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Methodology of designing durability test protocol for vehicular fuel cell system operated in soft run mode based on statistic results of on-road data

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ABSTRACT

In a polymer electrolyte membrane (PEM) fuel cell bus, there are at least two power sources, e.g., a hydrogen fuel cell system (FCS) and an energy storage system (ESS). Depending on powertrain configuration and control strategies, an FCS can work in different modes, which can be generally classified into so-called *power follow* (PF) and *soft run* (SR) modes. In the SR mode, the FCS serves as a stationary power source, and the ESS provides the dynamic power. Nowadays, most of the fuel cell buses in China operate in this mode, since it has advantages of long working lifetime. In order to evaluate the aging behavior of fuel cell stacks under conditions encountered in this kind of fuel cell buses, new durability test protocols based on statistical results obtained during actual driving tests are required. In this research, we propose a methodology for designing fuel cell durability test protocols that correspond to the SR mode. The powertrain configuration and control strategy are described herein, followed by a presentation of the statistical data for the real driving cycle in a demonstration project. Equations are derived based on constraints of keeping the battery in charging balance. One test protocol is presented as an example, and compared to existing protocols with respect to common factors, such as time at open circuit voltage and root-mean-square power.

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Introduction

Polymer electrolyte membrane (PEM) fuel cells are clean and highly efficient, and are favored for public transportation applications. The related technologies have been developing rapidly in recent years, and commercialization of fuel cell vehicles has just begun with vehicle costs still very high.

In a PEM fuel cell bus (FCB), there are at least two power sources, e.g., a hydrogen fuel cell system (FCS) and an energy storage system (ESS). Depending on powertrain configuration and control strategies, an FCS can work in different modes, which can be generally classified into so-called *power follow* (PF) and *soft run* (SR) modes. In the PF mode, the FCS works as the main power source, and follows the major dynamic processes of the powertrain requirement. The ESS serves as an auxiliary power source, and bears part of the dynamic load, i.e., the accelerating and decelerating power. In the SR mode, the FCS serves as a stationary power source, and the ESS provides the entire accelerating power and recycles braking energy.

There are diverse technical challenges and obstacles in developing fuel cell systems because of multiple chemical and physical interactions at component, individual cell, stack and system control levels [1]. Prognostics and health monitoring algorithms are strongly required to improve the durability, reliability and maintainability of fuel cell systems [2]. To understand the aging behavior of fuel cell stacks when operated under various duty cycles, it is necessary to develop new test platforms and protocols that characterize the performance of fuel cell systems. Shetzline et al. [3] proposed a miniature test platform for fuel cells. It can conduct diagnostic tests on disk-shaped membrane electrode assemblies (MEAs) using in-situ and ex-situ cyclic voltammetry (CV) measuring technologies. Wasterlain et al. [4] developed a new test instrument and protocols for fuel cell stack diagnose. The instrument can measure electrochemical impedances for individual cells and the entire stack meanwhile. Sharabi et al. [5] proposed design methodology for accelerated stress tests for non-precious metal catalysts (NPMCs) for fuel cell cathodes based on measuring technologies such as CV, chronoamperometry (CA), electrochemical impedance spectroscopy (EIS) and rotating ring disk electrode (RRDE). Results showed that NPMC degrades rapidly at low potentials and the support degrades at high potentials, and a tailor-made accelerated stress test protocol was designed to take these into account.

Nowadays, there are a variety of durability test protocols for PEM fuel cell components, e.g., electro-catalyst, catalyst support, membrane and gas diffusion layer, and for complete cells/stacks [6]. The United States Fuel Cell Technical Team (FCTT) has proposed two durability test methods [7] under wet and dry conditions. In the DOE Hydrogen Program, four kinds of durability test protocols were summarized as follows.

(1) Steady-state durability test [8], which involves the operation of either a single cell or a stack under constant voltage and constant current conditions for specific time intervals.
(2) Potential cycling durability test [8], whose assessments subject single cells to accelerated stress testing (AST) technology as a means of simulating the dynamic load in an automotive application.
(3) Start-up/shutdown cycling durability test [9], which examines the degradation of fuel cell components as they are subjected to start-up/shutdown cycles.
(4) Dynamic stress test (DST) duty cycling test [10], which determines the long-term durability of fuel cells when employed in vehicles.

The EU Fuel Cell Testing and Standardization Network (FCTestNet) published several fuel cell durability test protocols [11], among which there is an on-off cycle that is utilized in the International Electro-technical Commission (IEC) TS62282-7-1 standard. Based on the original New European Driving Cycle, i.e., the Economic Commission for Europe (ECE) R15, a fuel cell test protocol was proposed by calculating the Rated Power (%) and squaring the pulses [12]. The Rated Power (%) is defined as the ratio of the vehicle power and its maximal value. The original value of Rated Power ranges from 0 to 100%. The "squaring the pulses" is a method to calculate the approximate values of the Rated Power, where it is approximated to several discrete values. In the European project Fuel Cell Testing, Safety, and Quality Assurance (FCTESQA), several fuel cell durability test protocols were defined, including tests under constant current density [13] and dynamic load cycling [14]. In the European Development of PEM Fuel Cell Stack Reference Test Procedures for Industry (StackTest) project [15,16], various fuel cell test protocols for performance and durability evaluation have been defined.

Given the increasing number of test protocols for fuel cell durability, scientists have conducted research on comparing and validating them. It was reported by Bloom [11,12] that the performance degradation rate obtained from the four typical durability test protocols decreases in the following order: IEC > ECE R15 > DST ≈ FCTT (wet).

Based on these testing protocols, researchers have conducted studies on performance degradation of different components [17–22]. Harms et al. [17] studied the variability and comparability of test protocols for different PEM fuel cells. Jeon et al., [18,19] investigated accelerated lifetime tests under different load cycles for high temperature fuel cells. They found that, the membrane degradation is more dominant after the on-off tests, while more catalyst degradation is observed after the load cycling tests. Taccani et al. [20] studied the effects of accelerated aging tests on polybenzimidazole (PBI) based high temperature PEM fuel cells, and found that load cycling is more detrimental for performance degradation. Hengge et al. [21] conducted accelerated fuel cell tests of anodic Pt/Ru catalyst based on identical location transmission electron microscopy (IL-TEM) technology, and obtained new understanding of the degradation process. Hashimasa et al. [22] compared the results of durability tests of PEM fuel cell cathode catalysts under different cycles, which are defined by the Fuel Cell Commercialization Conference of Japan (FCCJ). Results showed that, the test protocols can effectively differentiate degradation behaviors of the cathode catalysts.

FCBs are regarded as the most likely to be commercialized in China [23]. Most of FCBs in China nowadays operate in the SR mode, since it has advantages of long working lifetime and high reliability. Hua et al. [24] summarized the status of

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