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Development of a Self-Excited Linear Induction Generator for Free-Piston Generator

Behrooz Rezaeealam

Abstract – *A short stroke Self-Excited Linear Induction Generator (SELIG) is constructed and its performance is predicted and compared with the experimental results. Self-excitation process, steady-state operation and stable operation region are analyzed. The effect of stroke length variation is discussed and the characteristics of the proposed generator are presented.* ***Copyright © 2012 Praise Worthy Prize S.r.l. - All rights reserved.***

***Keywords**: Self-Excitation, Linear Induction Generator, Free-Piston Generator*

Nomenclature

A	Magnetic vector potential
C_{dq}	Exciting capacitors
e_d, e_q	Emf of windings d and q
J	Current density
i_s	Stator phase current
l	Width of the stator iron core
$L_{\sigma dq}$	Inductances of the end windings
R_{dq}	Resistances of stator phases
R_L	Load resistance
S	Cross section of coil
U_{dq}	Terminal voltages
Ω_{dq}	Total cross section area of coils
υ	Reluctivity
σ	Conduction coefficient

I. Introduction

Free-Piston Generator System (FPGS) has been proposed for auxiliary power generating and hybrid electric vehicle application [1]-[5] which has high reliability and efficiency and is compact and lightweight.

Also, low emission of FPGS makes it environment-friendly, compared with the conventional spark-ignited engine.

In [1], [2], [12] permanent magnet machines have been introduced in which magnets are placed on the mover part. Permanent magnet machines have a higher thrust force density (1.2 N/cm^2) compared with induction machines (0.2-0.3 N/cm^2 in high saturation up to 0.4 N/cm^2).

However, permanent magnets have aging problem because of high temperature and pulsed forces and requires high maintenance cost and exact alignment between magnets and stator poles.

Also, the active length of the mover part is shorter than the length of the stator and this increases the leakage flux (Fig. 1). The main problem is the high mass of magnets, because the majority of the mover mass belongs to the magnets. A low mover mass is essential to allow the expected gains in the combustion process [2] and to keep output power capacity in a reasonable level; the output power is proportional to the square of reciprocating frequency and reciprocating frequency is proportional to the reverse mass of the mover [6].

This paper presents an induction-type generator for the free-piston that merits lightweight mover, low maintenance and robust structure as shown in Fig. 2.

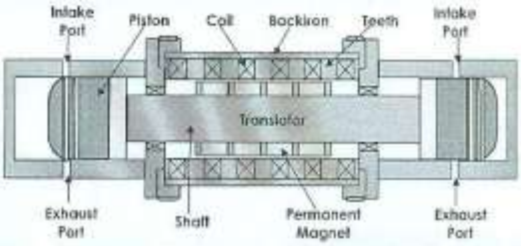

Fig. 1. Free-piston alternator-engine with movable permanent magnet [1]

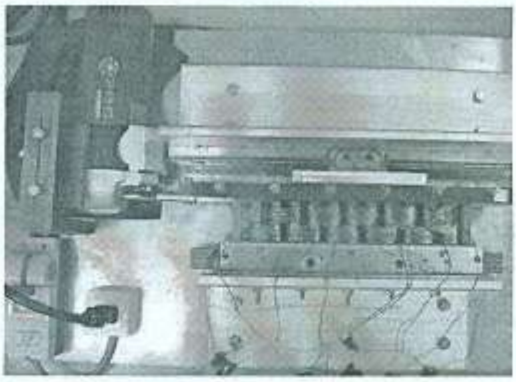

Fig. 2. Configuration of the prototype SELIG

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This offers improved reliability and is particularly attractive in military and other critical vehicle applications [7]. Also, the active length of the mover can be longer than the length of the stator because there is no magnet on the mover and this reduces the leakage flux as shown in Fig. 3. The lower mass of mover of the induction-type increases the reciprocating frequency, so the output power capacity increases that compensate the low thrust force density of the induction-type.

In this paper the performance of the constructed set-up of SELIG is examined and the experiment results are compared with the results obtained from finite element analysis to recognize the appropriate operating conditions of the proposed SELIG.

II. The Prototype Machine

Fig. 2 shows the prototype SELIG and the cross-sectional view of its model is shown in Fig. 3. The SELIG consists of two main components, stator and mover.

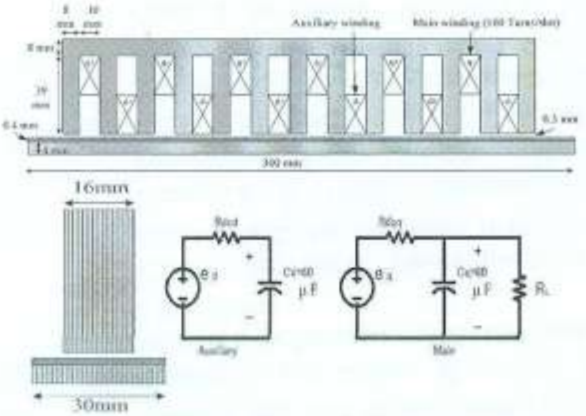

Fig. 3. Model used for finite element analysis

The stator consists of the back iron and armature windings. The mover is the moving portion of the machine which is made up of the back iron covered with a layer of copper as shown in Fig. 3 and is longer than the stator length which always covers the stator face. Instead of internal combustion engine, an electric sawing machine is employed as prime mover, to force the mover part back and forth in an adjustable frequency.

The oscillating frequency of the sawing machine can be manually adjusted from 12 to 53 Hz. Also the stroke length of the sawing machine is 26 mm.

Table I shows the parameters of the prototype SELIG and its dimensions are depicted in Fig. 3.

III. Analysis Model and Two-Dimensional Finite Element Analysis

The model of the proposed SELIG is nonlinear, because of magnetic saturation, longitudinal end-effect, reciprocating motion and unbalanced winding distribution that make the model being difficult to deal with by analytical methods, therefore numerical methods are employed to analyze it [7].

TABLE I
PARAMETERS OF THE DESIGNED SEIG

Parameter	Value
No. of phases (windings)	2
No. of poles	5
No. of turn/slot	2×80
No. of slots	12
Pole pitch	36 mm
Stator wire diameter	0.6 mm
Top cap thickness (copper layer on the mover)	0.4 mm
Air gap length	2-3 mm
Excitation capacitance/phase	60 μF
Stator windings resistance	1.23 Ohm

Time-stepping two-dimensional finite element is used that requires considering linear motion (mesh movement using a moving band) [8], [9], external circuit and magnetic saturation of the iron core (Newton-Raphson iteration). The analyzed model of the SELIG is shown in Fig. 3. The governing equation of the magnetic field is represented by Maxwell's equation in the form of a magnetic vector potential as:

$$\nabla \times (\upsilon \nabla \times A) = J \tag{1}$$

where A is the magnetic vector potential, J is the current density and υ is the reluctivity of the material. In the area of the stator conductor, the magnetic field equation can be represented as:

$$\nabla \times (\upsilon \nabla \times A) + \frac{i_s}{S} = 0 \tag{2}$$

In iron cores, air gap and the mover conductor areas, the magnetic field can be expressed as:

$$\nabla \times (\upsilon \nabla \times A) + \sigma \frac{\partial A}{\partial t} = 0 \tag{3}$$

In the air gap and laminated iron cores of the stator and the mover, the term $\sigma(\partial A / \partial t)$ is zero. It only exists in the solid mover conductor. In (1)-(3), i_s is the stator phase current, S is the total cross-sectional area of one turn on one coil side and σ is the conductivity of the material. The stator phase circuit equations for the proposed SELIG are:

$$U_{dq} = e_{dq} - R_{dq} i_{sdq} - L_{\sigma dq} \frac{di_{sdq}}{dt} \tag{4}$$

$$i_{sdq} = C_{dq} \frac{dU_{dq}}{dt} + \frac{U_{dq}}{R_L} \tag{5}$$