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Overview and benchmark analysis of fuel cell parameters estimation for energy management purposes

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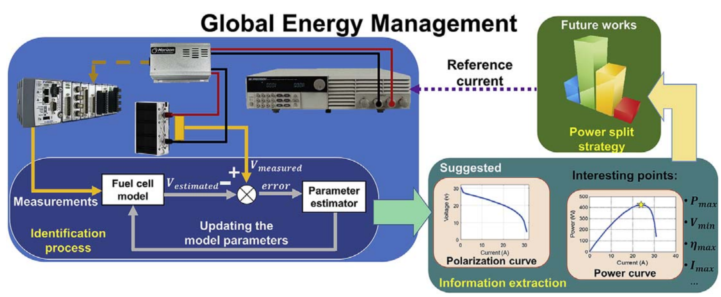
HIGHLIGHTS

- Thoroughgoing modeling and parameter estimation review of PEMFCs are presented.
- Nonlinear parameter identification is addressed by utilizing extended Kalman filter.
- Good precision of the results is proved via experimental tests.
- Application of this methodology to energy management design is demonstrated.

GRAPHICAL ABSTRACT



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ABSTRACT

Proton exchange membrane fuel cells (PEMFCs) have become the center of attention for energy conversion in many areas such as automotive industry, where they confront a high dynamic behavior resulting in their characteristics variation. In order to ensure appropriate modeling of PEMFCs, accurate parameters estimation is in demand. However, parameter estimation of PEMFC models is highly challenging due to their multivariate, nonlinear, and complex essence. This paper comprehensively reviews PEMFC models parameters estimation methods with a specific view to online identification algorithms, which are considered as the basis of global energy management strategy design, to estimate the linear and nonlinear parameters of a PEMFC model in real time. In this respect, different PEMFC models with different categories and purposes are discussed first. Subsequently, a thorough investigation of PEMFC parameter estimation methods in the literature is conducted in terms of applicability. Three potential algorithms for online applications, Recursive Least Square (RLS), Kalman filter, and extended Kalman filter (EKF), which has escaped the attention in previous works, have been then utilized to identify the parameters of two well-known semi-empirical models in the literature, Squadrito et al. and Amphlett et al. Ultimately, the achieved results and future challenges are discussed.

1. Introduction

The harmful discharges from the conventional vehicles, running on fossil fuels, play a significant part in the growth of CO_2 emissions. Therefore, the requisite energy of future vehicles should be supplied by cleaner sources [1,2]. Among the various technical solutions, i.e.

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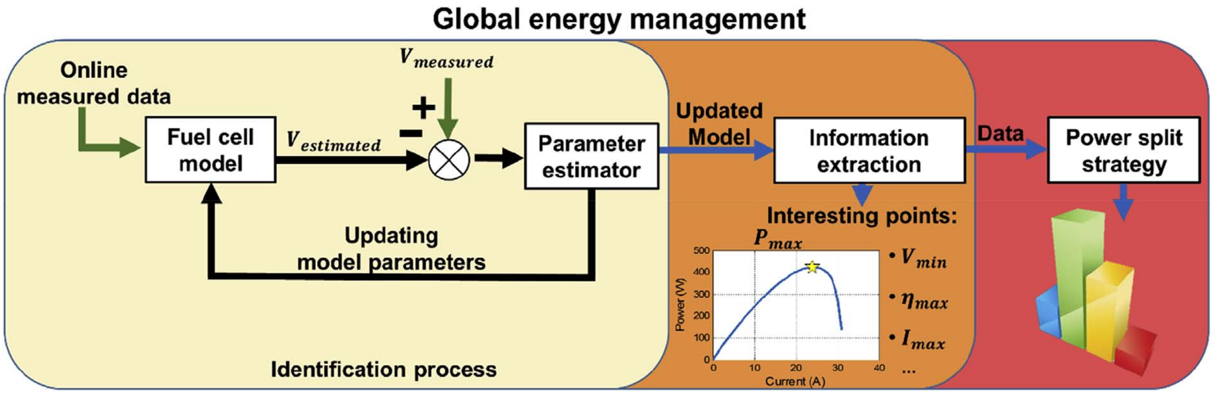

Fig. 1. Global EMS representation.

electric vehicles, hybrid electric vehicles etc., fuel cell vehicle (FCV) is one of the most promising due to no local emissions, high driving range, and very short refuelling duration [3]. FCVs mainly utilize proton exchange membrane fuel cells (PEMFCs) as the prime power source because of their low temperature and pressure operating range as well as their high power density in comparison to other fuel cell types such as carbon dioxide and solid membrane [4]. PEMFCs show satisfactory durability in slow dynamic applications. The intrinsic slow dynamic characteristic of a PEMFC and its incapability in storing extra energy make the utilization of a secondary power source, such as battery, necessary to satisfy the fast dynamic load in some applications like vehicles. Hybridization of the sources creates a multi-source system in which an energy management strategy (EMS) is in demand for splitting the power [5]. The majority of the existed EMSs in the literature, namely rule-based, and optimization-based, are premised on PEMFC models, especially static models [6–8]. In this respect, PEMFC modeling is of vital importance, and a wise selection of the model should be made with regard to the particular goals of the project. However, some factors such as dependency of PEMFC energetic performance on its operating conditions (temperature, pressure, and current), impact of aging and degradation phenomena on its performance, and so forth have made the design of a comprehensive PEMFC model immensely complicated. In this regard, utilization of identification algorithms has been suggested to deal with the problems caused by operating conditions change, degradation and aging by adjusting online the models parameters [9]. It should be noted that the careful selection of identification method is as important as the choice of model since it can complement the model and even compensate for its lack of details and considerations.

This paper provides an extensive review of identification methods for estimating PEMFC models parameters and introduces the suitable ones for EMS purposes. Moreover, an experimental benchmark study that compares three promising online identification techniques by using two renowned PEMFC models is conducted. It should be noted that in this work, online identification refers to the processing of the data in real time, i.e. the data is evaluated immediately after each sample. The remainder of this article is structured as follows:

A general description of the proposed article methodology is presented in section 2. An overview of the existed PEMFC models in the literature along with a broad review of identification algorithms, utilized for PEMFC parameter estimation, is provided in section 3. Section 4 deals with a benchmark study on online identification techniques. Finally, the conclusion is given in section 5.

2. Overall process

In a multi-source system, the operating points of the components can be determined by the EMS in a way to maximize the output power, system efficiency, lifetime, and autonomy. However, determining the operating point in a PEMFC, which is a multiphysics system and its energetic performances are operating conditions dependent, is very difficult, and the desired operating point constantly moves through the operating space. Regarding the FCVs, it is very interesting to keep PEMFC running at its best power. Nevertheless, the power versus current curve of the PEMFC is moving with temperature and aging. Moreover, comprehensive modeling of a PEMFC, including the effect of degradation and operation points drift, is very difficult, time-consuming, and still a study limitation.

Maximum power or efficiency point tracking (MPPT) could be a good solution for this problem if they were not limited to a single specific objective. Perturbation and observation (P&O) and incremental conductance are MPPT algorithms that vary the current to get the maximum power point from the power curve; this process is known as hill climbing. Those variations increase the hydrogen consumption. These algorithms are sensitive to rapid changes, and they might be trapped in a local maximum [10,11]. Moreover, the implementation of such techniques in PEMFC systems is highly challenging due to different electrochemical, fluidic, and thermal time constants that vary from milliseconds to minutes.

In order to address these issues, the employment of a global energy management, as shown in Fig. 1, is vital to reach a good compromise between energetic efficiency and durability under various operating conditions. The whole process is performed online during the operation of the PEMFC. The global energy management strategy is composed of three steps, namely parameter identification, information extraction, and power split strategy. The main idea is to perform a real time model identification to find the best operating points through an information extraction. Subsequently, the power split strategy can use the provided data from the updated PEMFC model to optimally distribute the power flow. As shown in Fig. 1, the information extraction step, which is maximum power (P_{max}) in this work, is one example out of several possibilities, such as maximum efficiency point (η_{max}), minimum voltage (V_{min}), maximum current (I_{max}), and so forth. This step provides the power split strategy with essential information based on which it can decide how to share the power among the components. It should be noted that this paper mainly takes care of the choice of identification method and PEMFC model, which are the core of the presented global energy management. The parameter estimation of PEMFC models is really challenging due to their complex behavior. Next section provides a broad review of PEMFC modeling and identification techniques. The future works can extend the information extraction step and use such basis to design online power split strategies.

3. Review

3.1. Modeling

Modeling has a significant part to play in the technological evolution of PEMFCs. Several applications, such as automotive industry