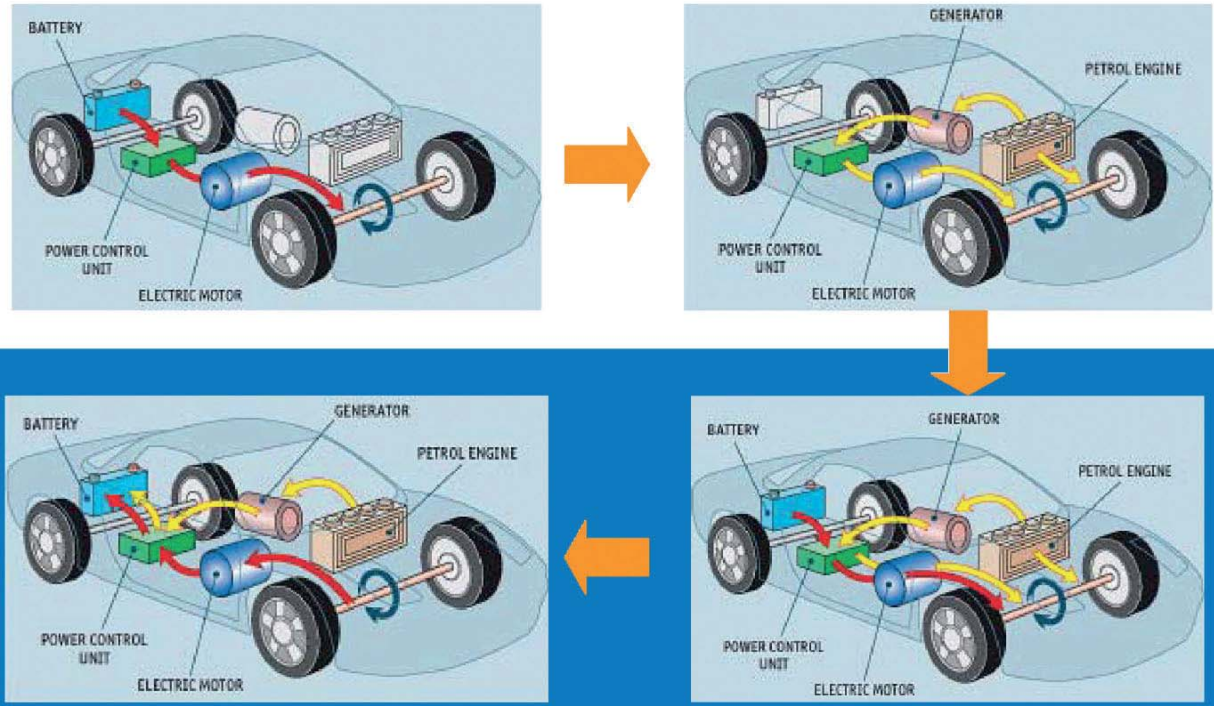


Sung In Jeong

# Comparative Study of Linear Oscillating Generators

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# Comparative Study of Linear Oscillating Generators

Von der Fakultät für Elektrotechnik, Informationstechnik, Physik
der Technischen Universität Carolo-Wilhelmina zu Braunschweig

zur Erlangung des Grades eines Doktors
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# Abstract

This thesis presents the comparative study of linear oscillating generators for hybrid electric vehicle application. The focus of the work is the suggestion of the optimal model through the comparison of each topology. First of all, there are five topologies of the proposed to this study on the basis of the existing literatures ; Cartesian topology, cylindrical topology, hybrid stepping generator, cylindrical reluctance machine, and transverse flux machine. All topology is achieved using equivalent magnetic circuit considering leakage elements as initial modeling.

First, the proposed topology is Cartesian topology with ironless translator. It is investigated by number of phases and number of pole pairs. In addition, the optimal process is performed by parameter studies of the design variables under the constraints. Second, cylindrical topology with back-iron translator is described by number of phases and displacement of stroke. Thirdly, new flux concentrating PMs mover of the hybrid stepping generator is proposed based on the symmetrical and non symmetrical stator cores of the surface mounted PMs mover, and non slanted PMs and slanted PMs of the flux concentrating PMs mover. The next thing, reluctance machine with cylindrical topology is studied. The shape of mover teeth in geometric aspect is used as the method for the force ripple minimization and increasing magnetic flux. Finally, transverse flux machine is considered by dividing the transverse flux electric excited type and the transverse flux permanent magnet excited type. Additionally, three-dimensional analysis in this machine is accomplished due to asymmetric structure with another three axes.

Among the five proposed topologies, the optimal topology is selected as cylindrical topology with back-iron translator of single-phase system by advantages / disadvantages of each topology, academic difference of single- and three-phase, and comparative evaluation by weight factors. The detailed design of the optimal model takes the magnetic saturation effects into account. Besides, the losses will be examined not only iron loss such as hysteresis and eddy-current by various materials but also cooper loss and eddy-current loss of PM.

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. Therefore, the design of shaft and bolt is achieved by fatigue analysis based on the kinetic equation considering mechanical load. Also, the thermal characteristic is analyzed by the operating frequency.

The results of this study 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.

# Kurzfassung

Die vorliegende Arbeit beschäftigt sich mit der vergleichenden Untersuchung Linear schwingender Generatoren im Anwendungsgebiet der Applikation von Hybridfahrzeugen. Der Schwerpunkt liegt dabei in der Suche nach dem optimalen Modell durch den Vergleich unterschiedlicher Topologien. Es gibt fünf Topologien, die in dieser Untersuchung nach der einschlägigen Literatur zugrunde liegen ; kartesischer- und zylindrischer (topologischer) Ansatz, Hybrid-Schrittmaschine, zylindrische Reluktanzmaschine und Transversalflussmaschine. Allen Topologien ein magnetisches Ersatzschatzschaltbild unter Berücksichtgung der magnetischen Verluste als Modell zugrunde.

Der als erstes betrachtete kartesische Ansatz beinhaltet einen eisenlosen Läufer. Das Modell beinhaltet die Anzahl der Phasen und Pohlpaare. Zusätzlich wird der Prozess optimiert durch Parametervariation unter den Voraussetzung im zugrundeliegenden Modell. Zweitens die zylindrische Topologie mit einem Eisenrückschluss Läufer ist besonders geprägt durch die Anzahl der Phasen und die Verschiebung des Hub. Drittens, neue Flusskonzentration PMs Läufer eines Hybridschrittgenerator basierend auf einem symmetrischen und nicht symmetrischen Statorkern auf dem oberflächen befestigten PMs Läufer, und schräger und gerade genuteter PMs des flusskonzentrierenden PMs Läufer. Als Nächstes wird die Reluktanzmaschine in zylindrischer Topologie untersucht. Die Variation der geometrische Form der Läuferzähne wird benutzt um die Kraftverlauf zu glätten und den magnetischen Fluss zu vergrößern. Am Schluss werden beide Typen der Transversalflussmaschine betrachtet ; die fremd- und Permanentmagnet-erregte. Zusätzlich wird eine drei dimensionale Analyse dieser Maschine durchgeführt wegen der asymetrischen Struktur auch in drei anderen Achsen.

Zwischen diesen fünf vorgestellten Topologien wurde der zylindrische Ansatz unter Abwägung der Vor- und Nachteile jeder Topologie, den Unterschieden ein- und drei Phasen, der Berücksichtigung von Gewichtsaspekten ausgewählt.

Das Design im Detail des optimalen Modells berücksichtigt magnetische sättigungs Effekte. Es werden nicht nur die Eisenverluste sondern auch Hysterese- und Wirbelstrom Veruste unterschiedlicher Materialien und Kupferverluste sowie Wirbelstromverluste durch den Permanentmagnet betrachtet.

Die Bedeutung der thermischen- und mechanischen Robustheit ist wichtig, weil der Generator normalerweise in einer direkter Nähe zum Verbrennungsmotor betrieben wird. Er ist so, grossen Beschleunigungen und schwingenden Massen stark ausgesetzt. Deswegen wird das optimale Design von Welle und Bolzen erreicht durch eine Alterungsanalyse basierend auf dem kinetischen Vergleich unter mechanischer Belastung. Ebenso werden die thermischen Eigenschaften unter Nennfrequenz betrachtet.

Das Ergebnis der Studie erarbeitet die Regeln zur Auslegung und die Performancedaten von linear schwingenden Maschinen gensets und parallel dazu Werkzeuge zur Berechnung und Simulation von neuen Maschinen.

# Table of Contents

# 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.