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Generic model identification framework for thermodynamic engines for use in hybrid power stations control and simulation

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ABSTRACT

Thermodynamic engines are focusing increasing attention in the context of solar-based electric power generation. Knowledge-based models of such engines are sometimes difficult to derive and when they are available, their simulation may be numerically a rather heavy task given the control updating period that may be needed. In the present work a generic nonlinear identification framework that enables the dynamics of the key quantities of a thermodynamic engine to be captured is proposed. Such a fast model can then be used in the simulation and the control design stage of the whole electric power generation station. The proposed identification framework is validated on a recently developed knowledge-based model of a beta-type Stirling engine with rhomic-drive mechanism.

1. Introduction

Thermodynamic engines transform the thermal energy into mechanical energy. This is done through a positive energy cycle in which a fluid circulates between a hot source and a cold source. The resulting mechanical energy can therefore be used to drive an alternator which is followed by a voltage conditioning stage leading to a usable electrical energy by the end user loads.

A typical view of a thermodynamic engine in such a global hybrid power station framework is shown in Fig. 1.

Running such hybrid power stations is today an important challenge as it can be attested by the recent works involving the use of renewable wind/photovoltaic related energy sources [7,1,10,11]. One reason is that more than 1.4 billion people have no access to electricity, mainly in Asia and Africa. Classical alternative fuel-based solutions such as diesel engines suffer from many drawbacks such as their low reactivity to load changes, their high emissions and noise to mention only few issues [8].

Roughly speaking, a thermodynamic engine in a hybrid power generation station provides the medium term power adaptation while an electric storage element (super-capacitor and/or battery) accommodates for sudden changes in the load power demand. It results (see [4] for a detailed demonstration) that the dynamics of the thermodynamic engine highly determine the size and the type of the storage element. It determines also to which extent one can avoid the use of batteries which is becoming nowadays necessary for obvious ecological reasons.

Now in order to perform such a closed-loop quantitative analysis on a variety of scenario, it is necessary to dispose of a fast simulator of the thermodynamic engine in its loop. This can be obtained either using a knowledge-based model or using a black-box model. Note also that even when a knowledge-based model is available, it can be used to derive black-box model in order to accelerate the simulation and the control algorithm development task.

To the authors knowledge, several companies are currently developing thermodynamic engines following the basic concepts of positive energy cycles (Stirling, Rankine, etc.). Based on some elementary computation schemes, the main parameters of the engine can be computed given the targeted output mechanical power range. It comes out that thermodynamic engines can be available before a dynamic model is derived. In this case, real-life experiments can be conducted to derive black-box models without the need for a mathematical knowledge-based model. Note however that knowledge-based models are mandatory for process optimization in dynamic context. Black-box models can only reproduce a predesigned process behavior.

The aim of this paper is to give a generic easily identifiable nonlinear structure that captures the dynamics of the key quantities of a thermodynamic engine which are necessary to simulate it in its

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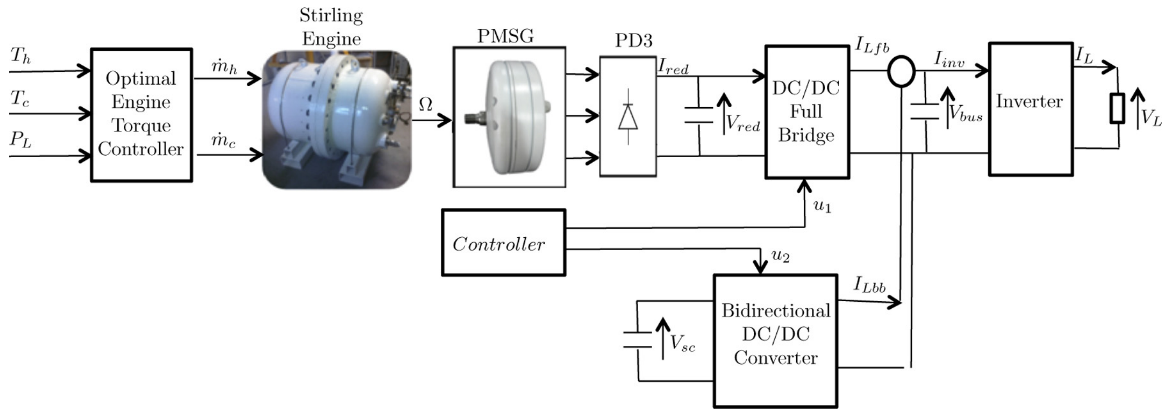

Fig. 1. An example of a hybrid power station with its thermodynamic engine (here a beta-type Stirling engine) followed by the electric power conditioning stage.

environment. The adopted structure has been recently proposed in [2,3] where it has been used to derive a fast moving-horizon state observer [2] and to derive a dynamic model of NOx emission in a diesel engine [3].

In the absence of experimental data, the proposed identification scheme is validated in the present contribution using the very detailed model of a beta-type Stirling engine recently proposed in [5]. This knowledge-based model takes into account, among other non-ideal features, the non-isothermal effects, the effectiveness of the regenerative channel, and the thermal resistance of the heating head. This is why such a detailed model can reasonably emulate an experimental data generator for the identification method proposed in this paper. This holds as far as only the presumably measured signals are used to build the black-box model.

It is worth underlying that although the above cited specific Stirling engine is used throughout the paper, the identification structure and methodology are quite general and should be successfully used to derive a databased model for any thermodynamic engine. This is because almost all thermodynamic engines involve the same components and describe very similar cycles in the (P, V) coordinates. For instance, the framework proposed in the present paper has been also successful in identifying a Rankine-cycle-based engine. However, the corresponding results cannot be published for industrial reasons.

The contributions of the papers can be summarized by the following items:

(1) The paper suggests a systematic parsimonious identification problem setting that targets only those variables that are relevant for power stations simulation and control. In the specific case of the Stirling engine considered in the present paper, these variables are the mean work and the mean heat exchange during an engine cycle. Note that this problem definition is independent of the method and the identification structure that can be used to solve the resulting identification problem.
(2) The second contribution of the paper is to show that using a recently developed identification framework, the identification problem described in the preceding item leads to astonishingly faithful models of the dynamics of the targeted key quantities (work and heat exchange) that need to be captured. It is also conjectured (for the reasons cited above) that this success is likely to be encountered on a whole family of thermodynamic engines that are currently widely developed for green energy generation and conversion.

It is by no means the claim of the present paper that the identification framework used herein is the only one capable of producing nice matching results. It is true however that the proposed framework does show nice properties that are recalled in Section 3.

The paper is organized as follows:

- In Section 2, the identification problem that has to be solved in order to derive a parsimonious dynamic model of the thermodynamic engine is stated. By *parsimonious*, it is meant a dynamic model that incorporates only the necessary elements that are needed to interact with the remaining blocks of the hybrid power generation station (see Fig. 1) and to design the feedback laws.
- In Section 3, the general identification scheme proposed in [2,3] is briefly recalled and its application in the specific identification context described in Section 2 is discussed. It is then shown that the identification problem can be put into a general nonlinear static map identification.
- Section 4 gives a brief sketch of the knowledge-based model of the beta-type Stirling engine with rhomic-drive mechanism that has been recently proposed in [5] and used in the next section as a data generator for the identification task.
- The identification framework is validated in Section 5 where the learning/validation data are described and the identification results are shown.
- Finally, Section 6 concludes the paper and give hints for further investigations.

2. The identification problem

In this section, the necessary elements that need to be identified regarding the thermodynamic engine in order to build the simulator of the whole hybrid power generation station are analyzed. This enables the identification problem to be clearly stated.

The hybrid power station model can be shortly written as follows:

$$I\dot{\Omega} = \Gamma_e(\Omega, x^e, u^e) + \Gamma_m(\Omega, x^{th}, u^{th}, w^{th}) - \Gamma_f(\ldots) \quad (1)$$

$$\dot{x}^e = F(x^e, \Omega, u^e, w^e) \quad (2)$$

where Ω (rad/s) is the angular velocity of the main shaft that is shared by the engine and the alternator. x^e and u^e are the state and the control vectors of the electrical part. x^{th} and u^{th} are the state and the control vectors of the thermodynamic engine. Γ_e is the torque applied on the shaft from the electric part while Γ_m is the mechanical torque that results from the Stirling engine positive energy cycle. Γ_f is the friction torque. Finally, the vectors w^e and w^{th} represent the non controlled signals acting on the electrical part (user power, disturbances) and the thermodynamic part (hot temperature T_H for instance). For the complete definition of F, interested readers can refer to the description given in [4].