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ANALYSIS OF A THREE PHASE TUBULAR PERMANENT MAGNET LINEAR GENERATOR

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ABSTRACT
This paper describes a three phase tubular permanent magnet linear generator design. The generator has a long translator with six coils. The finite element analysis is used in the design simulation. A 2D axisymmetry is applied. Parametric simulation is run to get the machine parameters which are used to calculate other parameters. The harmonics analysis is included in the design simulation. Optimization is performed to obtain the highest power to weight ratio of the machine, as the objective function of the optimization. The machine dimension is set up as the design variable, and the cogging force and output power as the state variables. The subproblem and first-order strategy is used in the design optimization.

KEY WORDS
Electrical machine, linear generator, modeling, simulation, finite element analysis, optimization.

1. Introduction

Linear generator is an alternative solution in the providing of the electrical power supply with high efficiency. Without any rotary part in the engine, the machine will be light weight and compact. Prospective applications of this machine are for industrial, commercial and personal purposes especially where a stand alone power generation is needed. It is also vital when grid power utility is unavailable. It can also be used as an alternative power generator for hybrid vehicles.
In this paper, design and simulation aspects of a three-phase tubular permanent magnet linear generator intended to be driven by a free-piston internal combustion engine are outlined. It is designed as the further improvement to the previous designs [1].
The generator will have to function as an electrical motor to drive the engine in starting operation, when current is injected to the machine to run it forward and backward or in continuous motion. Fulfilling this requirement, more aspects are considered in addition to the standard generator design.

2. Linear Generator Design

The linear generator is proposed to be driven by a single or a double two-stroke combustion linear engine. In the double engine, the combustion takes place alternately between two opposed chambers. In the single combustion engine, one of the combustion chambers is replaced by a kickback mechanism. The force on the translator generated by the explosion in the combustion chamber is used to compress the air in the kickback chamber. The pressed air will then release the energy stored to push back the translator in the opposite direction.
A highly accurate control system is required to maintain continuous engine operation. A position sensor is utilized to give the position of the piston at anytime. Unlike the rotary engine which uses a crank shaft to maintain the piston motion, the movement of the translator (piston) in a linear engine is not bounded by any mechanical linkage to the stator. Therefore, the motion of the piston is free and it can stop at any position. Consequently, advanced control is required.
The generator is placed between two combustion chambers or between a combustion chamber and a kickback chamber. The pistons are mounted at both ends of the shaft in rigid connection. The linear bearings are used to support the shaft and to keep it from deflection due to the high force generated by the interaction between permanent magnets and the stator.

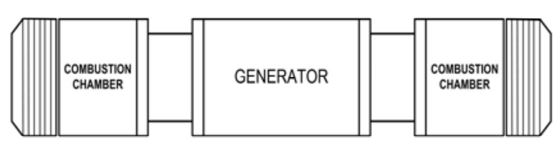


Fig.1 . Linear generator set

The long translator type is chosen since it has a better performance compared to long stator machine [2]. In this generator, the coils are always activated during the generator motion. In the long stator machine, the coils are activated during one half of generator stroke.

The machine has seven permanent magnets mounted on the translator back iron. The high power radially magnetized rare earth permanent magnet NdFeB is used to give a high magnet remanence. If there is a problem with manufacturing, the radial permanent magnet can be replaced by some segmented diametrically magnetized permanent magnets that arranged into one complete ring magnet.

The volume and weight of a machine using the permanent magnet as magnet flux source are low compared to that using coil. The disadvantage is the existence of cogging force. It becomes an important parameter since its peak value is significantly high especially when the engine is designed to have a low power. Therefore, the cogging force should be kept to be as low as possible.

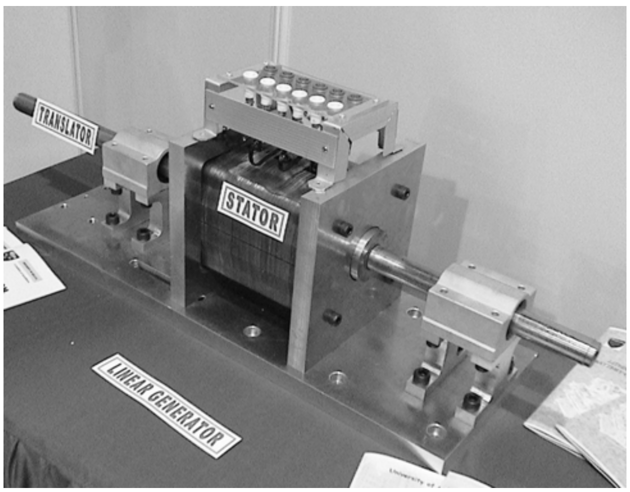


Fig. 2. Three-phase linear generator

A translator back iron is constructed of silicon steel laminations. Slotted lamination is stacked to reduce the eddy current losses. The flux will flow from one magnet to another magnet through this back iron; therefore the high permeability material is required.

A light weight material like aluminium alloy can actually be used for the shaft. It will decrease the total translator weight. However, the magnetic material is used to allow the magnetic flux flows in the shaft. It will also increase the magnetic path of the translator and it can reduce the translator back iron thickness.

The stator is built of silicon steel lamination which consists of 6 slots. The slotted axial lamination is used instead of radial lamination that has the problem in manufacturing. The air gap between lamination in the radial stacking is also avoided. As a result, the insulation of the lamination will be an additional part that has a low permeability. This part behaves like air gap. The advantage of this method of lamination stacking is easy to handle.

Instead of round wire, a flat or square typed copper wire is used as a coil material to get a high slot fill factor. Since there is almost no air gap among wires, the thermal trapped in this air is avoided. The thermal generated in the coil will be easily released to the stator, and it will increase the efficiency of cooling system of the generator.

Using the wire size of 1.65x3.8mm, the wire can withstand a current of 22.5 Amperes. This high current carrying capacity is required, especially when the generator is used as a motor in the engine starting operation.

The generator is run forward and backward in the distance of the engine stroke. In the translator motion, the flux linkage in the coil will be changed alternately and the emf will be generated.

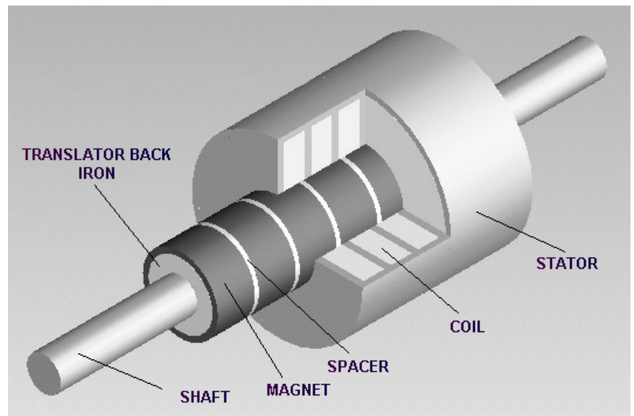


Fig. 3. Three-phase linear generator components

In one stroke of motion, the translator will move in a length of two poles of magnet. Therefore, the length of permanent magnet set, that is one magnet and one spacer, would be one half of stroke length. Since the stator has three coils in the distance of stroke, the stator pole length would be one third of the stroke length.

2.1 Flux Distribution

The dimension of magnetic parts is primarily defined by its flux density. Using the BH curve of the material, the maximum allowed flux density that flows in the material is kept below the saturation value. In the optimization process, these dimensions should be minimized toward the optimum point.

The magnetic potential vector $\overline{A}$ is used in the field analysis. In parametric simulation, the magnetostatic field principle is applied to calculate magnetic flux and electromagnetic force. Gauss's law is applied. For problems considering saturable material with permanent magnets, remanent intrinsic magnetization vector is involved in the flux density calculation. The flux flows through an area can be calculated as integral of flux density over the normal of surface area.

2.2. Output Voltage

The induced voltage is calculated using discrete data of the linkage flux in the coils resulted in the parametric simulation. In order to get the accurate result, the flux linkage is calculated for all coil elements, then it is summed to get the total flux. Using magnetic potential vector, the flux can be derived as:

$$\phi = -\int A \cdot dl \tag{1}$$

This emf is given in the term of flux difference and translator speed,

$$e = -N \frac{d\phi(x)}{d(x)} \frac{dx}{dt} \tag{2}$$

where N is number of turns, $d\phi(x)/dx$ is the derivative of flux with respect to displacement, and *dx/dt is speed* .

The main flux in the machine is generated by permanent magnet. The flux magnitude is affected by some factors, i.e., the dimension and material properties of generator magnetic components. In the design, the flux is required to be as high as possible.

2.3 Cogging Force

The cogging force is the magnetic attraction between the permanent magnets and the stator teeth. The force attempts to maintain the alignment between the permanent magnet and the teeth. The force will be produced when alignment is forced to be shifted. The negative of cogging force is the acceleration force. The cogging force in the one direction of translator motion will be acceleration in the opposite direction. The force magnitude is a function of the magnetic flux. The flux should be low to get the low cogging force.

The virtual work method is used in the force calculation. In this method, the force acting on a ferromagnetic object can be determined as a sum of forces in the air layer surrounding it. The force of an air material element in the s direction is given by:

$$F_s = \int_{vol} \overline{B}^T \frac{\partial \overline{H}}{\partial S} d(vol) + \int_{vol} \left(\int \overline{B}^T d\overline{H} \right) \frac{\partial}{\partial S} d(vol) \tag{3}$$

where:

F_s = force in element in the s direction

$\frac{\partial \overline{H}}{\partial S}$ = derivative of field intensity with respect to displacement

s = virtual displacement of the nodal coordinates taken alternately to be in the X,Y,Z global direction

vol = volume of the element.

Although the cogging force is not one of parameters having direct contribution in the machine power to weight ratio, it is included in the design optimization as a constraint variable. The thicker magnet used the higher output power will be obtained because the higher flux will be generated by the magnet. But, on other hand, the cogging force will increase. In the whole engine-generator system, the cogging force will give the effect in the system efficiency.

2.4 Harmonics

The dimension and shape of permanent magnet, spacer and teeth play a main contribution to the output voltage waveform. If the speed profile of the machine is not pure sinusoidal, the harmonics will be appears when the flux difference is not constant. If the speed is constant, the harmonic will be also generated when the flux difference is non-sinusoidal.

The length of spacer and teeth determine the shape of the flux curve and the voltage waveform. The voltage waveform will be low or zero when the spacers are aligned with the teeth. In a short distance of motion, the flux is still fully concentrated in the teeth. Therefore, the flux difference will be zero. Similar to the spacer, the teeth will give the same effect. If the spacer length is zero, the flux density curve will be better. However, the flux in the magnet ends will be bypassed to the next magnet. It will also give the low voltage magnitude. On other hand, the teeth can not be minimized after the flux density reaches the saturated value.

In the generator using axially permanent magnet, the application of teeth shoes can reduce the harmonics. The flux density that is concentrated in the spacer will be distributed over the shoe surface. The dimension shoe, however, is limited by the slot length and by the fact that there will be the flux flows directly from shoe tip to another. It can also reduce the flux and the voltage magnitude.

2.5 Losses

Two types of losses are included in the calculation, the copper loss and iron loss. The copper loss is defined as the product of current and coil resistance, the iron losses is consist of hysteresis and eddy current losses.

One way to reduce a copper loss is by choosing wire with large cross section, besides selecting a material with better properties. It will also increase the rating current of the machine. The constraint is that the number of turn of the coil will be decrease, and it will reduce the output voltage.

The core lamination contributes losses when the alternating flux flows inside. The loss curve is used to calculate the losses. If the flux flows tangentially to the lamination, the small slot can be put in the lamination and it will reduce the losses.

3. Simulation

3.1 Simulation Model

Using the axisymmetrical property, the generator is modeled as 2D object. The 2D model gives advantages over the 3D system; one of them is the simulation time. The parametric simulation is performed to give a series of discrete data required to calculate machine electrical parameters. The element type is defined with considering the element output required by other calculations and the specific output data. In the certain condition, the element size is refined especially in the critical region.

The model is built of object keypoints. These keypoints are easy to be changed and the distance between keypoints is easy to be varied. Dimension variables based on keypoints are used for parametric simulation and optimization.

The steel material is used for the shaft, while silicon steel is used for the back iron as well as stator material. A BH data is required for these materials to consider the non-linear properties. The translator is built of NdFeB 33EH-typed permanent magnets, that alternately arranged, and separated by aluminium spacers that have a relative permeability of one, in order to avoid the flux flows directly from one permanent magnet pole to the next. The 1 mm air gap is sufficient to handle the machine components for assembly process. The electrical copper material is used for coils with assumption that the slot fill factor is one.

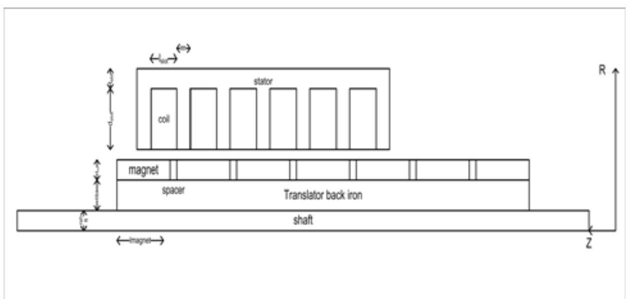


Fig. 5. Three-phase linear generator modeling

The fringing flux is also considered by applying a magnetic boundary condition. The infinity boundary can be used to include the zero electromagnetic potential in the surface boundary. However, the sufficient area can be applied as a boundary without the infinity boundary for the insensitive model.

The parametric simulation is performed to get all output parameters result, including flux distribution, coil flux linkage, and cogging force. The parametric method is also used in the design optimization.

The complete simulation is run for each step of translator motion. The translator motion is considered as sinusoidal. The simplification will further be corrected using the real engine speed curve. The emf is derived from the flux linkage difference in the coils at every consecutive translator position. The force is calculated in the translator or stator using virtual work method.

The optimization is performed using subproblem strategy, i.e. the original problem is divided into a smaller problem and clustered together to obtain a sequence of subproblems. Solution to the large problem is attempted iteratively through repeated solutions to the modest subproblems. All dimensional parameters – the translator back iron thickness, the magnet thickness, the magnet length, the slot width, the slot depth, and the stator back iron thickness - are involved in the design optimization. The cogging force, the output power, the translator flux density, the teeth flux density, and the stator flux density are set up as constraint variables. The objective function of the design optimization is power to weight ratio or power to volume ratio.

The flux density is kept below saturated point of the material in order to minimize the object dimension. The magnet length and slot length are limited by the stroke length. Other parameters can be freely varied. The target of output power is 6.5 kW.

3.2 Generator Specification

The generator component dimension parameters are defined by the engine specification and the design optimization results. Some parameters consider the manufacturing factor and standard. The established dimension is shown in the Table 1.

Speed	3000	rpm
Stroke length	69	mm
Shaft diameter	15	mm
Wire size	3.82x1.65	mm
Air gap	1	mm

Table 1. Linear generator Specification

3.3 Simulation Result

The optimization is performed using all design variables. The sweep or incremental pre-optimization is required to see the general behaviour of the output with respect to design variables changing. The refined optimization give accurate final results.

The generator dimension obtained from the design optimization is listed as flows.

Shaft radius	12.5	mm
Translator back iron thickness	7	mm
Magnet length	31.5	mm
Magnet thickness	8	mm
Spacer length	3	mm
Slot depth	26	mm
Slot width	15.2	mm
Tooth thickness	7.8	mm
Stator back iron thickness	4	mm
Number of turn	56	

Table 2. Simulation result

The power to weight ratio of 0.5kW/kg is achieved in the optimization. The induced voltage curves are plotted in the Fig.6. It is not as the same as in the rotary machine, each voltage waveform produced can not be pure sinusoidal. Since the translator motion is sinusoidal, voltage waveforms follow or be ‘enveloped by’ that speed profile.

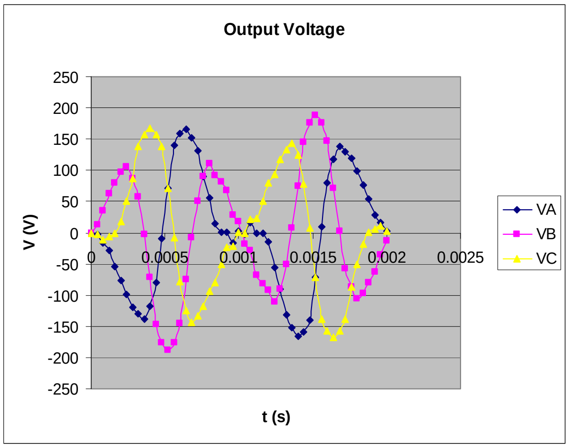


Fig. 6. Three-phase linear generator output voltage

The forward motion force is plotted in the Fig.7. From the figure, the positive portion of the curve is the cogging force, and the negative portion is the acceleration force. It will be reversed for the backward translator motion.

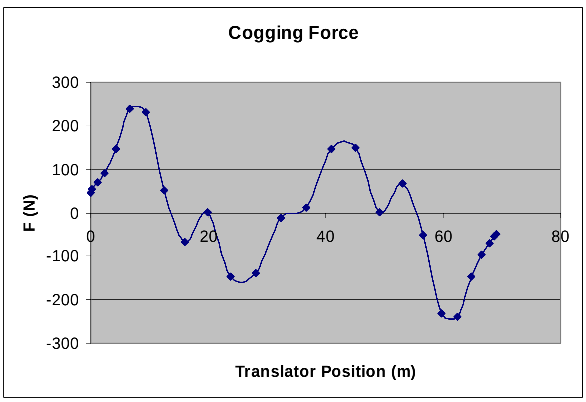
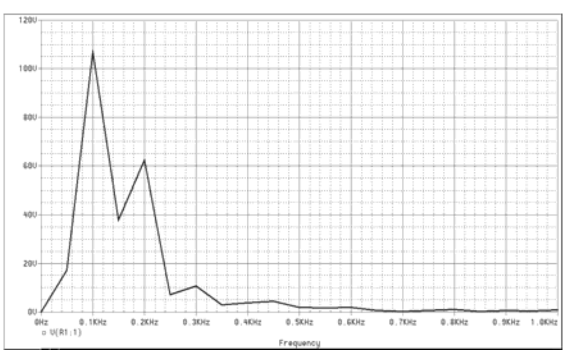
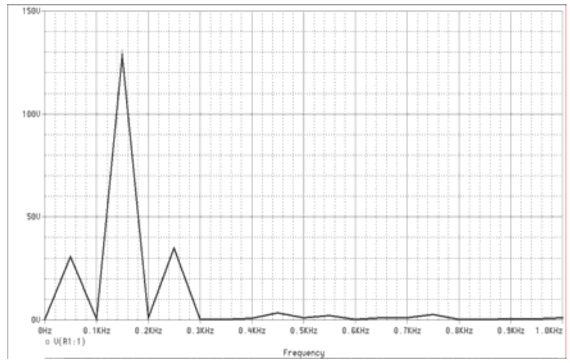


Fig.7. Three-phase linear generator cogging force

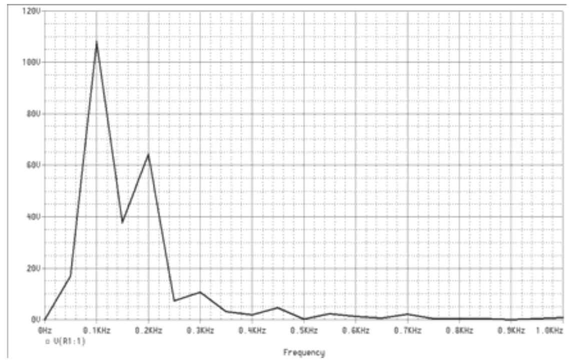
Since the number of magnet pole per stroke of the machine is two, then the voltage frequency is 100 Hz. The harmonics analysis result using Fast Fourier Transform for voltage waveform in the Fig. 6 is shown in the Fig. 8. The magnitude of 2nd harmonics component is relatively high for V_A and V_C. The curve in b) shows that the main component is at 150 Hz.



a) V_A



b) V_B



c) V_C

Fig. 8. Three-phase voltage harmonics components

4. Test Results

The generator is tested on a test-bed. The parameters are recorded using an online DAQ system. It is run in low speed of 600 rpm. The voltage waveform and the cogging force – in the unit of kg - are shown in the Fig. 9 and Fig.10.

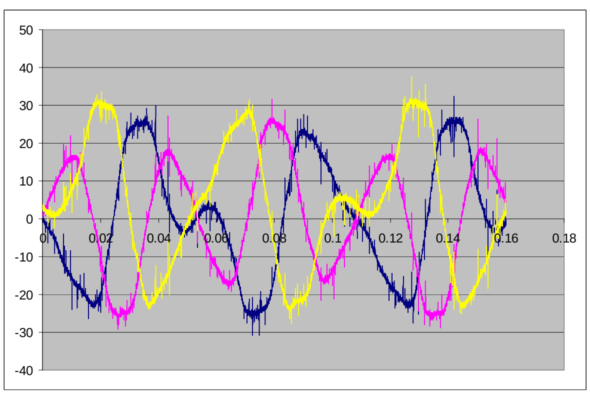


Fig. 9. Output Voltage

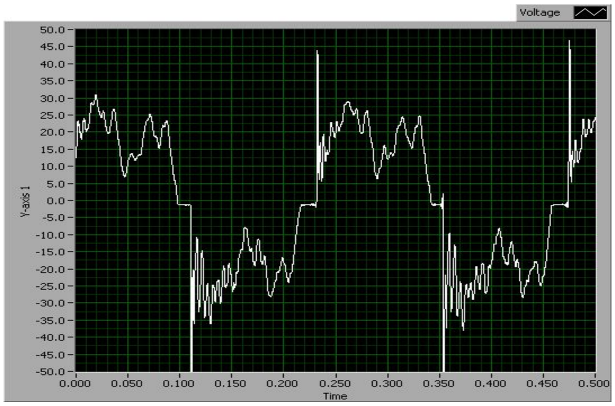


Fig. 10. Cogging Force

All the measured parameters are converted to voltage as a function of time. In the Fig. 6, 7, 9 and 10 it is shown that the analysis is confirmed to the test.

5. Discussion

From the induced voltage waveform, the curve will be sinusoidal if the speed is constant. In the rotary machine, the linear speed is constant, so the voltage waveform is sinusoidal.

The cogging force is one of the drawbacks in the permanent magnet machines. The radially permanent magnets can reduce the cogging force. The cogging force contributes in the efficiency of the whole system.

In the harmonic analysis, it shows that the voltage waveform has a significant harmonics. It is due to the translator construction – permanent magnet, spacer and teeth dimension.

The tests show that the overall simulations and the design optimization are accurate.

In order to increase the output power, the higher engine speed is required. If the speed is 6000 rpm for example, the output power, and also the power to weight ratio will be doubled.

6. Conclusion

The main advantage of a linear generator over a rotary generator is the high power to weight ratio. The higher efficiency is made possible due to the absence of many engine rotary parts. The un-continuous motion of the machine – it starts and stops at the end of each stroke – makes the generated output voltage waveform not a pure three-phase, but after converting the output to DC signal generating a three phase voltage will be not a significant problem. Such a compact, high efficiency and lightweight generator can be widely used to supply electric power as a stand alone system, emergency power supply or part of an integrated system with the main power network. It is also suitable for hybrid application where its small size and high efficiency are advantageous.

7. Acknowledgements

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