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Fuel cell flooding diagnosis based on time-constant spectrum analysis

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ABSTRACT

Proton Exchange Membrane (PEM) Fuel Cell is a key component for the exploitation of hydrogen energy. Its diagnosis relies on several in-situ diagnosis tools. Electrochemical impedance spectroscopy is a major one. But this technic has some drawbacks, among which the complexity of the required equipment and the measurement time. An alternative method for diagnosis is developed in this work. A time-constant spectrum (or relaxation-time distribution) is extracted from the fuel cell voltage response to small current steps. This spectrum can be read as a distribution of series RC cell representing, such as an impedance spectrum, the whole dynamic of the voltage response to a given current excitation. In order to demonstrate the ability of the method to diagnose flooding, different simulations of voltage responses are first performed using appropriated parameters' variations in a fuel cell model. The resulting time-constant spectrums are analyzed to underline the sensitivity to the flooding effect. Then, experiments are achieved to confirm the potentiality of this technic to diagnose flooding.

Introduction

Depending on application fields and environment, the fuel cells are submitted to various operating conditions. An appropriate gas feeding is then required to ensure an optimal operating of the fuel cell. Without this requirement, the large scale of operating points could lead to abnormal operation such as drying or flooding [1]. The fuel cell state of health could be degraded involving a possible decrease of its durability. Thus, fuel cell diagnosis is a key point for a large development of hydrogen based technologies. Currently, one of the most reliable approaches for diagnosis is based on parametric identification of a model through Electrochemical Impedance Spectroscopy (EIS). This method can be used to diagnose fuel cell flooding ([2,3]), drying or to measure high frequency impedance in order to track internal resistance value [4]. A review of different diagnosis schemes using EIS can be found in Ref. [5]. EIS signature can also be used to determine hydrogen leaks in a fuel cell [6,7], to derive a control strategy [8] or to evaluate stack performances ([9,10]). The extraction of time-constant spectrum explained in this work could also be obtained thanks to EIS [11]. More recently, a paper describes a method exploiting the distribution of

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relaxation times to diagnose cells polarity reversal by insufficient hydrogen supply [12].

An alternative method to EIS for estimating fuel cell model parameters is the response to current steps ([13–15]). However, in the literature, this technique is mainly used for internal resistance measurement [16,17].

This paper addresses a new application of current step approach for fuel cell diagnosis derived from thermal diagnosis of power semiconductors [18]. This technic is based on theoretical thermal flow propagation through materials of different kinds. The geometrical structure of these components is modeled by thermal resistors and capacitors which describe thermal transfer properties. Using a thermal flow step, an identification of associated parameters is performed and helps to identify degradation in the different layers of the component. The method can be transposed to fuel cell diagnosis considering that a current step applied to the fuel cell will involve a voltage variation related to gas diffusion properties of the different layers. A model based on resistors-capacitors network (RC network) is then identified to match the voltage evolution. The analysis of the parameter variation allows pointing out potential modifications of the diffusion properties.

In this paper, we first introduce a linearized fuel cell model that will be used for simulation purposes. The time-constant spectrum method is then explained. Thereafter, simulation results are performed from artificial layer degradation to assess the detection ability of the method. Finally, an experimental validation is carried out with a fuel cell in flooding conditions.

Model of fuel cell

The simulation model used in this work is based on an electrical model of a fuel cell developed in our laboratory [19]. Two forms of the model have to be distinguished: the general form which fits for large signals, and a derivate form which describes the fuel cell behavior linearized around a steady state operating point (fixed current).

The large-signal dynamic circuit model is based on a physical description of the different phenomena. The heart of the energy conversion process is considered, and then, the associated losses are subtracted; they are modeled by their consequences in the electrical field. Four phenomena are modeled: chemical activation, diffusion in active layer (AL), diffusion in gas diffusion layer (GDL) and charge transport (ohmic phenomena). The voltage drops associated to each phenomenon are given by:

$$\eta_{act} = \frac{RT}{\alpha nF}\ln\left(\frac{I}{I_0}\right)$$

$$\eta_{diff\ \ xxx} = \frac{RT}{\beta_{xxx} nF}\ln\left(1-\frac{I}{I_{\lim\ xxx}}\right)$$

$$\eta_{ohmic} = \sum_i R_{ohm,i}\cdot I \ \approx R_{mem}\cdot I$$

xxx can be active or gas diffusion layer (AL or GDL).

With:

$$I_{\lim\ gdl} = \frac{nFSD_{gdl}C_{eq}}{\delta_{gdl}}$$

$$I_{\lim\ al} = \frac{nFSD_{al}C_{eq}}{\delta_{al}}\left(1-\frac{I}{I_{\lim\ gdl}}\right)$$

Moreover a capacitance is associated in parallel to each activation and diffusion loss to take into account the dynamic of diffusion mechanisms.

$$C_{Diff\ \ xxx} = \frac{\delta_{xxx}}{2D_{xxx}R_{diff\ \ xxx}}$$

These equations can be linearized around a current steady state operating point I. The large signal model is then transformed into a RC electrical model (see Fig. 1). All the losses expressions are derived with respect to current to obtain the resistor parameters:

$$R_{act} = \frac{RT}{\alpha nFI}$$

$$R_{diff\ \ xxx} = \frac{RT}{\beta nF(I_{\lim\ xxx}-I)}$$

The equivalent circuit of the model is given in Fig. 1.

Leaving out R_{mem}, this model is a Cauer form of a resistor-capacitor network (imbricated RC cells), and can be transposed into a Foster form (serial RC cells shown in Fig. 2) following an analytical mathematic transformation [20]. Both representations have the same response whatever the excitation current. Unfortunately, during the Cauer–Foster transformation, the parameters related to each layer are mixed and the resulting Foster parameters may lead to a loss of physical meaning. This problem will be addressed in the next sections.

Deconvolution method for time-constant spectrum computation

The method has been hugely developed for thermal diagnosis of power electrical components by Székely et al. ([21–24]). The aim of this approach is to identify the parameters of a RC model starting from the voltage response to a current step. To achieve this goal, a Foster form of a RC circuit is considered. For a finite chain of n RC dipoles, the generalized voltage response to a unit step is given by (1).

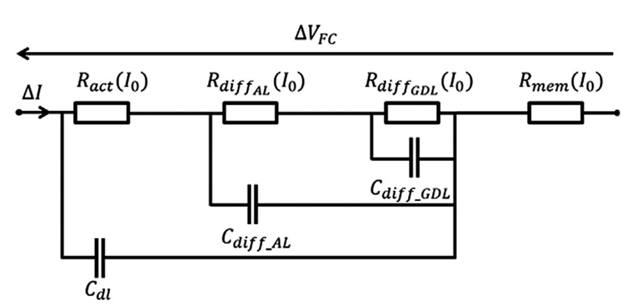

Fig. 1 – Fuel cell impedance model using 3 RC cells (Cauer form).