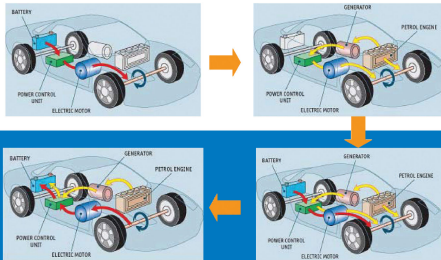




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Comparative Study of Linear Oscillating Generators



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1. Introduction

A broad variety of energy converters for primary energy (e.g. *Internal Combustion* machines, *IC* machines) are using oscillating principles. In general, these oscillating motions are converted to a continuous rotary motion by means of drive rod and crank shaft. The further energy conversion into electrical energy is achieved by a conventional rotating generator. This crank gear reduces the efficiency by introducing additional friction, requires additional weight and volume and causes wear. By using an oscillating linear generator these disadvantages can be avoided and very efficient, nearly wear free, small sized and lightweight electrical gensets can be constructed.

Hybrid electric vehicle (HEV) taking advantages of a lightweight linear oscillating generator may be a good solution to the problems of energy crisis and environmental pollution today. Also using these gensets as an *Auxiliary Power Unit (APU)* was often considered. The hybridization of automotive power-trains is a key step towards reducing emissions and improving fuel economy [1]. Of the various hybrid vehicle formats, series hybrids arguably offer the greatest modularity and potential for low cost, optimal energy utilization and emissions reduction being achieved by controlling the apportionment of energy between the energy storage devices, the IC engine / electrical generator and the electrical traction drive [2]. A linear oscillating generator converts the translator's kinetic energy directly to electrical energy, and is a potential energy efficient power source for use in a series hybrid vehicle power train. These features make it very suitable as a power unit in a series hybrid vehicle.

Furthermore, the free piston principle can be used by using linear oscillating motion. A free piston energy converter is a combination of a linear combustion engine and a linear electrical machine converting chemical into electrical energy.

The free piston energy converter has features as follows :

- The electrical machine can be used as a motor to start and stop the translator, as a generator for energy conversion and as an actuator to control the combustion.
- There is no crankshaft constraining the translator motion, which enables variable compression.

Meanwhile, test results of some prototype equipment with linear IC engines have been published. But a comprehensive study of linear oscillating generators is still missing. Especially questions concerning the generator topology, number of phases, excitation method, bearing construction, voltage stability under load, sensor and inverter equipment are not satisfying answered.

As task for this study, it has been the investigation and assessment of different generator topologies



in terms of

- Power to weight and volume ratio,
- Efficiency,
- Reactive power consumption,
- Size of the additional oscillating mass and
- Shaft design taking acceleration force into account

Generally, several methods have been presented to evaluate characteristic of linear oscillating motion. Among these, the equivalent magnetic circuit network method calculates the characteristics after dividing magnetic field into small regions and constructing magnetic network like electric circuit. This method is comparatively flexible and allows for fast determination of the properties of different machine topologies. At the end of the design process, the chosen topology is modelled by Finite Element Method (FEM) which takes nonlinear materials properties into account and accurate results close to the experimental ones can be expected. FEM has a solution that is close to experimental results and can model complicate magnetic field including nonlinear material properties.

All proposed topologies will be analyzed for the average force and force density using magnetic energy by 2-D equivalent magnetic circuit network method. The analysis of each topology considering leakage reactance is compared to the result of FEM by static magnetic field, and then the optimal model will be selected by characteristics and results of all topologies. Finally, the optimal topology will be approached through detailed design taking nonlinear properties of iron-core into account. Especially, it is absolutely essential to analyze by 3-D Finite Element Analysis (FEA) in case of transverse flux machine that is not symmetrical in anything axis. Accordingly, the result of transverse flux machine through 3-D equivalent magnetic circuit will be also compared with that of the 2-D equivalent magnetic circuit. In addition, comparison results between this analytical calculations and 3-D of simulation will be evaluated.

Of importance is also thermal and mechanical robustness, because the generator is usually operating in close vicinity to the combustion chamber and has to withstand high accelerations resulting from the oscillating masses.

Concerning the topologies at least the most important types shall be investigated :

1 Cartesian Topology

- 1-1 One-phase system with two magnets and two pole-pairs
- 2-1 Two-phase system with one magnet and one pole-pair (Half-side)
- 3-1 Two-phase system with one magnet and one pole-pair (Double-side)

- 2 Cylindrical Topology
 - 2-1 One-phase system
 - 2-2 Two-phase system
 - 2-3 One-phase system with 3 coils and long stroke
- 3 Hybrid Stepping Machine
- 4 Tubular Reluctance Topology
- 5 Transverse Flux Machines
 - 5-1 Single-sided system with reluctance type
 - 5-1 Double-sided system with magnets

To collect data about existing machines a literature study is necessary. The next step will be the development of analytical design data for the different machines and the checking of the design by numerical field calculations and thermal calculations. In addition, shaft design will be performed considering acceleration force by load mass because the shaft is seriously affected by bending and axial loads. A simulation of the generator taking into account also nonlinear effects of the combustion process will complete the knowledge about the operational behaviour of the machine and inverter. At last a scheme for the assessment of the different types of machines has to be elaborated and the assessment process has to be performed.

The results of this project will give elaborate information about the design rules and the performance data of linear oscillating gensets and in parallel tools for the calculation, simulation and the design of linear oscillating machines will be available.



2 Linear Oscillating Machines

2.1 Linear Machine

The need of electro-mechanical power generation has increased dramatically in industrial field as time goes by. In general, linear motion is mostly produced by devices which transform rotating movement into linear movement in factory and office automatic system. Using rotating devices increases complexity of the system, reduces efficiency by mechanical losses and declines precision by framework limitations and restrictions of driving speed. On the other hand, linear machines have fewer limits than rotating machines in driving speed. Also, linear machines are direct drives which need no gears to generate linear thrust force. In this reason, its application field shows increasing diversification since linear machines have been proposed by Professor *Laithwaite* in the middle of 19th century [3].

In most cases the linear machines are treated as cut and unrolled conventional rotating machines, that is, the machines with rather complicated structure. In some case such treatment is good, especially studying linear machines for continuous translation.

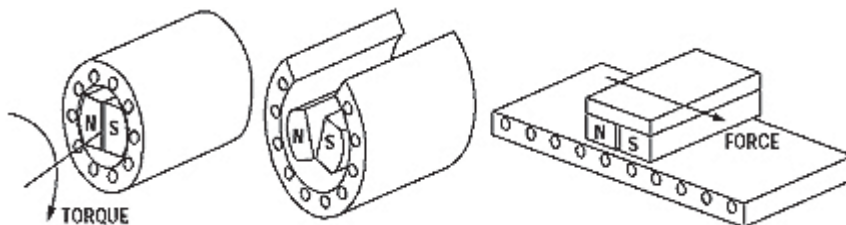


Figure 2.1 : Linear Machine

The majority of electrical machines are designed to produce rotary motion. In behalf of pointing out certain differences between a linear and its rotary counterpart, we consider a polyphase rotary machine. By the imagination, a rotary machine will be transformed into a linear machine if the stator of rotary machine is cut at a radial plane and unrolled and the rotor is replaced by at least two adjacent PM and back iron like in figure 2.1. The stator is named the *primary* and the rotor is the *secondary*. As a result, the primary has a finite length, called the *active length*. Additionally now *End Effects* occur which is unique to linear machines and does not exist in conventional rotating machines [4].

This PM excited linear machine has been considered to be the most suitable electric machine for linear control with high speed and high precision. The thrust of the linear machine is one of the important factors to specify machine performance. Maximum thrust can be obtained by increasing



the magnitude of current in the conductors and is relative to the size of conductor and PM. It can directly perform linear motion without auxiliary machine parts such as gears or cranks. Since it is possible to make smaller machine with high power, it has also been applied to small-sized precision products such as hard disk and CD player [5].

Based on above properties, linear machines exhibit the following advantages in contrast to the conventional rotational machines :

- High Precision
- High Acceleration
- High Stiffness
- High Efficiency
- No Limit of Motion
- Simplicity in Maintenance, Repair, Replacement and in Structure

2.2 Linear Oscillating Machine

2.2.1 Introduction

An object of this study is one kind of special machines with peculiarities of mechanical movement, that is, with periodical movement (oscillation) of the moving part. These oscillating machines have appeared already at daybreak of electro-mechanics, however nowadays they are nearly imperceptible in the whole of the special electrical machines. Partly, it is the result of imperfection of classification and grouping of electrical machines with specific properties of movement : it is necessary to classify them separately by the temporal and spatial properties of movement. Thus, the oscillating machines are distinguished by their specific temporal property of movement, meanwhile the spatial property (a trajectory) can be various. Also, it is proven that oscillating machines are a specific and independent type of electrical machines. These machines can be analyzed in the unified way, irrespective of the concrete domain of their application [6].

Linear type oscillating machines based on above properties, which are electromagnetic devices which develop directly short travel progressive linear motion, have already found some applications and are fabricated in moderate numbers for machine tool sliding tables, pen recorders, textile sewing machine, free piston pumps and compressors. In addition to high efficiency, the parameters of a linear oscillating machine should be nearly constant regardless of the amount of the current flow and position of the piston in order to control the position of piston without an additional sensor [7]. Several types of the linear oscillating machines are investigated to meet reliable enough and has more efficiency requirements. A structure of moving PM machine with back iron was designed for its high force density and efficiency in electrical features and strong structural advantages. They are built in very large numbers for a wide range of applications from home appliance to industry fields.

Recently they have been proposed for free piston engine in hybrid vehicles. Moreover, extensive use of high energy PMs has brought the thrust densities and energy conversion ratios to market competitive levels. A similar impact has been made by power electronics and digital nonlinear control. Thus, vigorous research and industrial developments in linear oscillating electrical machines are expected in the near future with an ever wider range of applications.

2.2.2 Period Studies and Application

More serious studies and application of linear oscillating machines have begun at the turn of 19th and 20th century. In the beginning of the 20th century (in the period from 1900 to 1910) *Paul Boucherot* from France was the first to perform serious theoretical and experimental researches of oscillating synchronous machines [8]. He tried to create a single-phase commanded speed motor of continuous rotation on a base of oscillating motor for traction. The weight of this motor was about 1000 [kg]. The calculated output power was 15 [kW] and speed 60 [rpm], but real one was only 5 [kW] and 40 [rpm] with approximate 50 [%] efficiency because of some mistakes of theoretical study. So, in the 20th century we can observe more or less profound studies of different oscillating machines for separated domains of application. These studies were more intensive during different periods and in different countries.

In 1930 ~ 40, in different countries some patents were issued for oscillating motor-compressors, including compressors for refrigerators. It seems that the most active job was done in Germany. For instance, interesting motor-compressor of *W. Koenig* [9] : The oscillating synchronous pulsating current motor with the control by electromagnet valve.

Numerous patents show that those different oscillating motor compressors were being created in the USA for many decades. The *Ray W. Herrick* Laboratories at Purdue University is one of the centers of research and development for oscillating motor compressors. In the period 1967 ~ 80, there were defended three Ph.D. thesis on electrodynamic oscillating compressors [10 ~ 12].

As we see, there was some rise of researches and development of the compressors driven by an oscillating machine of the last century. Maybe some unsolved problems (or solving with difficulty) have decreased researcher's enthusiasm.

However in the last years (or even decades) we can observe certain renaissance of interest for the oscillating motor-compressor. Many facts confirm such situation. The works of *Sunpower Inc.* (USA) could be marked out as studies since 1975 of oscillating motor-compressor, which are continued actually as well. In 2001, Korea firm *LG Electronics* started successfully manufacturing household refrigerators [13], the first compressor variant of which was created by the above mentioned Sunpower Inc.

As it was mentioned above, even in the early period of oscillating electrical machines development, the oscillating generators were proposed. Markedly later, in the period 1955 ~ 65 the brothers *Jean* and *Jaques Jarret* (France) achieved interesting results in creating an alternator with free piston internal combustion engine. [14].

The present-day problems of the protection of environment stimulate to create more effective, more economic and decreasing pollution mobile source of electric energy, which could compete with traditional diesel generator. Many specialists of electricity and mechanics have studied the oscillating machines continuously.

This topic will be designed to characterize the linear oscillating generator for hybrid vehicle vehicles. However, it can be involved for free piston linear generator in parallel. Thus, the tendency of development of linear oscillating generators as specific devices is well-founded and promising.

2.3 Application Fields

2.3.1 Hybrid Vehicles

The interest in HEV has increased dramatically the last year. The rising oil price has made it more appealing to have a vehicle with a good fuel economy and as hybrid solutions can achieve this without deteriorated performance [15]. So, the HEV is a good solution to the energy crisis and environmental pollution problems, considering the limit of the energy density of batteries today [16]. It integrates the functions of a combustion engine, the crankshaft, the connecting rod, and the rotating electrical generator used in conventional hybrid schemes into a single unit, which may have the advantages of high efficiency, compact structure, and reliable operation [17]. It has promising applications in series hybrid vehicles and in distributed generation units. The series HEV has a powertrain where the primary power unit should generate electrical power. The configuration is illustrated in figure 2.2.

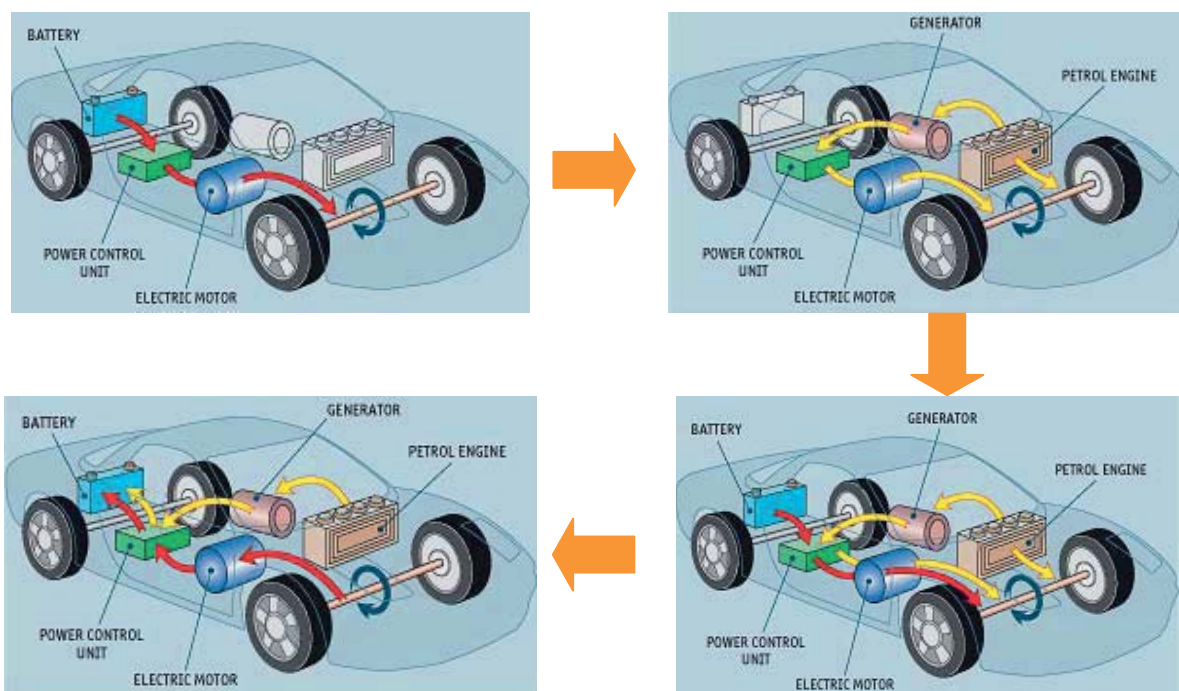


Figure 2.2 : Typical Series Hybrid Electric System

When a starting and running at low speeds, the vehicles runs on battery power alone which drives the electric motor. In normal driving conditions, power from the petrol engine is divided and used both to drive the wheels directly, and to turn the generator, which in turn drives the electric motor. When sudden acceleration is needed, the battery provides extra power to the electric motor, supplementing the power from the petrol engine. The battery is recharged in two ways. When braking, the electric motor acts as a generator, converting the vehicle's kinetic energy into electrical energy and storing it in battery. The engine can also recharge the battery directly when necessary.

2.3.2 Free Piston Generator

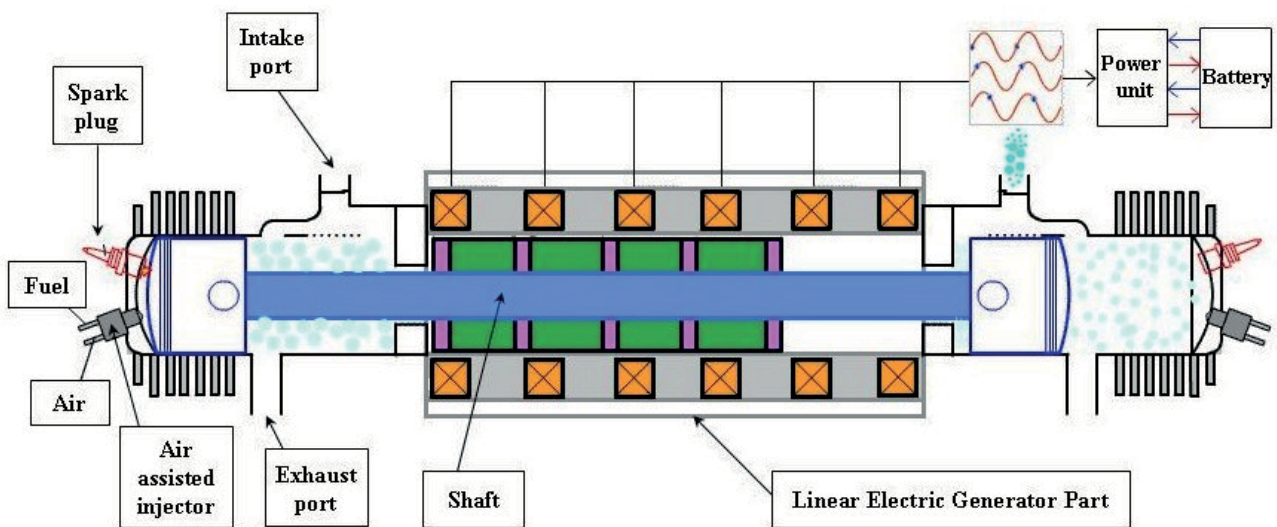


Figure 2.3 : Free Piston Linear Combustion Engine [18]

The hybrid vehicle concept is environmentally friendly, highly efficient, and is gaining popularity by the day. The free piston generator concept is one of the relatively new (and still emerging) hybrid vehicle concepts that could offer good solutions to some of these demands. The free piston generator is an energy conversion device that integrates a combustion engine and an electrical generator into a single unit. Thereby the intermediary crankshaft stage present in conventional hybrid topologies is eliminated. This has benefits in efficiency, weight reduction, robustness, variable compression operation and multi-fuel possibilities. This is shown in figure 2.3. The rod that connects the two oppositely placed combustion chambers also acts as a prime mover for the generator. The reciprocating, ignition and compression processes, in the two chambers cause the connecting rod to have an oscillating motion [19].

Now, if this rod is combined with a linear generator, it can produce electricity directly from the linear motion of the pistons.



3 Analysis Procedure

This chapter proposes an analytical approach that is generalized for the design of various types of linear oscillating generator based on a physical magnetic circuit model. Conventional approaches have been used to predict the behavior of electric machines but have limitations in accurate flux saturation analysis and hence machine dimensioning at the initial design stage. In particular, magnetic saturation is generally ignored or compensated by correction factors in simplified models since it is difficult to determine the flux in each stator tooth for machines with any slot-pole combinations. In this first step, the properties of each proposed topology are investigated by machine dimensioning with help of the equivalent circuit method. The optimal model will be selected by comparing each topology from result of electrical analysis by equivalent magnetic circuit and structural aspect. In the next step, the model will be designed in detail taking saturation into account. Furthermore it needs thermal analysis because the linear oscillating generator is usually operating in close vicinity to the combustion chamber. To have mechanical robustness, it will be also calculated by shaft fatigue analysis.

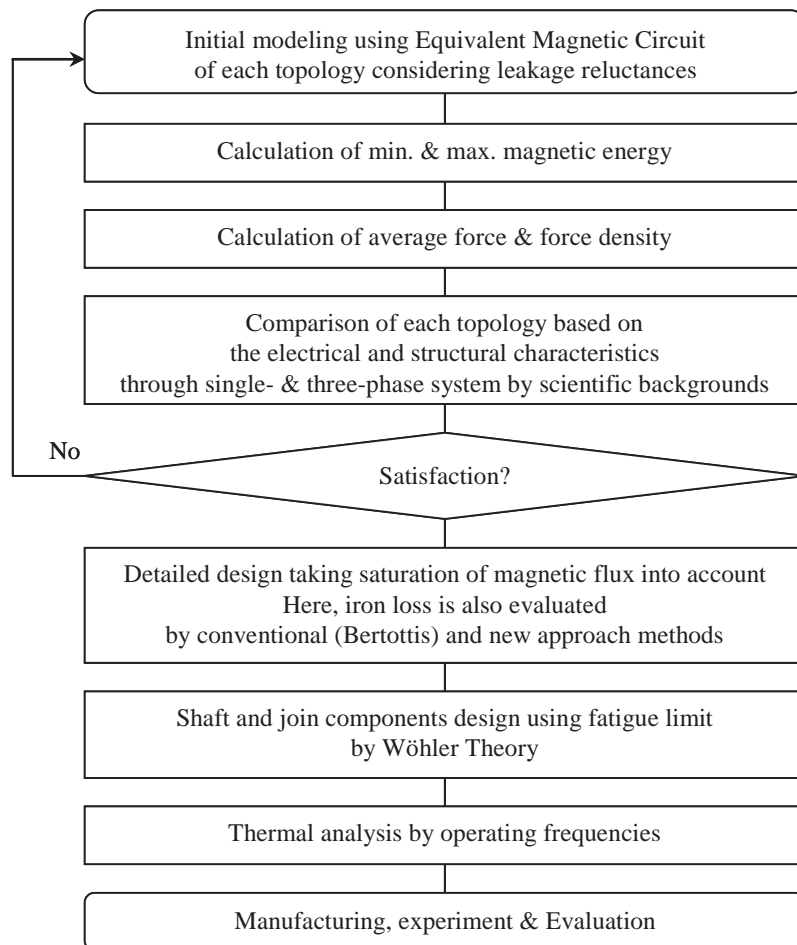


Figure 3.1 : Analysis Flow

When designing an electrical machine, it is important to consider magnetic saturation as it will increase losses and limit machine performance. The equivalent magnetic circuit analysis has been widely applied to analysis and design of electrical machines [20]. Most of the studies are based on the same concept mimicking the electrical circuit behavior. Due to excessive simplification, conventional equivalent magnetic circuit analysis often suffers from the problem of considerably low accuracy, and correction factors based on experiences are often employed for compensation. Therefore, it is commonly used for preliminary design, and confirmation or modification using other approaches (e.g., FEA) is required. The FEM dominating nowadays in the design procedures of electrical machines is applied [21].

3.1 Proposed Topologies

This chapter summarizes the results of the design calculations. The different types of linear oscillating generators implemented are overviewed and their main characteristics are discussed. Each topology will be explained concretely with configuration and information in each paragraph.

3.1.1 Cartesian

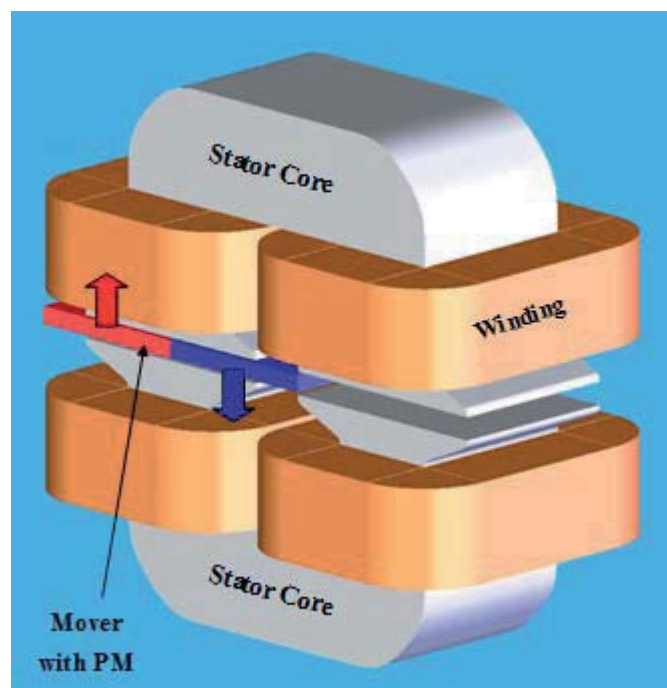


Figure 3.2 : Cartesian Topology

The Cartesian type of linear generator increases the force output of the machine due to generation of the magnetic field created by the armature winding. There is a strong attractive force between the iron-core armature and the permanent magnet. As shown figure 3.2, the upper and lower U-shaped part is the stator core with a winding of coils, meanwhile the center part is the translator composed

of only permanent magnet. By this structure, one of the weaknesses of linear machine has big leakage flux in both end parts of machine as a PM translator moves. Another shortcoming of this topology is that its volume is too large compared to the force.

3.1.2 Cylindrical

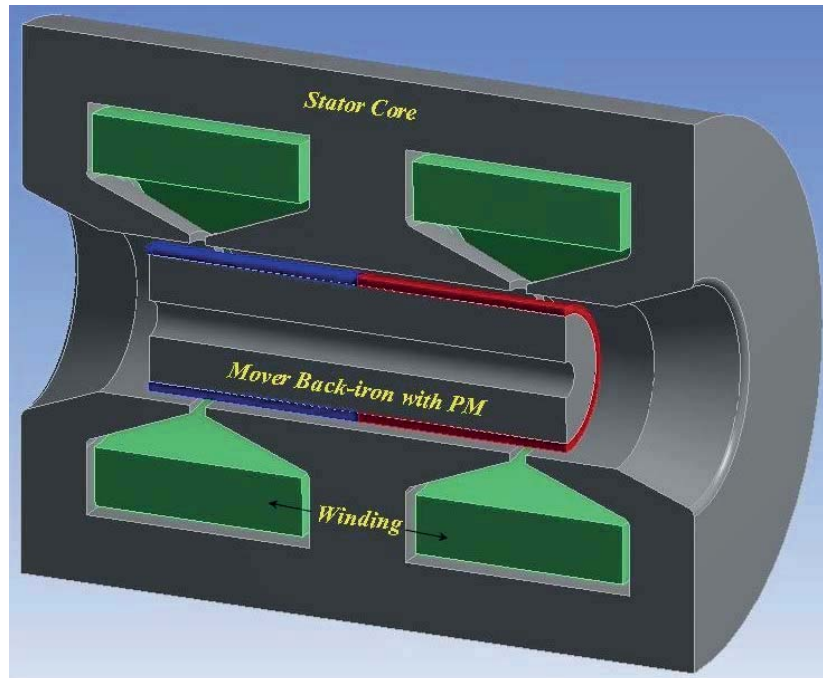


Figure 3.3 : Cylindrical Topology

The previous studies show that flat-type linear oscillating generator is rarely used in free piston gensets and indeed inferior to the tubular-type one in terms of structural merits. The piston has the degree of freedom to rotate without affecting the electrical properties of the generator. The amount of leakage flux is small. Despite these advantages, magnetic ring, laminations stacked stator and the winding in tubular stator are hard to manufacture and to assemble. However, the problems of 3-D flux path can be overcome by *Soft Magnetic Composite (SMC)*. The tubular-type linear generator has higher efficiency and reliability than the flat-type one because of its structural merits. The tubular-type linear generator has some better qualities than the flat-type one. Also the amount of coil is smaller and the benefit of the cylindrical arrangement is that it has no end-windings, therefore the end effects are better than flat-type and the copper loss becomes less than that of flat-type generator.



3.1.3 Hybrid Stepping

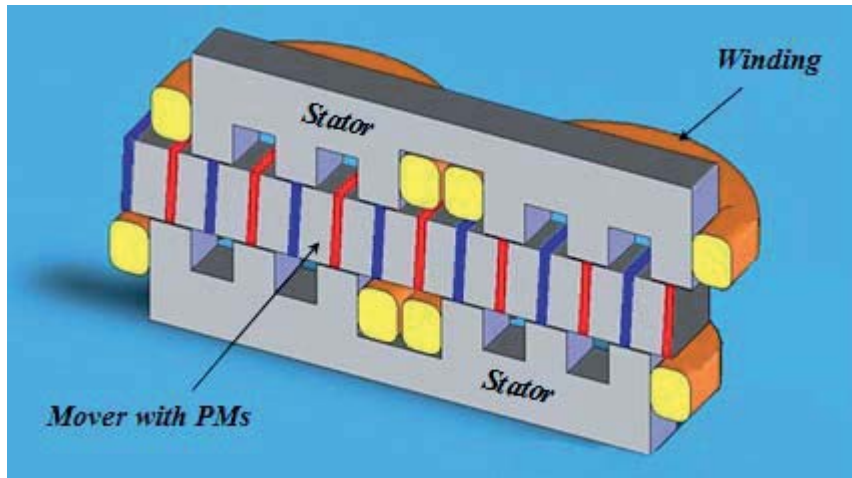


Figure 3.4 : Hybrid Stepping

A hybrid stepping oscillating generator has a simple and robust stator construction with inherently high synchronous reactance. The translator is sandwiched between two stators that carry flux in the longitudinal direction, while the translator carries flux in the transverse direction. Similarly, the flux path of a hybrid stepping machine is longitudinal, or parallel to the direction of movement ; it is distinguished from transverse flux that flux lines go perpendicular to the moving of translator.

This hybrid stepping topology is inevitable to reduce the ripple in the electromagnetic forces due to the attractive force between stator teeth and translator with permanent magnets. It needs in-depth investigation to minimize ripple by buried type of permanent magnet thorough analysis of the magnetic circuit.

3.1.4 Tubular Reluctance

The motion is caused by the tangential force which tends to align poles of the moving part with the excited poles of the static part. The linear generators using tubular reluctance configurations have significant advantages in comparison with their counterparts based on reluctance Cartesian configurations. Theoretically enables it neutralization of normal forces, by this allowing a smaller air-gap and better use of active material. Furthermore, this topology has a low reactance and high power factor.

However, since the force for a given excitation current diminishes rapidly as the air-gap length increases, (approximately with the square of air-gap) they are generally only suitable for short stroke applications (typically in the millimeter range).

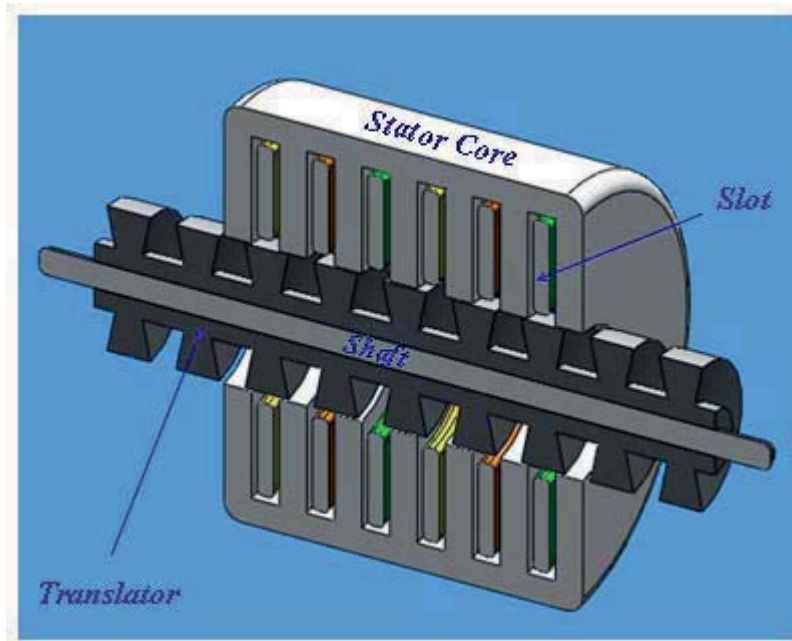
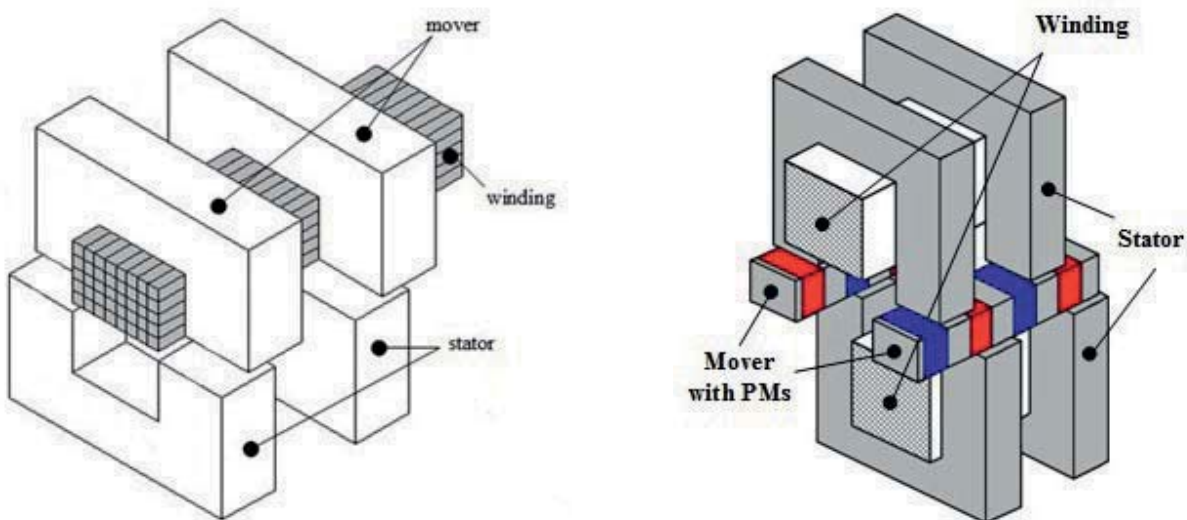


Figure 3.5 : Tubular Reluctance

3.1.5 Transverse Flux



Transverse Flux Element excited (TFE)

Transverse Flux Permanent Magnet excited (TFPM)

Figure 3.6 : Transverse Flux Machine (TFM)

Transverse flux machines inherently use unconventional magnetic structures due to their 3-D flux paths. In this machine, the plane on which the flux path lies is transverse, or perpendicular to the direction of movement. There has been discussion favoring the transverse flux because of its capabilities to obtain a high force density. However, there are drawbacks to a transverse flux design in the design and the construction of a transverse flux machine can become difficult due to high leakage reactance resulting in a low power factor as price for a high force density. In addition, this