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A reconstructed fuel cell life-prediction model for a fuel cell hybrid city bus

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ABSTRACT

Life prediction is a significant and difficult topic for a proton-exchange membrane fuel cell stack, especially a commercial fuel cell stack. This paper proposes a reconstructed fuel cell life-prediction model to estimate the fuel cell lifetime adopted in a city bus. Considering the temperature fluctuation and sensor errors, the voltage model is separated into three parts to simplify the fitting process, and the validation results show that the proposed degradation model is credible and robust. Furthermore, the 14-day training data show that the deviation of the predicted voltage is less than 1%. In this study, the most important innovation is separating the time into different categories. Compared to the traditional method without classification, the proposed model obtains an improved predicted deviation of 50–100%.

1. Introduction

Fuel cells are a popular new-energy technology to reduce environment pollution and solve the growing energy crisis. The fuel cell hybrid city bus [1], with its long range, low environment impact, and relatively long service life, has been recognized by many governments and research institutions, and many operations have demonstrated its feasibility globally [2]. The performance of city buses satisfies the commercial demand [3], but their major bottleneck is the service life of the fuel cell stack [4]. Therefore, life prediction [5] is very important in the application research to lengthen the lifetime of fuel cell stacks, and previous research indicates that the analysis of the performance degradation of a fuel cell stack can be mainly divided into two categories: data-driven and model-based approaches.

Data-driven approaches [6] are widely used in engineering analysis. For example, Pei et al. [7] proposed a quick evaluating method to determine the automotive fuel cell lifetime. Based on the laboratory-tested degradation rates of four specific operating conditions, the calculated lifetime fits the real running lifetime well. However, in that study, only one voltage point was analyzed and the accelerating coefficient k_p was unclear. Hissel et al. conducted much research on the residual life estimation. The extended Kalman filter approach [8], particle filter-based approach [9], summation wavelet-extreme learning machine (SW-ELM) algorithm [10], wavelet-based approach [11], and SW-ELM with new incremental learning [12] have also been used to process the degradation data; these methods have been validated by bench test results. Furthermore, Silva et al. [13] proposed a methodology based on adaptive neuro-fuzzy inference systems; this methodology used measures of fuel cell output voltage during operation as the input. However, the correctness of data-driven approaches depends on the repeatability and regularity of the degradation mechanism. When the operating condition changes, the parameters of data-driven approaches need to be adjusted.

In addition, model-based approaches [14] appear more attractive than data-driven approaches for research. For example, Lu et al. [15] proposed a semi-empirical voltage-degradation model for a low-pressure proton exchange membrane (PEM) fuel cell stack under a bus city drive cycle, where the degradation rates of several variables were assumed to have a linear relation with operating time. Jouin et al. [16] presented a more complex voltage model for life degradation, where almost all parameters were regarded as variables. Empirically, the time-based linear, logarithmic, and exponential models were used to describe the degradation rate of different variables. However, both papers did not distinguish the different operating conditions because they used regular operating conditions.

Some model-based approaches have been concluded from the accelerated life test. For example, Bi et al. [17] used a semi-empirical degradation model to estimate the loss rate of platinum mass. The potential of the cell was cycled at a temperature of 60 °C with a square wave between 0.87 and 1.2 V. The results showed a good prediction about the effect of humidity and oxygen pressure on the degradation of a catalyst in a PEM fuel cell. Furthermore, Zhang et al. [18] analyzed

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the impact of potential cycling on PEM fuel cell durability using the electrochemical kinetics model. This study focused on the interaction between the upper potential limit and lower potential limit on PEMFC stability, and suggested that when cycling to a lower potential of 0.8 V, the fuel cell reached a peak degradation rate. These research results about the degradation rate of a catalyst are very useful for qualitative analysis. However, the actual operating condition of an FCS on road are totally different from that of an accelerated life test. Determining how to build the relation between the bench test and the on-road test is very important in obtaining a good prediction result.

Evidently, few studies have been conducted on the combination of data-driven and model-based approaches, especially for FCS on road. Most studies are based on ideal bench test results or accelerated stress tests of monolithic fuel cells. However, the ambient condition of FCS on road is fickle, and the sensors are inaccurate in some regions. For a typical hybrid fuel cell city bus, the operating regulation may be seasonal and estimating the decline rate of FCS on road is difficult. Besides, the traditional mechanism model is inconvenient for real-time estimation because it needs considerable computation or can only be used at some points. Thus, the relations among performance degradation, ambient condition, and operating conditions must be clarified for model simplification, and the combination of two analysis methods can be an effective approach to solve this problem.

The current paper presents a comprehensive analysis on the operating condition-based life-prediction method. Section 2 analyzes the operating condition of fuel cell buses, and a new classified method is used to define two typical operating conditions to analyze the performance degradation. Section 3 describes the voltage decline process in a fixed output current. The classified operating time obtained in Section 2 is used to estimate the voltage drop rate. Then, the relation between operating time and characteristic parameter degradation is established. Section 4 presents a reconstructed fuel cell voltage model, to which the degradation model of ECA and resistance are added. A four-step life prediction process is then proposed to estimate the voltage degradation. Section 5 presents the validation result of the reconstructed model and compares the life prediction results of the new model with those of the traditional life-prediction method. Finally, Section 6 presents the conclusion.

2. Operating mode analysis

To build a reasonable life prediction model, we analyze a fuel cell city bus running in Beijing. This bus operates in a routine cycle from March to July, and the related information is shown in the following paragraphs.

The fuel cell city bus shown in Fig. 1(a) uses a typical hybrid powertrain system and a fuel cell stack and a battery pack to provide electricity to the motor in parallel. This structure is useful in lengthening the lifetime of fuel cell stacks, which are widely used in city buses.

Fig. 1(b) presents a daily operation cycle of the powertrain system. The blue line indicates the output current of the fuel cell stack, and the red line indicates the state of charge of the battery. To reduce the performance degradation of the FCE, a soft run strategy is designed. Furthermore, the battery pack satisfies the dynamic power demand of the city bus, which results in a remarkable fluctuation in SOC.

Fig. 1(c) shows the distribution of output current density. More than 95% of the time, the FCE works at two stable points, about 120 A and 170 A, where 170 A is the rated operation point and 120 A is the minimum level required to avoid the battery overcharge. As shown in Fig. 1(b), such a strategy successfully avoids rapid load variation in this system.

Fig. 1(d) shows the voltage distribution. Normally, the voltage points above 0.8 V are regarded as harmful to fuel cell stacks. Owing to the control strategy, the high voltage percentage in this powertrain system is much less than that in previous reports, which is more than 20%. It is meaningful for the protection of fuel cell stacks, and the idling condition can be ignored in this system.

In conclusion, the control strategy in this fuel cell city bus simplifies the operating condition of fuel cell stacks, and these methods help reduce the performance degradation of fuel cell stacks. From March to July, the fuel cell city bus operates for more than 200 h; a more detailed information on this can be obtained from the previous paper [19]. Furthermore, the total operating data of the fuel cell stack, including the output current and voltage, are shown in Fig. 2.

The green line in the figure represents the fuel cell output current; the irregular current signals around 170 A are caused by the sensor errors. The blue line represents the total voltage of the fuel cell stack, and shows a remarkable voltage drop. For a commercial FCE, the voltage degradation estimation is very important for product design. However, on-site performance degradation analysis is very complex for a fuel cell stack used in the vehicle. Especially considering the environment condition variation and the sensor errors in the vehicle, it is very difficult to verify the reasons for FCE degradation. Based on engineering experience [7], Eq. (1) provides an effective life-prediction method to estimate the residual life of an FCE, which has been validated by SAIC and Toyota.

$$L_f = \frac{\Delta P}{k\cdot\left(n_1 P_1' + n_2 P_2' + \frac{t_1 P_3'}{60} + \frac{t_2 P_4'}{60}\right)} \tag{1}$$

The above equation indicates that the performance degradation results from a specific operating condition. The driving cycle is divided into four categories: start-stop cycle n_1, rapid load-changing cycle n_2, idling time t_1, and high-power load time t_2. Furthermore, ΔP represents the allowed maximum performance degradation, and L_f represents the predicted lifetime. In addition, the four degradation coefficients in the equation are derived from the bench test results, and k represents the accelerating coefficient for the actual operating conditions. However, the relevant tests in Eq. (1) are too expensive and time-consuming, and the degradation rates may vary in different load cycles and operating conditions. Consequently, a more flexible method is needed to estimate FCE performance degradation.

According to the analysis of Fig. 1, the idling and load changes can be ignored in this demonstration, and only the start-stop process and operating condition are meaningful. Generally, a start-stop process contains two steps for a real fuel cell engine: gas supply and system warm up. When the reaction gas is supplied to the fuel cell stack, the open-circuit voltage is developed, and the system turns to work and starts the warm-up process. Furthermore, the allowable maximum output current is limited by the system temperature to avoid performance degradation in the warm-up process. However, the limited current also results in an increase in the operating voltage. In different seasons, ambient temperatures are different, which leads to a different warm-up time, which varies from several minutes to twenty minutes. Therefore, only the start-stop count is inexact for the degradation analysis of the start-stop process. Considering a longer warm-up process, which may cause a more serious degradation, the start-stop count is replaced by high voltage time, which is more reasonable in such a fuel cell control strategy.

Fig. 3(a) presents the cumulative time above 0.7 V. According to the control strategy, the warm-up operating region is normally above the voltage boundary of 0.7 V, and the cumulative time is linear with the number of days, which is about 15 min per day, which is close to actual experience. Fig. 3(b) presents the cumulative time above 0.4 A/cm^2. This working region is the complementary set of FCE, and is defined as the high-power load condition, as shown in Eq. (1). The growth rate of the operating time increases considerably in the latter half of the demonstration, because the bus operates overtime from 8 am to 10 pm.

Based on Eq. (1), the degradation rate is related to the cumulative time of the two working conditions. In the next section, the performance degradation of the FCE in a fixed output current is analyzed.