THE STUDY, DESIGN AND SIMULATION OF A FREE PISTON STIRLING ENGINE LINEAR ALTERNATOR

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Abstract: *This paper presents a study, design and simulation of a Free Piston Stirling Engine Linear Alternator. There are presented the main steps of the magnetic and electric calculations for a permanent magnet linear alternator of fixed coil and moving magnets type. Finally, a detailed thermal, mechanical and electrical model for a Stirling engine linear alternator have been made in SIMULINK simulation program. The linear alternator simulation model uses a controllable DC voltage which simulates the linear alternator combined with a rectifier, a variable load and a DC-DC converter, which compensates for the variable nature of Stirling engine operation, and ensures a constant voltage output regardless of the load.*

1. INTRODUCTION

Environmental concerns and increasing electricity demand increased interest on the use of renewable energy, the energy recovery from organic waste, in special agricultural waste and wood waste. Stirling engines technology was developed based on their advantages over other heat engines:

- higher efficiency;
- possibility of using a large class of fuels or other sources of unconventional heat;
- the noiseless operation without vibration.

A potential market is that a small-power systems for electricity generation in cogeneration mode for residential applications.

So far, the research done in of Stirling engines field have not given importance to the interaction between the thermo-mechanical part and the electrical of a Stirling engines. This paper tries to compensate for this shortcoming by developing a model in SIMULINK simulation environment for electrical part of a cogeneration system of electricity and heat based on Stirling engine. Has been designed an electrical system which assure an adaptation between the variable voltage of a Stirling engine linear alternator based cogeneration system and a variable load connected to the power consumer, based on a DC-DC converter of the buck-converter type. The principle of operation, the design, the achievement of this system and the simulation results will be presented in the following paragraphs.

2. FREE PISTON STIRLING ENGINE DESIGN

For this paper, a typical cogeneration system based on Stirling engine is studied, designed, modeled and simulated, this system is shown in figure 1.

The heat produced by burning organic waste put the free-piston Stirling engine in operation. The operation the linear alternator produces a variable single-phase alternating voltage, that will be rectified with a diode rectifier. This voltage will be converted in a prescribed DC constant voltage by using a DC-DC converter of the type buck-converter by means of a feedback controller based on a PI controller.

Engines using the Stirling cycle have clear advantages compared with the small internal combustion engines in the field of power generation as: dish solar systems, biomass energy conversion, residential heat and power cogeneration and another applications. The main advantages are: bigger thermal efficiency; long life and multiple fuel capability.

In the last sixty years, hundreds of millions of dolars have been invested in development of kinematic Stirling engines, in which the pistons are conected in various mechanical linkages. Despite this significant effort, neither efficient mechanically reliability nor large scale commercial production of kinematic Stirling engines has been achieved.

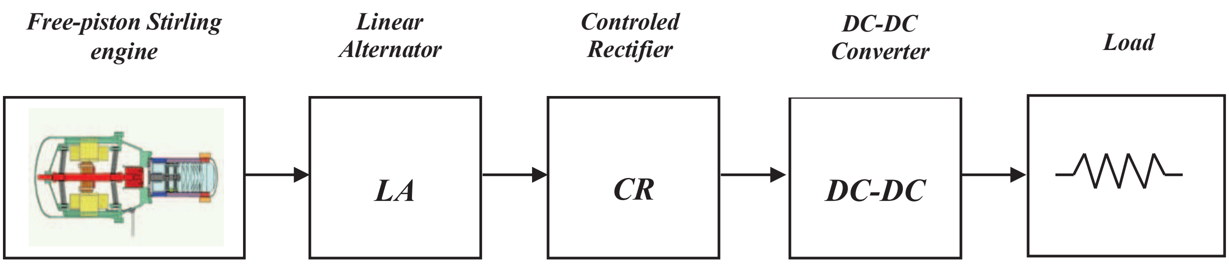

Fig. 1. The studied system configuration.

In order to avoid the kinematic Stirling engines design problems, a new class of Stirling engines have been developed: free piston Stirling engines.

The free piston Stirling engines have the following characteristics:

- mechanically simple construction – only two pistons in a common cylynder;
- the using of mechanically springing;
- high mechanical and electrical efficiency;
- the using of a direct driven permanent magnet linear alternator;
- extremely easy starting;
- no lubricant other than working gas.

In this configuration, the power piston is not mechanically connected to an output shaft. It bounces alternately between the space containing the working gas and a spring (usually a gas spring). In many designs, the displacer is also free to bounce on gas springs or mechanical springs (figure 2). This configuration is called the Beale "free-piston" Stirling engine after its inventor, William Beale [1]. Piston stroke, frequency, and the timing between the two pistons are established by the dynamics of the spring/mass system coupled with the variations in cycle pressure. To extract power, a magnet can be attached to the power piston and electric power generated as it moves past stationary coils [2]. These Stirling engine/alternator units are called "free-piston" Stirling converters.

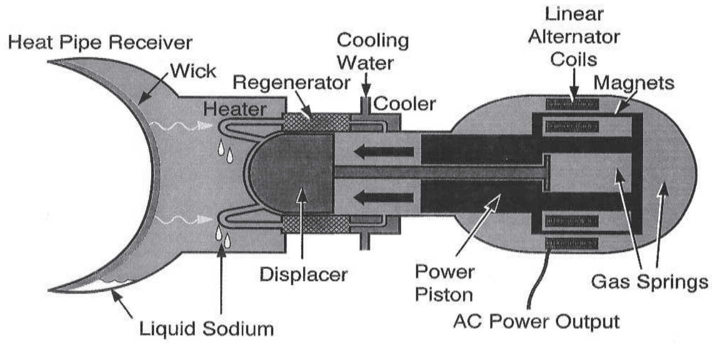

Fig. 2 Basic components of Beale "free-piston" Stirling engine [3].

The free piston Stirling engine can operate as a constant voltage generator. The linear alternator is the most expensive component of the system. The springs supports all and avoid any friction and wear during linear oscillation. The flexures can be designed for a long life of about 40,000 hours of operation. Theese flexures serve as friction free bearings to maintain the magnets in the flux gap. If the air gap is about 1 mm, there are no severe demands for radial position, and the springs can be made inexpensively.

The design starts with the Beale developed power formula [5]. Beale indicated that the power output of several Stirling engines observed could be calculated from the equation:

$$P = 0.015 \cdot p_m \cdot f \cdot V_p \tag{1}$$

where: 0.015 is the Beale number, P is the engine power output in Watts, p_m the mean cycle pressure in bar, f the cycle frequency in Hz, and V_p is the displacement of power piston in cm^3. The Beale number was modified by West as follows:

$$P = F \cdot p_m \cdot f \cdot V_p \cdot \frac{T_H - T_C}{T_H + T_C} \tag{2}$$

where the factor F=0.25-0.35 can be used for practical use, T_H is the hot side temperature and T_C is the cold side temperature.

From this we can calculate:

$$V_P = \frac{P}{F \cdot p_m \cdot f} \cdot \frac{T_H + T_C}{T_H - T_C} = \frac{200}{0.25 \cdot 3 \cdot 10} \cdot \frac{766}{180} = 117\,cm^3, \tag{3}$$

where P=200 W is the power rate of the engine as design datum, $p_m=(0+6)/2=3$ *bar*, $f=10$ *Hz*, $T_H=473$ *K* and $T_C=293$ *K*.

The oscilating amplitude must be as high as pole pitch, which has been chosen as high as permanent magnet height:

$$A = \tau = h_m = 0.0133m = 1.33cm \tag{4}$$

The oscilating amplitude A give us the swept volume of power piston.

$$V_p = A \cdot A_p \tag{5}$$

where A_p is the power piston area:

$$A_p = \frac{V_p}{A} = \frac{117cm^3}{1.33cm} = 88cm^2 \tag{6}$$

Now we can calculate the power piston diameter:

$$d_p = \sqrt{\frac{4 \cdot A_p}{\pi}} = \sqrt{\frac{4 \cdot 88}{\pi}} = 10.6cm = 106mm \tag{7}$$

This dimension was used in the drawing of the designed “free-piston” Stirling engine presented in figure 3.

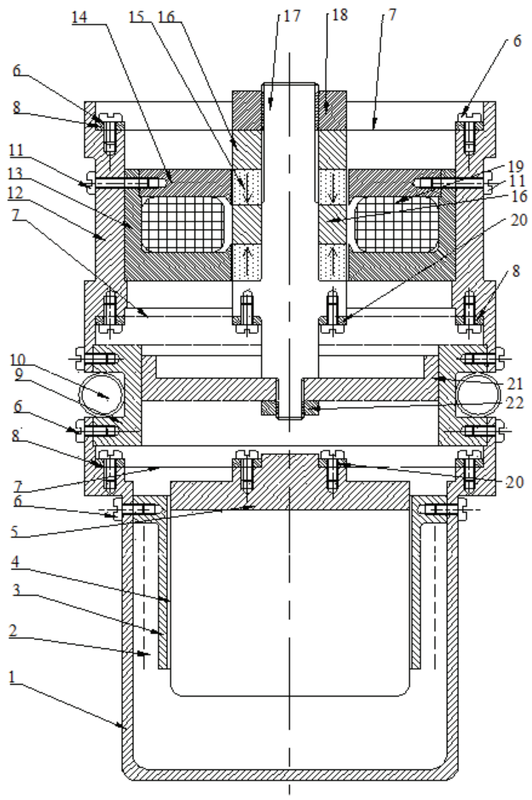

Fig. 3. The designed free-piston Stirling engine

3. PERMANENT MAGNET LINEAR ALTERNATOR DESIGN

3.1 The Magnetic Circuit Design

This alternator is of the synchronous type with excitation from the permanent magnets. From the figure 3 it can be seen that field line passes the air gap for two times, so the necessary magnetomotive force is:

$$F_{mm} = \frac{B_0}{\mu_0} \cdot 2 \cdot \delta = \frac{1}{4\pi \cdot 10^{-7}} \cdot 2 \cdot 1 \cdot 10^{-3} = 1592A \tag{8}$$

where $B_0=1T$ is the mean value of magnetic flux density in the air-gap, $\delta=1mm$ is the air-gap lenght and μ_0 is the magnetic permeability of the air.

For the magnetization it was chosen two ring permanent magnets of the type EURONEOS 40x20x13.3, which have the properties presented in the table 1.

Table 1. The permanent magnets properties of the type EURONEO 3 40X20X13.3

Material	B_r *[T]*	H_c *[kA/m]*	BH_{max} *[kJ/m³]*	*D [mm]*	*d [mm]*	*h [mm]*
N35	*1.2*	*868*	*280*	*40*	*20*	*13.3*

The magnetomotive force of the one magnet is:

$$F_{mm} = H_m \cdot h = 500 \cdot 0.0133 = 6{,}65kA \tag{9}$$

Can be seen that 6.65kA=6650A>1592A, therefore, the magnets were chosen correctly.

3.2 The Coil Design

The indus coil design will be made according to the voltage that is aimed to be induced in the coil. We considered an induced voltage at 10 Hz frecvency of U=18 V_{ef} voltage. The magnetic flux by this coil varies between + Φ_{max} and -Φ_{max} so that the magnetic flux variations:

$$\Delta\Phi = \Phi_{max} - (-\Phi_{max}) = 2\Phi_{max} = 2B_m A_m \tag{10}$$

The permanent magnet area is:

$$A_m = \frac{\pi(D^2 - d^2)}{4} = \frac{\pi(40^2 - 20^2)}{4} \cdot 10^{-6} m^2 = 942 \cdot 10^{-6} m^2. \tag{11}$$

Now, the magnetic flux variation is:

$$\Delta\Phi = 2B_m \cdot A_m = 2 \cdot \frac{B_r}{2} \cdot A_m = B_r \cdot A_m = 1.2T \cdot 942 \cdot 10^{-6} m^2 = 1130 \cdot 10^{-6} Wb. \tag{12}$$

The turn voltage is:

$$e = \frac{\Delta\Phi}{T} = f \cdot \Delta\Phi = 10Hz \cdot 1.13 \cdot 10^{-3} Wb = 11.3 \cdot 10^{-3} V / turn \tag{13}$$

considering f=10Hz from mechanical design stage.

For a voltage of U=18Vef we will need:

$$N = \frac{\sqrt{2} \cdot U}{e} = \frac{\sqrt{2} \cdot 18}{11.3 \cdot 10^{-3}} = 2252\ turns. \quad (14)$$

The magnetic circuit window where the coil is placed has the area:

$$A_f = a \cdot b = 20 \cdot 30 = 600 mm^2 \quad (15)$$

The coil conductor cross-section area is:

$$s_c = \frac{A_f \cdot k_1}{N} = \frac{600 \cdot 0.6}{2252} = 0.16 mm^2 \quad (16)$$

where k_1=0.6 is the winding filling factor.

Now we can calculate the fixed coil conductor diameter:

$$d_c = \sqrt{\frac{4 \cdot s_c}{\pi}} = \sqrt{\frac{4 \cdot 0.16}{\pi}} = 0.45 mm. \quad (17)$$

4. SIMULATION MODEL OF FREE PISTON STIRLING ENGINE LINEAR ALTERNATOR

In figure 4 is presented the SIMULINK model of the linear alternator (DC controlled source), DC-DC converter of buck type and the load composed from a fixed part and a cyclic load with 200 Hz frequency.

The linear alternator combined with a rectifier is designed to produce a variable voltage around the value of 18Vdc. The DC-DC buck converter is combined with a voltage control loop which assures to the load, just in case of variable load, a constant DC voltage of prescribed value, in the case above of 12 Vdc.

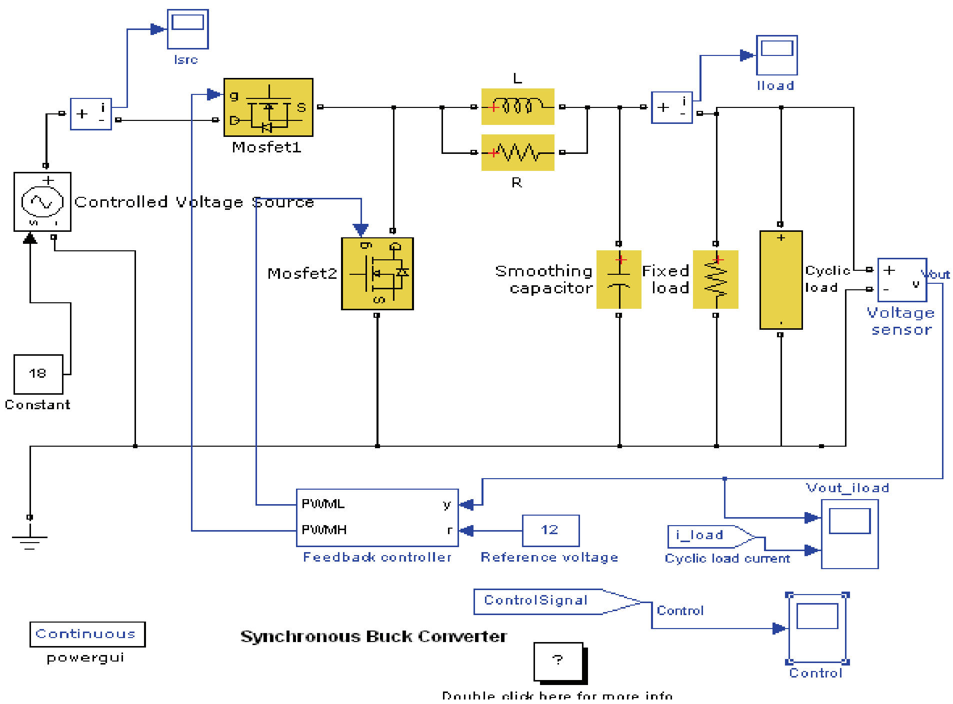

Fig. 4 The SIMULINK model of the Free piston Stirling engine linear alternator

5. SIMULATION RESULTS

In the next figures are presented some simulation results. In figure 5 is presented the out voltage Vout and the cyclic load current.

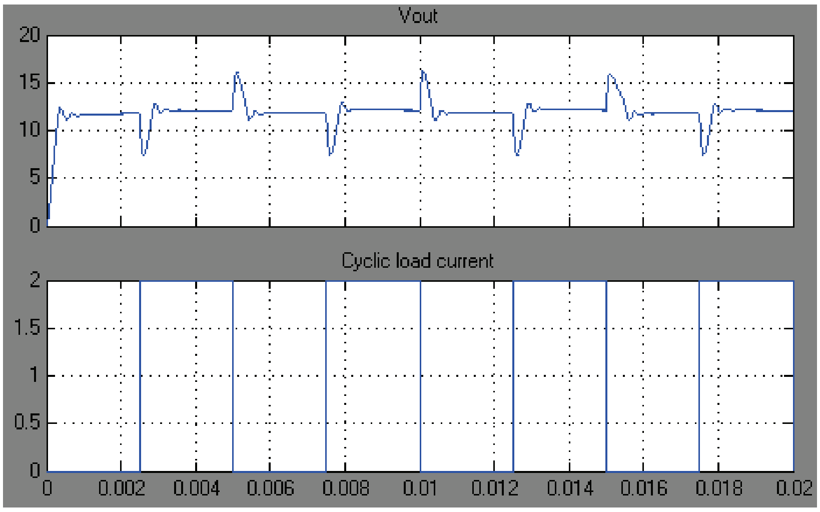

Fig. 5 The stabilized Vout and the cyclic load current.

In the figure 6 is presented the total load current.

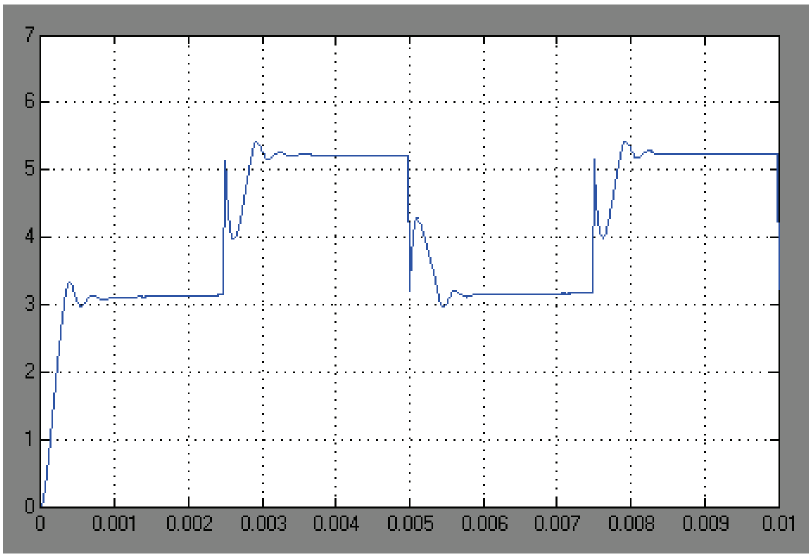

Fig. 6 The total load current.

Here can be seen the constant load of about 3 A and the cyclic load of 2 A.

In the figure 7 can be seen the PI control signal of PWM generator.

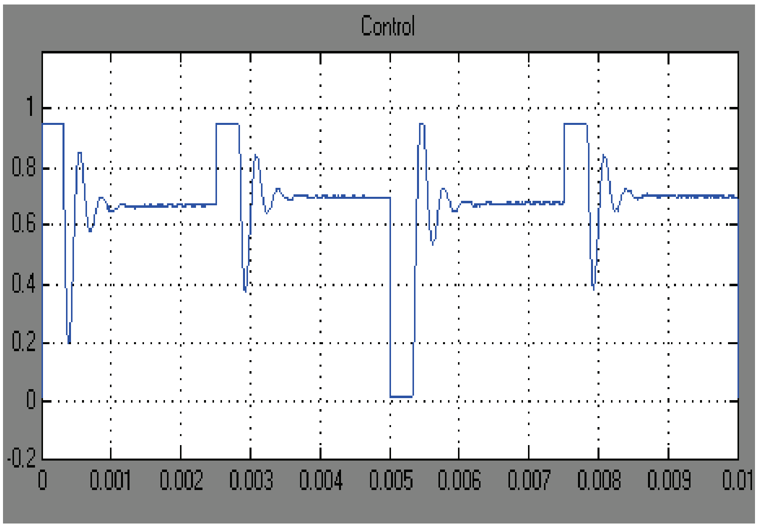

Fig. 7 The PI control signal of PWM generator.

6. CONCLUSIONS

In this paper a tubular type linear generator for a free piston stirling engine is studied and designed. The ring-shaped iron rotor with the rare earth axially magnetized permanent magnets is used as magnetic pole of the mover, because in the case of symmetric structure the leakage magnetic flux is smaller than that of the flat type one. Also, the mass of the copper coil is less than that in the case of flat-type generator because there is no end coil.

This paper also presents a SIMULINK simulation of the electrical part of a free piston Stirling engine cogeneration system. Because the linear alternator together with the diode rectifier produces a variable DC voltage, a voltage stabilizer loop is provided in order to assure a constant output voltage of prescribed value. This SIMULINK model is similar with a real electrical system used in the case of a free piston Stirling engine cogeneration system of small power for residential applications.

ACNOWLEDGMENT

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REFERENCES

1. Thombare D.G., Verma S.K., 2008, *"Tehnological development in the Stirling cycle engine"*, Science Direct Renewable and Sustainable Energy Reviews 12 (2008) 1-38, Elsevier, 2008.

2. Beale, W., 1981, *"Stirling Engines for Developing Countries"*, U.S. National Academy of Sciences, Energy for Rural Development, 1981.
3. Jahromi Z.M et all, 2001, *"Simulation of a Stirling Engine Solar Power Generation System Using Simulink"*, (ACEMP) and Electromotion Joint Conference, Istanbul, Turkey, 8-10 September 2011, ISSN: 978-1-4673-5003-7, pp. 676-681, 2011.