Abstract – This paper present our experience in the design of a permanent magnet generator. The generator has a long translator and a permanent magnet mover as magnetic field source. It generates a three phase electrical current. The generator is proposed to be operated using a dual chamber free piston internal combustion linear engine. The finished product is to be placed in a hybrid electric vehicle to generate electricity to run the motors and to charge the batteries [1],[2]. The machine design is performed using a 2D finite element analysis. The generator produces a three phase voltage and the power output is 7 kW. This paper also presents the fabrication of the prototype.

I. INTRODUCTION

Linear generator is an alternative solution in providing an electrical power supply with high efficiency [3],[4]. 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 and electric 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. A finite element analysis simulation is used in the generator design. A prototype of the machine is fabricated and tested to investigate its performance [5].

II. LINEAR GENERATOR DESIGN

A. Generator design selection

There are two types of linear generator design, i.e. long translator type and long stator type. In the long translator generator, the translator or mover is longer than the stator, and in the long stator it is vice versa. The translator of a long translator type always activates all windings in every generator motion, on other hand, in the long stator type, only a part of stator is activated.

From the efficiency of the machine point of view, the long translator generator will be the best choice. The long translator type is chosen in this design since it has a better performance compared to long stator machine. The selection of the generator type may also depend on the space provided in the generator system.

Three types of translator can be noted in the consideration; the moving coil, the moving magnet and the moving iron. They all provide magnetic field for the machine coils. In this design, a translator equipped with permanent magnets is considered.

The permanent magnet is used as the magnetic field source for the machine. It gives a high flux density in the air gap compared to other translator type for the same volume. It will also give a translator mass reduction and in turn the moment of the translator is also reduced. It is one of the most important considerations in a linear machine design.

In our previous designs axial and radial permanent magnets had been used [6],[7],[8],[9]. In the axial permanent magnet machine, a high cogging force is produced due to the interaction between permanent magnet and stator teeth. Since the cogging force becomes a serious problem, radial permanent magnets is applied to reduce the cogging force. As a result, a quasi Halbach permanent magnet configuration is used [10]. This arrangement reduces the translator mass by removing the permanent magnet back iron used in the radial permanent magnet machine.

The generator is a three phase electrical power supply. The three phase system is chosen since the generator will also be used as a motor in the engine starting mechanism. A single phase generator will not generate a smooth thrust force when it is operated in the motoring mode.

B. Generator construction and operation

The linear generator system contains a linear electrical generator and a dual chamber linear internal combustion engine, as shown in the Fig. 1. The engine can be fueled by petrol or natural gas.

The generator includes a stator and a translator, as shown in the Fig.2. Two groups of six coils are located in the stator slot to generate a three phase electrical system. The translator moves forward and backward inside the stator.

In this machine, seven radial permanent magnets and six axial permanent magnets are arranged alternately in a series to build a discrete or quasi Halbach permanent magnet arrangement. Fig. 3 shows a discrete or quasi Halbach permanent magnet arrangement. All the permanent magnets are mounted on an aluminum shaft.

![Fig. 1. Linear generator.](image-url)
The combustion takes place in a combustion chamber containing a mixture of fuel and oxygen that is excited by an electrical spark generated by a spark plug. The mechanical energy generated is delivered to the generator translator through the shaft. Another piston will move and press the air in the second chamber. It will increase the pressure of the second combustion chamber. As the piston reaches the stroke end, the second chamber combustion will take place and the piston will be pushed back to the opposite direction. This sequence of operation will be repeated during the operation of the machine. A control system is required to control this firing system.

The linear motion of the generator translator pushes the magnetic field generated by the permanent magnet across the stator conductors. As a result, a three-phase voltage will be induced in the coil terminals. It will then be able to deliver electrical power to the loads.

C. Simulation and Analysis

Initially, an analytical approach is used to get a preliminary design [7]. Although it only provides a rough estimation, the general machine parameters can be obtained faster from the initial guidelines. From this result, refinements are performed using either analytical calculation or finite element analysis simulation.

In this design, the generator has a axisymmetry shape. It gives an advantage in the simulation modeling. Instead of using 3D model that time consuming, the 2D model is used. It can reduce the simulation time and will give a more accurate result. A high density model meshing, that is difficult to get in the 3D simulation, can be created in the 2D models.

The model objects are carefully meshed. Object that contain a high electromagnetic energy need a high density mesh. The air gap is one of that should be meshed an extra density. Using high elements density, we can get an accurate calculation results.

Two types of simulation are performed in the design, a parametric simulation and transient simulation. In the parametric simulation, a series of static or nominal simulation gives a set of output parameter data. This data is further manipulated to calculate other machine parameters, such as the induced voltage that derived from the coil flux linkage.

In the transient simulation, the simulation is performed using time stepping. It is useful to calculate some machine parameters that are dependent on time or frequency. The variables that are used in the parametric simulation need to be converted to the time domain. Using this type of simulation, an additional simulation such as load simulation can also be done at the same time. Sometimes, a mechanical property can be added to the calculation using an electromagnetic parameter such as force. This combination gives a comprehensive simulation of an electrical machine.

The model is shown in the Fig. 4. It contains one half of the axial section on the machine. The materials of all objects are defined either using a linear material properties or non linear properties. A BH curve is provided for the stator core to involve the non linearity property of the silicon steel lamination; magnetization and magnetic remanence are provided for permanent magnet. Other materials are defined using its permeability.

The generator dimension and other parameter are shown in Table 1. If the generator speed is 3000 cycles per minute, it generates an induced voltage having a frequency of 100 Hz. The calculated three phase induced voltage is shown in Fig. 5.
Using a wire that has current capacity of 7 Ampere, the generator gives a 7 kW output power. In the case that the engine speed is 2000 rpm, the generator will produce a 5 kW output power.

III. GENERATOR PROTOTYPE

The generator prototype is shown in the Fig. 6. This prototype is ready to run in the linear engine. It is equipped by a cooling system including static fins covering the machine casing and a liquid cooling system inside the casing. When the heat flowing in the machine is quite low, the cooling fins can emit the heat to the surrounding, but in the case of over heating, the cooling pump should run to deliver the cooling fluid into the machine. An external control circuit is needed to control this mechanism automatically. The shaft may be drilled to let the air flow for an additional cooling system as far as the mechanical properties of its material allows.

To protect the permanent magnets, tubular flanges are placed on the casing. A magnetic displacement sensor is placed on the shaft surface and connected to the control circuit. It is required when the generator is operated in motoring mode.

The six coil terminal is mounted on the casing. The external connection is provided for measurement and three phase connection.

IV. FABRICATION

The machine has components that are easy to fabricate and assemble. Excluding permanent magnets, the generator components can be manufactured in a small workshop. A steel ring can be used to combine segmented radial permanent magnets into a compact construction if the permanent magnet ring is unavailable. The ring should be thin avoiding reduction in the magnetic flux. Fig. 7 shows the segmented permanent magnets arranged into a single ring magnet.

The stator lamination stacking is another problem. A radial lamination stack with axial slot is used. In order to get a rigid construction, a special glue is injected to the stator and coil gaps. It is also done to the translator to avoid the vibration between permanent magnets.

TABLE I
GENERATOR DIMENSION AND PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Stroke length</td>
<td>69 mm</td>
</tr>
<tr>
<td>Shaft radius (non ferromagnetic material)</td>
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</tr>
<tr>
<td>Magnet (axial and radial) inner radius</td>
<td>12.5 mm</td>
</tr>
<tr>
<td>Radial Magnet length</td>
<td>22.5 mm</td>
</tr>
<tr>
<td>Radial Magnet thickness</td>
<td>12 mm</td>
</tr>
<tr>
<td>Axial Magnet length</td>
<td>12 mm</td>
</tr>
<tr>
<td>Axial Magnet thickness</td>
<td>12 mm</td>
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<tr>
<td>Air gap</td>
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</tr>
<tr>
<td>Tooth width</td>
<td>6 mm</td>
</tr>
<tr>
<td>Stator back iron</td>
<td>6 mm</td>
</tr>
<tr>
<td>Slot width</td>
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</tr>
<tr>
<td>Slot depth</td>
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<tr>
<td>Wire AWG#</td>
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</tr>
<tr>
<td>Number of turn per coil</td>
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</tr>
</tbody>
</table>

Fig.5. Three phase induced voltage.

Fig.6. Generator Prototype.

Fig.7. Ring and segmented permanent magnets.

V. CONCLUSIONS
A 7 kW linear generator has been designed and fabricated. It is proposed to be driven by a dual chamber internal combustion linear engine. The design is mainly performed using finite element method to get the accurate results. The generator can be used as a general purpose ac power source or to produce power for the electrical system in hybrid vehicles.

VI. FUTURE WORK

The further optimization is one of our plans. It includes the further investigations on material properties and reduction of machine dimensions and machine weight. A practical linear generator should have a high power to weight ratio and small enough to be fitted into a hybrid vehicle.

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