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Tracking maximum efficiency of hydrogen genset used as electric vehicle range extender

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This paper investigates a hydrogen-based genset maximum efficiency tracking problem in the context of electric vehicle range extension. This genset is cheaper than fuel cells and has the desirable property of being greenhouse gas emission free in addition to being less pollutant than the conventional gasoline based gensets. Using Taylor's series, a parametric efficiency model is built iteratively. This model is used by a nonlinear optimization method which searches for the optimal operating conditions for a maximum achievable efficiency. The root-mean-square-error between experimental data and the model is less than 5×10^{-4}. The hardware-in-the-loop simulation demonstrated that the proposed tracking approach is effective. In addition, it can improve the hydrogen-based genset efficiency up to 7.15% compared to the commonly used industrial method based on a constant speed drive approach.

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1. Introduction

Vehicle powertrain electrification is considered as a promising technology to reduce greenhouse gas emission sources and improve fuel usage [1–3]. However, with batteries alone as the primary energy source of an electric vehicle, it is difficult to obtain the same autonomy as internal-combustion engine vehicles. Therefore, vehicle source hybridization has been proposed as a practical way to extend operating range [4]. Recently, different vehicles with energy source hybridization have been reported: plugin hybrid vehicles (PHEV) using gasoline internal-combustion engines (ICEs) as range extenders [5,6], PHEVs using hydrogen fuel cells as range extenders [7–9]. However, PHEVs using gasoline internal-combustion engines still contribute to the greenhouse gas emission problem [10] and the use of fuel cells raises several issues such as slow transient response and inefficient cold startup [7,11,12]. In addition, fuel cell systems are currently much more expensive than internal combustion engines.

It is possible to take advantage of the use of hydrogen (which can provide a local zero greenhouse gas emissions) in

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internal combustion engine. By combining a hydrogen-based genset with a battery pack on a vehicle, the obtained PHEV has the desirable properties of being more robust during cold startup at less expensive than fuel cell based PHEV. Since a genset efficiency is lower than a fuel cell efficiency, it becomes critical to have this genset operate at peak efficiency in order to reduce this gap. This paper investigates a new approach for a realtime maximum efficiency tracking of a hydrogen-based genset in the context of PHEV range extension.

The genset maximum efficiency tracking is challenging because of the nonlinear behavior of the internal combustion engine when hydrogen is used as fuel. The most commonly reported method is based on the engine efficiency map provided by the genset manufacturer [13]. The operating conditions corresponding to the maximum efficiency is retrieved from the map and imposed to the genset. However, this static efficiency map does not incorporate the unavoidable perturbations (ambient temperature, humidity ratio, filters fouling, etc.). Even if some of these parameters were taken into account during the mapping process, the effect of the engine aging and wear are not. Moreover, the static map construction is a time-consuming process [14]. Therefore, a maximum efficiency tracking based on an adaptive efficiency map is a more promising approach to deal with this perturbation as well as the engine aging phenomena and filters fouling.

Adaptive approaches require the identification of hydrogen genset parameters, which is challenging due to the complex thermodynamic models of the combustion process occurring in the engine [15]. Two modeling approaches have been reported for spark ignition engine: the generic mean value models (MVM) and the discrete event models (DEM) [16,17]. The MVM approach is built upon the basic physical and thermodynamical principles and aims at providing the average values of engine efficiency and exhaust manifold pressure whereas the DEM approach returns nonlinear differential equations for each of the following four strokes: compression, ignition, expansion and exhaust [17]. With the DEM approach, the engine state is obtained by solving these four differential equations. Unfortunately, the MVM and the DEM approaches are not suitable for a realtime maximum efficiency tracking since several engine parameters need to be known precisely beforehand.

Modeling the electrical machine (synchronous motor) of the genset is well established [18]. However, predicting the electric power production when this machine is mechanically driven by a hydrogen-based ICE requires accurate knowledge of the synchronous motor parameters (phase inductors, resistors, rotor inertia, engine torque, etc.). Moreover, the miss-modeling of the synchronous motor and the four stoke engine would make it difficult to derive the overall genset behavior representation for maximum efficiency tracking. So, instead of using complex modeling approaches, this paper proposes a data-driven approach based on in-situ experimental operation of the genset. Data collected when the genset is running is used to represent the time-varying representation between the observed efficiency and the imposed operating conditions. Using this representation, we search for operating conditions that correspond to the maximum efficiency.

Several methods for online identification methods have been reported: artificial neural networks (ANN) [19,20], fuzzy logic [21], genetic algorithms, support vector machines [22], lookup tables, etc. Thus, in Refs. [23], an ANN was built and used to identify a spark ignition engine using a large amount of experimental data. Hametner [24] has also used ANN approach to represent the nonlinear behavior of an engine in different operating regimes. An aggregated model was obtained using each previously established regime-based representation. The ANN method can adequately model the time-varying behavior of the engine as well as the synchronous machine. However, the convergence rate of the ANN training process depends on how well the collected data fits with the engine behavior. Lookup table methods are simple but require data from the complete observation space. They are often used for engine control calibration [25]. Genetic algorithms are too complex to use in the context of realtime maximum efficiency tracking.

The maximum efficiency tracking often involves a search process over the observation space in order to localize, the maximum value of the efficiency and to find the corresponding operating conditions. One can use the genset model obtained with the previously mentioned identification methods to approximate the efficiency-operating condition relationship. Subsequently, a search for maximum point is performed. The operating conditions corresponding to the maximum point are imposed to the genset for efficiency optimization. Among reported optimization methods are genetic algorithm, simulated annealing [26] and negative gradient-based methods.

This paper proposes a new approach for maximum efficiency tracking in three steps. Step 1: as the genset is running, the collected data is used online to identify the parameter representing the relationship between efficiency and operating conditions around the maximum efficiency point. This identification process is based on the well-known recursive least squares (RLS) method. Step 2: the obtained model is subsequently used to search for operating conditions that correspond to the maximum efficiency using line search algorithm [27]. Step 3: once found the operating conditions are imposed to the genset and a new observable efficiency is obtained. A backtracking method is proposed if the observed efficiency is not improved over the previous one.

The rest of paper is organized as follows. A justification of the use of hydrogen based-engine is presented in Section 2. The hydrogen-based genset and the PHEV are described in Section 3. The local optimization problem of the genset efficiency is formulated in Section 4, whereas in Section 5, we propose a method for maximum efficiency tracking. Experimental validation, comparative study and discussion are provided in Section 6. The conclusion is presented in Section 7.

2. Why use hydrogen based-genset?

A hydrogen based-genset H_2ICE is obtained by a simple modification of the injection system and ECU of a conventional internal combustion engine [28,29], so the few additional costs come from these components alone. According to the literature, the efficiency of an H_2ICE is about 35%–44% depending on the injection type [15,28,30,31]. H_2 should be

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