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Real time adaptive efficient cold start strategy for proton exchange membrane fuel cells

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HIGHLIGHTS

- Coping with fuel cell parameters variations and keeping the current at high levels.
- Providing the PEMFC maximum power, and producing high reaction heat.
- Being effective in terms of heating time, energy, adaptability and repeatability.
- Requiring minimal user intervention, which minimizes parameterization errors.

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ABSTRACT

Cold start of proton exchange membrane fuel cells (PEMFCs) at sub-zero temperatures is perceived as one of the obstacles in their commercialization way in automotive application. This paper proposes a novel internal-based adaptive strategy for the cold start of PEMFC to control its operating current in real time in a way to maximize the generated heat flux and electrical power in a short time span. In this respect, firstly, an online parameter identification method is integrated into a semi-empirical model to cope with the PEMFC performances drifts during cold start. Subsequently, an optimization algorithm is launched to find the best operating points from the updated model. Finally, the determined operating point, which is the current corresponding to the maximum power, is applied to PEMFC to achieve a rapid cold start. It should be noted that the utilization of adaptive filters has escaped the attention of previous PEMFC cold start studies. The ultimate results of the proposed strategy are experimentally validated and compared to the most commonly used cold start strategies based on Potentiostatic and Galvanostatic modes. The experimental outcomes of the comparative study indicate the striking superior performance of the proposed strategy in terms of heating time and energy requirement.

1. Introduction

Passenger cars have been voiced as the most significant sources of transportation-related greenhouse gas emission. In this light, substituting fossil fuel-powered vehicles by green ones is an important measure to tackle this worldwide issue [1]. Electric and hybrid electric vehicles could be appropriate solutions. However, the latter still relies on fossil fuels and the former suffers from restricted driving range as well as long charging time. These pitfalls have paved the way for the emergence of fuel cell vehicles (FCVs). FCVs do not have the limitations of their competitors and benefit from definite merits, such as high efficiency, pollution free essence, and convenient maintenance, by comparison [2]. Among various types of fuel cells, PEMFC is regarded as the most potential one for automotive applications owing to its distinct features such as high efficiency, high power density, and quick response [3]. FCVs have not nevertheless achieved their utmost market development in the automotive industry yet due to some barriers such as confined hydrogen and its infrastructure availability, high price, and limited extreme cold weather condition employment [4]. The limitation of using PEMFCs in cold weather countries is mainly due to the well-known cold start problem [5]. Several researches have been conducted on the freezing mechanisms in PEMFCs. It has been found that the produced water inside the PEMFC freezes mainly in the cathode, which can prevent the passage of oxygen, increase membrane resistance and decrease the cathodic oxidation reaction [6–9]. These phenomena cause a significant voltage drop and fail the cold start [10–12]. The PEMFC cold start can be perceived as an interaction between the water produced by the electrochemical reaction and the required heat for

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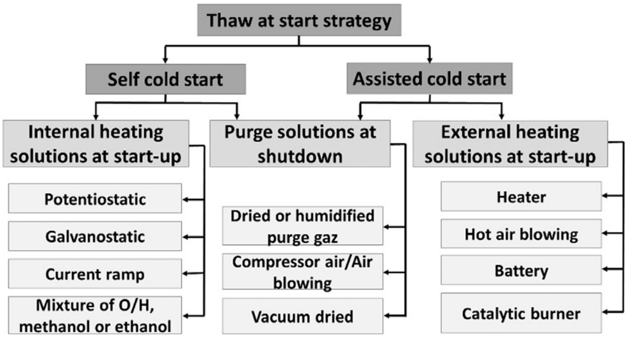

Fig. 1. Solution category chart for PEMFC cold start solutions and strategies.

warming up the cell [13]. If the produced water cannot be sufficiently removed and the generated heat is insufficient to raise PEMFC temperature above the freezing point, ice formation occurs in the cathode catalyst and gas transfer channels, resulting in cold start failure and PEMFC degradation [10,14,15]. In this regard, new purge and heating solutions, as shown in Fig. 1, have been recently developed to prevent the PEMFC from ice formation and develop cold start strategies [16]. Cold start strategies fall into two categories of Keep Warm and Thaw at Start. Keep Warm strategies revolve around the idea of heating the PEMFC during parking to avoid freezing [17–20]. Thaw at Start strategies are chiefly based on heating the PEMFC at start-up to raise its temperature above zero [21–36]. The previous work of the authors, regarding the comparison of the above-mentioned strategies, shows that Thaw at Start strategies are more adapted to be used for the cold start of private PEMFC vehicles, in which the parking time is almost unpredictable [37]. The Thaw at Start approaches fall into two groups according to their heating source. The first one, which is known as Assisted Cold Start strategies, uses an external heating source to generate heat and delivers it into the stack through a heat transfer medium [16]. The methods based on this group can be effective in terms of start-up time [22,25,27,28,34,38]. However, adding heating material impacts the volume, weight, cost and energy efficiency of a PEMFC system [16]. In this regard, the second group, which is called Self-Cold Start strategies, has been introduced to compensate for the shortcoming of the first group. Self-Cold Start strategies mainly follow a two-stage procedure of purging during the shutdown, to prevent water accumulation and thus ice formation in the cathode catalyst layer, and internal-based heating during the start-up. The internal heating methods utilize the heat generated by the exothermic reaction and can be grouped into three sorts. The first one fixes current density (Galvanostatic startup) or cell voltage (Ptentiostatic startup), which favors the production of the heat in the PEMFC. The second one, called Reactant Starvation, has an effect on stoichiometry and current density, and the third one employs a mixture of Oxygen/Hydrogen (O_2/H_2), methanol, or ethanol to increase the stack temperature (Fig. 1). Among the internal heating solutions, Galvanostatic and Potentiostatic startups are the most commonly used solutions, and it is claimed that they are very effective in terms of energy requirement and system cost [16]. Lin et al. [30] and Hishinuma et al. [35] propose a Self-Cold Start strategy which consists in purging the PEMFC at shutdown and using the Galvanostatic solution at startup to heat the PEMFC. This strategy is effective for a cold start from -5°C but ineffective for lower temperatures. Guo et al. [26] attempt to increase the heat flux supplied by the Galvanostatic solution by introducing an O_2/H_2 mixture on the anode side in order to provide a Self-Cold Start strategy from −20 °C. This strategy requires a modification of the PEMFC system, and its performances depend strongly on the state of the PEMFC (temperature, membrane hydration, degradation). Another Self-Cold Start strategy, proposed in [21,23,31,33], consists in purging the PEMFC at shut-down and using Potentiostatic mode at startup to escalate PEMFC temperature. This strategy is proven to be effective at cold start from −20 °C, but its performances rely highly on the state of the PEMFC. Jiang et al. [32] and Gwak et al. [36] aim at optimizing Self-Cold Start strategies by suggesting to purge the PEMFC at shut-down and imposing a linear increase in current density at startup. The performance of this strategy is dependent on the membrane hydration and the PEMFC thermal mass [32]. Jian et al. [21] have compared Potentiostatic and Galvanostatic solutions and concluded that the former one is more advantageous than the latter regarding the heating time and energy requirements. In the light of the discussed articles, it can be concluded that the Potentiostatic based cold start solution is one of the best methodologies which has been proposed so far in terms of energy requirements and system cost. However, it has still a long way to go for automotive applications due to the several limitations such as demanding procedure for determining the required value of voltage, dependence on the states of the PEMFC, and being incapable of adapting to degradation and operating conditions variations.

The main contribution of this work is to put forward a novel adaptive cold start strategy in order to cope with the discussed shortcomings, such as fuel cell parameters variations, and also to ameliorate the cold start performances concerning the heating time and energy requirement. Therefore, a semi-empirical PEMFFC model coupled with an adaptive recursive least square (ARLS) is employed to keep track of the operating conditions and performance drifts in the first stage. Immediately afterwards, a procedure is proposed to conduct the cold start. To the best of the authors' knowledge, this is one of the first attempts, if any, to perform the internal PEMFC cold start while taking into account operating conditions uncertainties. The final results of this work have been experimentally validated by means of a developed test bench. Section 2 gives an account of the overall process of the proposed cold start methodology along with the PEMFC modeling and implementation of the adaptive algorithm. In Section 3, experimental outcomes are reported and explored. Finally, the conclusion is drawn in Section 4 with some remarks and suggestions for further studies concerning this problem.

2. Adaptive cold start strategy

To enhance the PEMFC performance and avoid cold start failure, the produced heat from the fuel cell can be reused to warm up the PEMFC without external heating assistance. In order to minimize the heating time, it is crucial to maximize the generated heat by the exothermic reaction. It should be noted that drawing higher currents from the PEMFC leads to the generation of more heat. This is highly favorable for performing the cold start. However, an important limitation arises in this regard, which is the failure of PEMFC in providing high current loads at sub-zero temperature conditions, as discussed in [21]. Therefore, it is absolutely crucial to find the best current which can maximize the generation of residual heat while avoiding cold start failure.

During PEMFC operation, reduction in oxygen and hydrogen concentration naturally causes a mass transportation voltage drop. In fact, the rate at which the current is being drawn from the PEMFC affects directly the oxygen and hydrogen concentration. The reduction in oxygen and hydrogen concentration leads to a drop in hydrogen and oxygen pressure. This drop causes a cell voltage drop commonly known as concentration loss. The point which needs to be highlighted is that the concentration loss becomes significant at higher current levels, when the hydrogen and oxygen are used at higher rates [39,40]. In this respect, it can be stated that PEMFC systems have a limiting current (the current corresponding to the maximum power) and going beyond this limit results in the increase of concentration loss as well as PEMFC degradation. Therefore, it is suggested to operate the PEMFC at its maximum power (P_{max}) during the cold start. This mode of operation maximizes residual heat production and electrical power while avoiding concentration loss. Fig. 2 indicates the predicted polarization curve and its corresponded power curve to clarify the previously discussed points. As it can be seen in this figure, there is a clear connection