short and the operation frequency is high so that the velocity of the mover is not constant. In the design process, a sinusoidal velocity profile of the mover is assumed. At both end sides, the velocity of the mover is zero and the velocity is the maximum value at the center of the stroke. In this case, the maximum velocity of the mover is over 6 m/s and the average velocity is about 4.3 m/s. Under this velocity profile, the sinusoidal output waveform is preferred and the maximum output line to line voltage should be under 300V. The finite element method is used to analyze the magnetic characteristics of the linear generator. Figure 5 shows the magnetic flux density and equal-potential lines as the result of the axis-symmetric analysis of the test model.

Design and Analysis of Tubular Type Linear Generator for Free Piston Engine

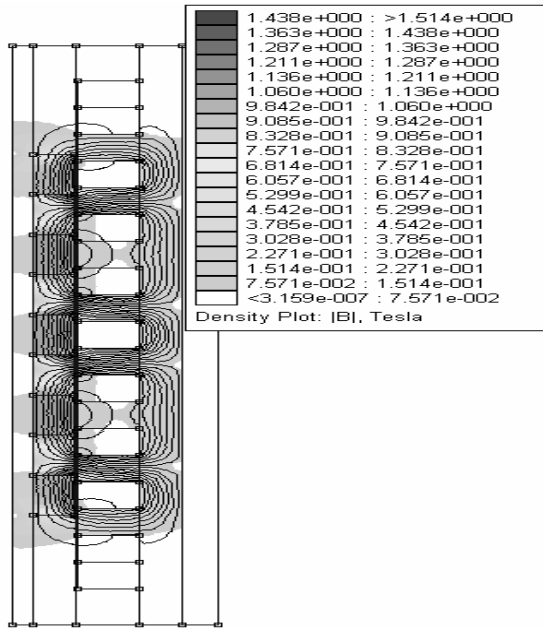


Figure5. Magnetic flux density of the tubular linear generator

The result of the phase voltage analysis with the sinusoidal velocity profile is presented in Figure 6. The output line-to-line voltage is shown in Figure 7. The final output waveform to the output circuit after the regulation process becomes the largest envelopes of each phase voltage. The maximum value of the output voltage is not enough and the shape is somewhat little sinusoidal. A new design which can increase the output voltage and can get more sinusoidal waveform is needed to satisfy the required specifications.

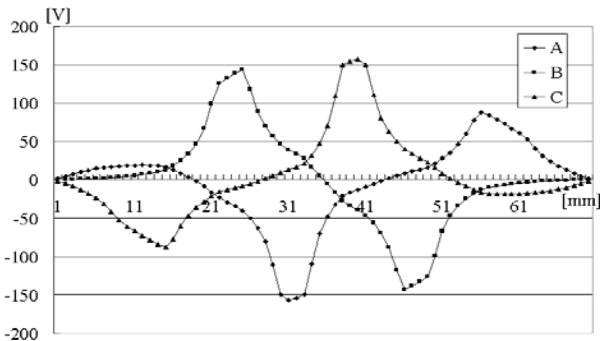


Figure6. Phase voltage with the sinusoidal velocity

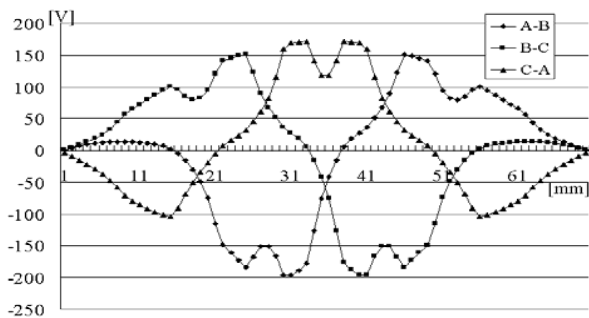


Figure7. Line-to-line voltage

A. Detent Force Reduction

The maximum detent force of the basic linear generator model is about 70N. This is a relatively large value compared to the rated reaction force of the test model, which is about 250 N. For the stable operation of the free-piston engine system, small detent force of the linear generator is required.

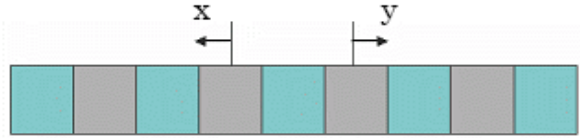


Figure8. Pole pitch modulation of mover

There are many conventional detent force reduction like the skew, chamfering, adjusting pole width, etc. However, in this case, those methods cannot guarantee good performances of both the output voltage and the detent force. To realize the high output voltage and the small detent force, irregular pole pitch is adopted to the mover. By changing some pole pitch, some harmonics cancel each other and the total detent force can be reduced. Though, in a normal case, the irregular pole pitch can cause a phase unbalance problem or the reduction of the peak voltage. The output waveform and the peak value is improved in this case. The detent force decreases or increases with the variations of the pole pitch x and y . Figure 8 shows the pole pitch modulation. In the case of $x=3$, the detent force has the smallest value. The detent force is smallest when $y=-3$. Figure 9 shows the simulation results of the detent force distribution with the variation of y when $x = 3$.

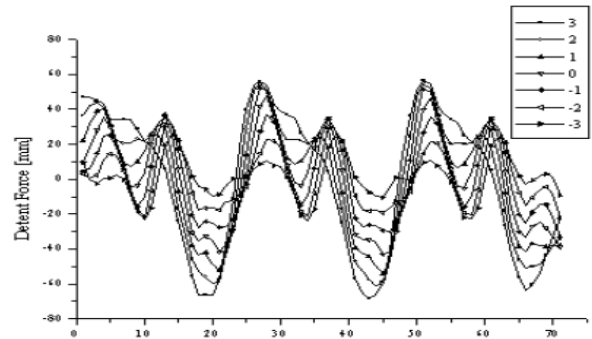


Figure9. Detent force distribution with the variation y

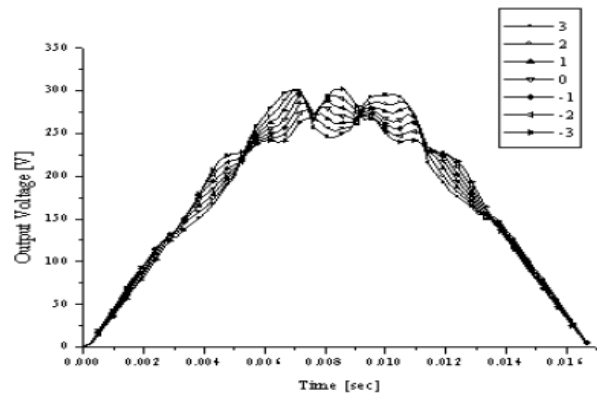


Figure10. Output voltages with the variation of y

Figure 10 shows the output voltage waveforms which are regulated. In the case of $y=-3$, though the peak value of the output voltage decreases little, the total waveform is more sinusoidal and this result is acceptable. In conclusion, the irregular pole pitch is very useful to realize the small detent force and the sinusoidal output waveform in this research.

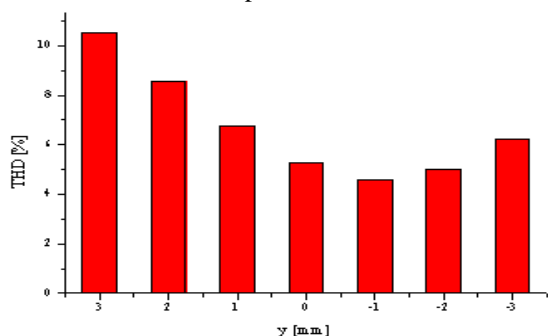


Figure11. THD with the variation of y

Figure11 shows the THD with the variation of y when $x = 3$. When $y = 3$, THD = 10.57 % and when $y = -3$ THD becomes 6.23 %, which is not smallest value, however $y = 3$ is selected because the detent force is smallest at this point. From these simulation results, the tubular type linear synchronous generator is manufactured. In the manufacturing process, tubular type has more difficulties than planer type.

III. EXPERIMENTAL RESULT OF TUBULAR TYPE LINEAR GENERATOR

Figure12 shows the manufactured mover of the tubular type linear generator. The middle part of the mover becomes the permanent magnets and magnetic path ring. The move is supported by the linear bushing which is attached each sides of stator. For the first step of experiment, rotary type induction motor is used instead of the free piston engine, and crank structure is employed for conversing rotating motion to rectilinear motion. For reducing mechanical stress which is comes from the vibration of the mover, fan shaped crank structure is applied. The shaft is connected to crank structure and one side of connecting rod is linked to linear guide for supporting connecting part. Linear guide also helps giving no normal force in linear bushing.



Figure12. Manufactured mover.

Figure13 shows the comparison of the simulation and experiments for no-load back emf. As can be seen in the figure, the experimental results have good agreement with the simulation. Figure 14 shows the back emf wave form for full load.

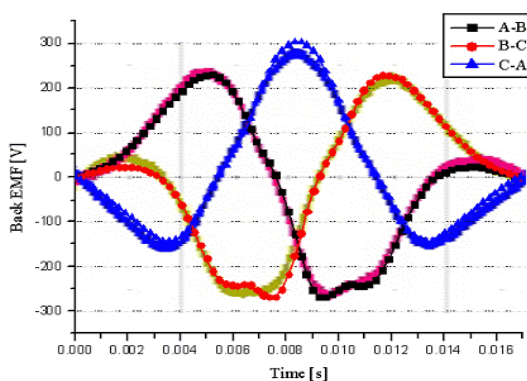


Figure13. Output voltage with no load

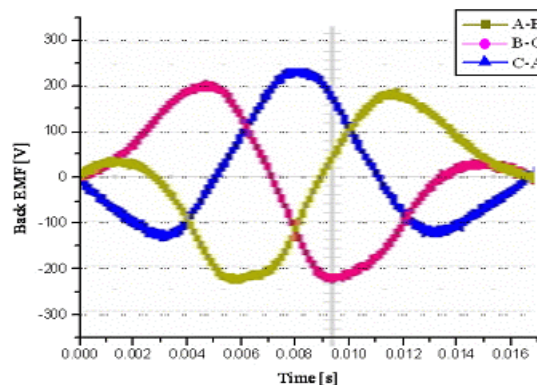


Figure14. Output voltage with full load

IV. CONCLUSION

In this paper, tubular-type linear generator for free-piston engine system of high efficiency is analyzed and compared the simulation results with the experiments. The ring-shaped iron with axially magnetized magnet rather than radial type magnet is used as the magnetic pole of the mover because the ring shapes for the manufacturing feasibility and the low price. Basic information regarding the Free Piston Engine structure and principle were presented and a motivation was presented for using a FPE – LEG system for producing electric energy for a hybrid vehicle. A linear generator suitable for such a system should have a low weight translator, a multiphase structure and high power density values that could be obtained by using rare-earth permanent magnets To realize small detent force and sinusoidal output waveform of the linear generator, the irregular pole pitch is adapted in this research. The irregular pole pitch gives merits to producing more sinusoidal waveform as well as reducing the detent force. The generator is manufactured and tested with some experimental devices and the results show good agreements with the simulations.

V. REFERENCES

- [1] Waqas M. Arshad, Thomas Backstrom, Peter Thelin and Chandur Sadarangani : “Integrated free-piston generators : an overview”, Electrical Vehicle Symposium, 2002.
- [2] William R. Cawthorne : “Optimization of a brushless permanent magnet linear alternator for use with a linear internal combustion engine”, West Virginia University, 1999.

Design and Analysis of Tubular Type Linear Generator for Free Piston Engine

[3] A. Cosic, J. Lindback, W. M. Arshad, M. Leksell, P. Thelin, E. Nordlund : “Application of a free-piston generator in a series hybrid vehicle”, LDIA, 2003.

[4] Arshad W.M., Backstrom T., Thelin P. and Sadarangani C, “Integrated Free-Piston Generators: An Overview”, IEEE NORPIE- 02 Conference, Stockholm, 2002.

[5] Mikalsen, R, Roskilly, A.P. “A review of free-piston engine history and applications”, Applied Thermal Engineering 27, (2007): 2339- 2359.

[5] Waqas M. Arshad, Chandur Sadarangani, Thomas Backstrom and Peter Thelin : Finding an appropriate electrical machine for a free piston generator”, Electrical Vehicle Symposium, 2002.

[6] Ho-Yong Choi, Jae-Won Lim, Hyun-Kyo Jung, Sun-Ki Hong, Dong-Hyeok Cho, Sang-Yeon Hwang, Si-Doek Oh : “Design of Flat-type Linear Generator for Free-Piston Engine”, ICEMS, 2004.

[7] Ho-Yong Choi, Sang-Yong Jung, Hyun-Kyo Jung : “Performance evaluation of permanent magnet linear generator for charging the battery of mobile apparatus”, LDIA, 2001.

[8] Jae-Won Lim, Ho-Yong Choi, Hyun-Kyo Jung, Sun-Ki Hong, Chul-Gyun Lee, “Shape Optimization of Teeth Structure in Tubular-Type Linear Gnerator”, pp.148-151, LDIA 2005.

[9] Young-wook Kim Jaewon Lim Ho-Yong Choi Sun-Ki Hong Heesoo Lim Si-Deok Oh Hyun-Kyo Jung, “Starting mode analysis of tubulartype linear generator for free-piston engine with dynamic characteristics”, International Conference on Electrical Machines and Systems, ICEMS, page 926 (2007), ISBN:978-89-86510-07-2.