Thermodynamic modeling and controlling of a combined Free Piston Stirling Engine System (FPSE) with a Permanent Magnet Linear Synchronous Machine (PMLSM)

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Abstract. Converting thermal energy to electricity is one of the most common energy conversions in the field of electricity production. This transformation of energy is essential for both renewable and non-renewable heat sources. One of the main parameters of such a system that is responsible for this conversion is its efficiency. To have an efficient transformation, many improvements have been made to the old methods, and also new techniques were developed. One of these new methods that will be discussed here is a combined system of a Free Piston Stirling Engine (FPSE) with a Permanent Magnet Linear Synchronous Machine (PMLSM). The two purposes of presenting such a system are that firstly, the theoretical efficiency of a Stirling engine is high. Secondly, by eliminating crank-shaft from this system compared to the standard Stirling engine system, some of the losses will be removed. To study this system, a thermodynamic model of a RE-1000 FPSE was presented and validated. Then it was coupled with a PMLSM, and the combined system was controlled. The total efficiency of this system in steady-state is 14.4%.

1. Introduction

Due to the increase in energy demand, many methods were developed to produce it. In most of these methods, a heat source is converted into electricity [1]. This conversion should be done most efficiently. Among all the developed methods for this purpose, Stirling engines, due to their high theoretical efficiency and capability of working with different heat sources [2–5], are interesting.

A Free Piston Stirling Engine (FPSE) is a standard Stirling engine that its crank-shaft and rotary generator were replaced with a linear alternator. For the present case, a Permanent Magnet Linear Synchronous Machine (PMLSM) was used as the alternator. By doing this, the result will be a more reliable system that is more compact and lightweight and also has better sealing [6–8]. Due to such interesting aspects of this system, in the present study, a combined FPSE with PMLSM was studied.

First, a non-linear thermodynamic model of the RE-1000 FPSE was developed and validated. PMLSM also was modeled separately and controlled. Then, both systems were combined and controlled.

Most of the FPSE-PMLSM studies developed a linear model for FPSE. Part of these studies focused on the FPSE system and did not present a detailed model for PMLSM. These studies presented PMLSM as a damper for the linear model of FPSE. Boucher et al. [9] modeled PMLSM as a damper besides the analytical linear model of a dual FPSE. Karabulut et al. [10] also presented the thermodynamic behavior of a Martini FPSE by a linear model combined with a PMLSM as a damper.
On the other side, some studies focused on the PMLSM model and did not present a detailed model for FPSE. Some of these studies theoretically and experimentally tried to design an optimum PMLSM that can be used as an FPSE generator [11–14] without presenting a model for FPSE. Zheng et al. [15] also, by defining two simple equations for the FPSE model, theoretically and experimentally tried to identify the best control method for the combined system.

There are also a few studies that proposed a linear model for both systems. Zhu et al. [16] proposed a linear model for the combined system based on the thermoacoustic theory and validated their model with the experimental setup. Zheng et al. [17] also developed their previous system [15] with a linear model of FPSE.

As can be seen, first of all, there are a few numbers of studies that developed a detailed model for both PMLSM and FPSE systems in the combined model. In the present study, a detailed model for both systems is presented. Secondly, all these studies used a linear model for FPSE. Majidniya et al. [1] showed that a linear model for FPSE is not always a reliable model, and it is necessary to develop a non-linear model for that. Thus, in the present study, a non-linear model of the FPSE was used. Lastly, most researchers did not present the thermal behavior of the system; thus, developing a non-linear thermodynamic model of an FPSE in such a system is a new idea that has not been developed already. Accompanying this non-linear model with a linear model of the PMLSM makes this study unique and new.

In the present study, first, a non-linear thermodynamic model of RE-1000 FPSE was presented and validated. Then the PMLSM was modeled and controlled. Finally, two models were combined and controlled. Controlling this system makes it possible to lead the system to its best performance at each operating point. Also, an thermic model allows studying the behavior of the system in transient mode. In most of the energy sources, especially renewable ones, the heat source has unsteady behavior. A thermodynamic model combined with a PMLSM model makes it possible to analyze the impact of the system's control on its performance.

2. Combined system analysis

The proposed system is a combined system of a RE-1000 FPSE with a three-phase PMLSM. The schematic of the system is shown in Figure 1.

As can be seen in Figure 1, the PMLSM mover is connected to the FPSE power piston. The control system delivers the required three-phase reference voltages (\(v_{\text{aref}}, v_{\text{bref}}, v_{\text{cref}}\)) based on two currents (\(i_a, i_b\)) and the mover position. Then, three required voltages will be produced by an inverter.

2.1. Thermodynamic model of FPSE

The main spaces of the FPSE were shown in Figure 1. Based on these spaces, the force balance around the power piston and displacer piston was obtained. These dynamic equations of the system were studied
in detail in the previous study of authors [1]. Furthermore, gas temperatures \( T_i \) in each space can be calculated based on the energy balance equation of each space [18]:

\[
\dot{Q}_{in} + \left( mC_pT \right)_{in} - \left( mC_pT \right)_{out} - \dot{W}_{out} = C_v \frac{d}{dt}(mT)
\]  

(1)

For the heater, cooler, and regenerator, the work \( \dot{W} \) is equal to zero, and for expansion and compression spaces it is assumed there is no heat transfer/loss \( \dot{Q} \). The detailed thermal formulations were presented in Majidniya et al. [18] study for temperature calculation of each space.

The results of coupling the energy equation with dynamic equations are presented in Table 1. The results were validated with experimental results of Schreiber [19] at the same conditions for the same system.

| Table 1. Validation of FPSE thermodynamic model |
|-----------------------------------------------|
| Exp. [19] | Power | Frequency | Phase Shift | Stroke\(_p\) | Stroke\(_d\) | Efficiency   |
|-----------|-------|-----------|-------------|---------|---------|--------------|
| Theoretical | 1000 W | 30.2 Hz   | 47.6\(^\circ\) | 2.32 cm | 2.55 cm | 27.4 %       |
| Error (\%) | 0.39 % | 5.4 %     | 30.8 %      | 18.4 %  | 6.7 %   | 9.56 %       |

As can be seen in Table 1, there is a good agreement between the theoretical and experimental results. The maximum error is in the phase shift that might be due to ignoring the heat losses including the enthalpy pumping and the shuttle effect around the pistons.

2.2. PMLSM model

The model of PMLSM was developed in the previous papers of the authors [20–22]. For the control system, two PR (Proportional Resonant) controllers for controlling mover velocity and current in \( q \) frame and one PI (Proportional Integrator) controller for controlling current in \( d \) frame are used. Input parameters of PMLSM have been shown in Table 2. In this table \( R \) is resistance, \( L_i \) are inductances, \( \psi_f \) is flux linkage, \( B_v \) is friction coefficient, \( m_m \) is mover mass and \( \tau \) is pole pitch.

| Table 2. PMLSM input data |
|---------------------------|
| \( R \) | 0.1\( \Omega \) | \( L_d \) | 1.77 mH | \( L_q \) | 1.77 mH | \( \psi_f \) | 0.0513 Wb | \( B_v \) | 10 | \( m_m \) | 0.824 kg | \( \tau \) | 9 mm |

3. Results and discussion

After modeling each system, their dynamic equations were coupled. The results of the combined FPSE-PMLSM system are shown in Figure 2 - Figure 5.
In Figure 2 - Figure 5, results of the combined system from starting point to the steady-state situation of the system were shown. In these figures, piston stands for power piston, and displacer stands for displacer piston. The input parameters of each system in combined mode are the same input parameters that they have in the last section. For the combined system, it was assumed that the walls’ temperatures are constant, and their values are based on Schreiber study [19]. As can be seen in Figure 2 and Figure 3, the combined system was well controlled, and all the modeling results are following very well their reference values. As it was discussed before, two PR controllers and one PI controller were used to control the system. The reference velocity is chosen a 30 (Hz) sinusoidal wave with an amplitude of 1.5 (m/s). The system gets a steady state at about 0.4 (s). Also, the gas temperature variations in each space were shown in Figure 5. In steady behavior, the temperatures are varying around a specific value. The efficiency of the combined system in steady-state mode is equal to 14.4%.

4. Conclusions
In the present study, first, a thermodynamic model of the Free Piston Stirling Engine was developed. Then, this model was validated with the existed experimental results. After validation, it was coupled with the electro-dynamic model of the Permanent Magnet Linear Synchronous Machine and its control system. The controlled parameters were $i_d$, $i_q$ and $\dot{x}_p$ that one PI and two PR controllers were used to control them, respectively. Finally, the results of the combined FPSE-PMLSM system were presented. It was shown that the system met its steady-state condition at about 0.4 (s). Also, the results showed that the selected controllers (one PI and two PRs) were well adapted for the presented combined system, and $i_d$, $i_q$ and $\dot{x}_p$ were following their references accurately.

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