Applied Energy 142 (2015) 154–163

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Lifetime prediction and the economic lifetime of Proton Exchange Membrane fuel cells

Huicui Chen, Pucheng Pei *, Mancun Song

State Key Lab. of Automotive Safety and Energy, Tsinghua University, Beijing 100084, China

HIGHLIGHTS

- A formula to predict the PEMFC lifetime is presented.
- A PEMFC residual life evaluation method is presented.
- The evaluation method realizes online forecasting of the PEMFC residual life.
- The PEMFC economic lifetime is studied to confirm the best design lifetime.

ARTICLE INFO

Article history:
Received 18 June 2014
Received in revised form 7 November 2014
Accepted 28 December 2014
Available online 14 January 2015

Keywords:
PEM fuel cell
Lifetime prediction
Residual lifetime
Economic lifetime

ABSTRACT

Lifetime and cost are two main factors that restrict the commercialization of Proton Exchange Membrane (PEM) fuel cells. This paper mainly studies the prediction and the evaluation methods of PEM fuel cell lifetime. A formula to predict the PEM fuel cell lifetime is presented. The formula is based on the vehicular operation records and the tested results in the lab. Also the difference between the vehicular operation condition and the test is taken into consideration. The formula realizes the PEM fuel cell lifetime rapid prediction. A PEM fuel cell residual life evaluation method is also presented. The evaluation method realizes online forecasting of the residual life through updating the environmental affecting factor and voltage degradation rate caused by the operating conditions. Furthermore, the PEM fuel cell economic lifetime is studied. The economic lifetime is the working lifetime which gains the lowest average cost. The synthesis of the lifetime and the cost provides a basis to confirm the best design lifetime.

1. Introduction

Over the past decades, the environmental pollution problem and the energy crisis problems were seriously highlighted. Because Proton Exchange Membrane fuel cells are high efficiency and environmental friendly [1]. Many research institutes, universities worldwide have conducted research on the PEM fuel cells [2]. Mentioning PEM fuel cells on vehicle applications, people mainly focus on whether the lifetime and the cost have reached the commercial requirements [3].

The PEM fuel cell firstly come to space 30 years ago, and it is too expensive for the other applications until now. The cost is one of the main factors hindering the widely use of PEM fuel cells. In order to realize the commercialization of the PEM fuel cells, the cost competence with other powers is necessary. When the PEM fuel cell is applied on vehicle, such as cars, trucks and buses, service life is less than 3000 h and the price is over US$50/kW, and unable to compete with the internal combustion engine nowadays [4,5]. Lee et al.[6] studied the hydrogen lifecycle cost by measuring the well-to-tank cost, the tank-to-wheel cost, the gas emission cost, the greenhouse gas cost and the external cost, the result indicated that the lifecycle cost mainly depends on the fuel cell cost, the production capacity, the fuel efficiency, the social cost, and the hydrogen production method.

In recent years, studies to prolonging PEM fuel cell lifetime and reducing the manufacturing cost have made considerable progress. The PEM fuel cell cost has been reduced form $275/kW in 2002 to $73 kW in 2008, further reduced to $61/kW in 2009 ($34 for balance of plant including assembly and testing, and 27$/kW for stack). More than 35% reduction in the 2008 and 2009. And there is room for further reduction. The DOE targets for the fuel cell cost is $30/kW for transportation applications [7]. Marquis and Coppens [8] decreased the cost of the catalyst layer by changing the micro-structure of the cathode catalyst layer to increase the Pt utilization rate. Avasarala and Haldar [9] applied the synthetic

---

* Corresponding author. Tel.: +86 10 62788558.
E-mail address: pchpei@mail.tsinghua.edu.cn (P. Pei).

http://dx.doi.org/10.1016/j.apenergy.2014.12.062

Pt/TiN catalyst instead of Pt/C to improve the catalytic effect and lower the cost of the catalyst layer. Nikolic et al. [10] pointed out that the Pd/WC catalyst effect is the same as Pt/C, and can be used as the anode catalyst to decrease the catalyst cost. Heinzel et al. [11] cut down the manufacturing cycle through the injection modeling, further decreasing the manufacturing cost. Hou et al. [12] presented a method that evaluated the efficiency of the fuel cell reasonably and objectively. Bar-On et al. [13] built a technical cost model. They considered the fuel cell design standard, the subsidiary equipment cost, the technological design cost and the details machining cost, to study PEM fuel cell stack assemble cost and the whole system cost. Kamarudin et al. [14] built an economics model to study the fuel cell manufacture cost and system accessories, and predicted the PEM fuel cell stack and system income and cost. Sun et al. [4] applied societal lifetime cost to evaluation the PEM fuel cell cost. The defined social lifetime cost includes the vehicle retail cost (usually the function of fuel cell performance), the energy consume cost (the function of fuel cost), the run and maintenance cost, especially the fuel consumption, the noise and contamination gas disposal cost. They compared the PEM fuel cell with the traditional internal combustion engine form the perspective of societal welfare, and also applied many models to estimate the system cost changes with time then compared with the combustion engine. Their conclusion indicates that the PEM fuel cell cost is much higher than internal combustion engine at the beginning, but with the increase of PEM fuel cell production, their lifetime cost will be more competition than the internal combustion engine. The above researches are very important, but they did not give a evaluation method that combines the lifetime and the exciting cost level to confirm a best fuel cell design-lifetime.

Until now, a unified PEM fuel cell lifetime evaluation method has not existed. The method of real road driving tests requires a long testing period involving high costs. There are various laboratory researches on PEM fuel cell durability. Bae et al. [15] proposed an accelerated degradation testing (ADT) procedure for a PEMFC stack with a series reliability structure and estimated the lifetime of PEMFC stack with a series reliability structure. Jung et al. [16] performed the ADT test to elucidate the membrane electrode assembly (MEA) degradation mechanisms. Onanena et al. [17] conducted interval loading method to evaluate the performance degradation and resistance change during degradation of the fuel cell. By measuring the Electrochemical Impedance Spectra (EIS) and the current voltage curves, it was possible to evaluate the PEM fuel cell residual life. Zhang et al. [18] applied the cyclic voltammetry test to evaluate the Pt active area degradation. Kocha et al. [19] applied the cyclic voltammetry test to study the change of hydrogen permeation current. Bouzek et al. [20] applied hydrogen gas with mercury vapor contamination to study the PEM fuel cell durability. Mukundan et al. reported on the DOE Hydrogen and Fuel cell Program, they conducted the Accelerate Stress Tests on the real bus to study the fuel cell failure modes. Marrony et al. [21] studied the PEM fuel cell durability and conducted lifetime tests during the load cycling. Bae et al. [22] presented a PEM fuel cell lifetime evaluation method by means of acceleration and start-stop degradation tests. Cheng et al. [23] reinforced the PEM fuel cell catalyst layer by polymer to mitigate the catalyst layer decay, further to prolong the lifetime of the fuel cells. However, there is no corresponding relationship between fuel cell durability and the real road running lifetime. Besides there is no PEM fuel cell real road cycling for comparison. And different driving cycles or different test modes mean that different fuel cells lifetime is obtained. The PEM fuel cell research group in Tsinghua University worked out a PEM fuel cell lifetime quick evaluation method. The method combines the real road running results and the test results [24].

There is always cost problems when researchers seeking for the fuel cells' long lifetime, and the lifetime was shortened when prolonging for low cost. Therefore searching for the best fuel cells design lifetime based on the existing cost is of great significance. Users' double requirements of lifetime and cost can be considered from the perspective of an economic lifetime. But there are fewer studies on the composite indicator of PEM fuel cells lifetime and cost. This paper presents the PEM fuel cell lifetime quick evaluation formula, and then propounds the PEM fuel cells residual life forecasting during operation, further investigates the PEM fuel cells economic lifetime evaluation method.

2. The lifetime prediction based on operation conditions

Running conditions of the PEM fuel cell vehicle vary greatly, but they are mainly composed of start, idling, load changing, high power load and stop, as seen in Fig. 1. Fig. 1 is the real running data of our self-developed fuel cell bus in Beijing during 29th Olympic Games in 2008. The rated power of the PEM fuel cell stack is 10 kW, and the rated current is 100 A. The operating temperature is 60 °C, and the operation pressure is the atmospheric pressure. The stoichiometric ratio of hydrogen is 1.1, and the stoichiometric ratio is 2.5. The stack is a 100-cell PEM fuel cell stack with 274 cm^2 effective area in every single cell, which is provided by Shanghai Shen-li High tech Co., Ltd. The fuel cell bus had operated on a specific bus line for one year as a green energy vehicle demonstration project for public transportation. Therefore PEM fuel cell vehicle real driving condition can be simulated as the sum of start-stop, idling, load changing and high power load four typical operating conditions.

$$\text{Driving cycle} = \{\bar{n}_1, \bar{t}_1, \bar{n}_2, \bar{t}_2\} \tag{1}$$

Here, $\bar{n}_1$ stands for the average start-stop cycles per hour; $\bar{t}_1$ stands for the average idling time per hour; $\bar{n}_2$ stands for the average load change cycles per hour; $\bar{t}_2$ stands for the average high power load operation time per hour. These parameters will be called the load spectrum of the driving cycle.

Consider a PEM fuel cell bus real driving cycle, as seen in Fig. 1; what follows is the load spectrum of the driving cycle in per hour:

$$\text{Driving cycle} = \{\bar{n}_1 = 1,\quad \bar{t}_1 = 13\ \text{min},\quad \bar{n}_2 = 56, \bar{t}_2 = 14\ \text{min}\} \tag{2}$$

Fig. 2 shows the corresponding tested load cycle results in the lab. The fuel cell stack we used in the experiment is the same as the fuel cell stack applied on the bus. The performance degradation rate of start-stop, idling, load change and high power load under rated current are tested respectively. The fuel cell stack start-stop cycling test was carried out in the strict process, start-up, idling 1 min at constant current of 10 mA/cm^2, stop, purging hydrogen by nitrogen gas, waiting until the stack voltage falls to zero, and then to the next cycle. During the fuel cell stack idling condition

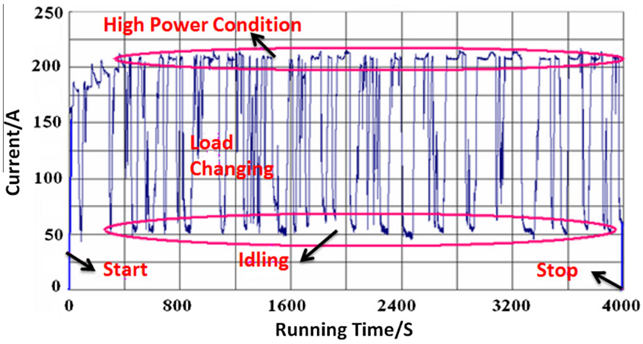

Fig. 1. The real driving cycle of a PEM fuel cell bus.