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Dynamic performance of a high-temperature PEM (proton exchange membrane) fuel cell – Modelling and fuzzy control of purging process

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A B S T R A C T

To improve fuel utilization of HT-PEMFC (high-temperature proton exchange membrane fuel cell), which normally operates under dead-end mode, with properly periodical purging to flush out the accumulated water vapour in the anode flow-field is necessary, otherwise the performance of HT-PEMFC would drop gradually. In this paper, a semi-empirical dynamic voltage model of HT-PEMFC is developed for controller design purpose via fitting the experimental data and validated with experimental results. Then, a fuzzy controller is designed to schedule the purging based on the obtained model. According to the result, the developed model well reflects transient characteristics of HT-PEMFC voltage and the fuzzy controller offers good performance for purging scheduling under uncertain load demands.

1. Introduction

High temperature PEM fuel cell (HT-PEMFC), based on PBI (polybenzimidazole) membrane which doped with H_3PO_4, have promising future for mobile and stationary applications because of its several virtues: high carbon monoxide tolerance, fast reaction kinetics and high quality of exhaust heat [1–5]. In addition, the relaxation of water flooding is an often advertised advantage in HT-PEMFC, because water exists in vapour phase in HT-PEMFC [6,7]. In contrast, water exists in two phase in traditional LT-PEMFC (low temperature PEM fuel cell) and leads to the water flooding as common issue in LT-PEMFC [8–12]. Currently, the fuel utilization is an important consideration of fuel cell operation and the dead-end mode operation offers a solution to that challenge [13]. When a fuel cell operates in anodic dead-end mode, the fuel is supplied to anode via a regulator at anode inlet and a solenoid valve located at the anode outlet remains fully closed except for intermittent purging. However, the performance of HT-PEMFC drops gradually when it operates under dead-end mode [14], because the water vapour can be transported from cathode to anode side [15–17] and the accumulated water vapour dilutes the fuel concentration [18]. Thereby, the anodic purging process is still needed and must be controlled in HT-PEMFC system.

Generally, the purging interval between two purging events is scheduled on-line, which is in a way of fixed purging interval or varying purging interval [19,20]. The fixed purging interval considered an average duration of close time may be too often at low load but infrequent at high load. On the contrary, varying purging interval method is related to the real-time monitored states of fuel cell, such as transient voltage, output power, the current load, the internal resistance or a combination thereof [21–23]. The later method is a more reasonable scheduling way. The transient voltage of fuel cell is an important criterion for triggering purging [24–26]. Several dynamic models are developed to investigate and to predict transient voltage of HT-PEMFC [27–32]. However, these models are phenomenological models derived from conservation laws, which are good for understanding of the fundamental properties in HT-PEMFC, but not suitable for the control purpose, because of their complicated computational

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feature [33]. By contrast, the semi-empirical models are more applicable for control system because of the less computational expense. In LT-PEMFC, Meiler et al. [34] applied the system identification approach to develop the dynamic model. Hou et al. [35–37] investigated the transient characteristics of stack and derived the semi-empirical voltage models from the experimental result. In Refs. [38–42], the effects of temperature, equivalent internal resistance, purging effect, pressure and hydrogen consumption are partially considered in different semi-empirical models for special purpose. These models [34,36–42] are simple but sufficient to characterize and to predict the transient behaviours of LT-PEMFC for controller design. In control aspect, fuzzy controller is capable to apply expert's knowledge and to handle the multiple inputs/outputs [43]. In addition, it offers robust performance for dynamic system since it is a nonlinear control algorithm in nature [44]. Hence, fuzzy logic controller for the purging scheduling may be intelligent and effective by taking several parameters in considerations [43,45]. However, the semi-empirical models of HT-PEMFC to predict the transient process during current load variation and the control approach are scarce to manage purging process when HT-PEMFC operates under dead-end mode.

In this paper, a semi-empirical model is developed to characterize the dynamic behaviours of HT-PEMFC's voltage and a fuzzy controller is designed for scheduling of purging based on the proposed model. The results show that the model well reflects the transient properties of voltage during dead-end mode in HT-PEMFC and the fuzzy controller is effective for purging programming under the variations of current loads.

2. Fuel cell modelling

The model presented here is to capture the essential behaviours of HT-PEMFC, which represents the variations under different conditions. Then a feedback control based on fuzzy logic algorithm is designed using the model. The experimental study conducted at temperature of 160 °C, anode pressure of 0.05 bar and cathode at flow-through mode with flow-rate of 487 sccm, was reported in previous study [46]. According to the results and discussions, the hydration/dehydration processes of acid affect the dynamic behaviours of HT-PEMFC and the dynamics of the HT-PEMFC can be described as follows:

1. The hysteresis phenomena were viewed in polarization curves and dynamic voltage curves, which reflect that the performance of backward sweep was better than the forward sweep.
2. The overshoots and undershoots of cell voltage under flow-through mode during the current load step-up and step-down, respectively, were exhibited. In addition, the magnitudes varied with the variation of current loads.
3. The fuel dilution and consumption in anode side lead to gradually drop of cell voltage after purging in dead-end mode. Furthermore, the losses of performance become more serious under high current load and longer purging interval. The shape of dynamic voltage curve of the longer purging intervals overlapped with the curves of shorter purging intervals.
4. Under dead-end mode, though the dynamic voltage curve exhibited more fluctuation, the shape of peak voltage of the dynamic voltage curve under dead-end mode followed the same tendency compared with the shape of voltage curve under flow-through mode. However, the peak voltage of the cell was increased a little bit under dead-end mode compared with the voltage in flow-through mode.

The first bullet point indicates that the dynamic performance of HT-PEMFC must be modelled the forward and backward sweeping separately, the experimental data also can be found Fig. 2 of reference [46]. The second and third ones are the key dynamic behaviours of HT-PEMFC, the experimental data can be found in Fig. 8 of reference [46] and in Figs. 6 and 7 of this study. The fourth point indicates that the peak voltage of HT-PEMFC under dead-end mode can be predicted from the voltage obtained at the flow-through mode with suitable correction. In addition, the effect of load variation (peak voltage of HT-PEMFC) and dead-end mode on the dynamic behaviour of HT-PEMFC can be modelled separately and coupled them together. Thus, the dynamic voltage (V_{dynamic}) behaviour of HT-PEMFC can be modelled as in Eq. (1).

$$V_{\text{dynamic}} = V_{FLM} + \Delta V_{dead-end} + \Delta V_{\text{correction}} \quad (1)$$

The Eq. (1) combinations of the voltage model of flow-through mode (V_{FLM}), the voltage variation between two purging events under dead-end mode, which is due to the effect of fuel consumption and fuel dilution by water vapour in the anode side of HT-PEMFC under dead-end mode operation ($\Delta V_{dead\text{-}end}$) and the corrected voltages $\Delta V_{\text{correction}}$ which is to convert V_{FLM} to the peak voltage under dead-end mode.

In this model, the current load (I) and purging interval (T_p) are considered as the two input variables, others, such as temperature, pressure and flow-rate are as fixed values. The structure of the developed model is shown in Fig. 1. The technique applied to develop dynamic model and to find out parameters of the semi-empirical model is by fitting the experimental data using the Curve Fitting Toolbox of MATLAB.

Under flow-through mode, the voltage undershoots and overshoots of fuel cell take place instantaneously accompanying the current step-down or step-up, respectively. Then the voltage slowly raised or dropped to reach steady performance after the initial fast transient process. That transient behaviour can be modelled by a logarithmic function, Eq. (2), which has been depicted in detail in Refs. [36,37,42]. The parameters of "a" and "b" in Eq. (2) are constants and "a" affects the magnitude of the initial transient shape of the function, while the "b" determines the start point of the function.

$$f = a \times \log(t + 1) + b \quad (2)$$

Due to the magnitudes of the undershoots and overshoots of voltage and the initial voltage after each current step change under different current loads, the current dependent coefficients ($f_{a\_j}(i)$, $f_{b\_j}(i)$) functions expressed in Eq. (3) are proposed to represent the dynamic behaviour of HT-PEMFC voltage under flow-through mode. The subscribed "j" in the coefficient functions, $f_{a\_j}(i)$ and $f_{b\_j}(i)$, represents the forward sweeping or backward sweeping (the hysteresis phenomenon). The polynomial functions, Eqs. (4)–(7), are proposed to describe that. The constants of Eqs. (4)–(7) will be obtained by fitting experimental data in Section 4 and shown in Table 1.

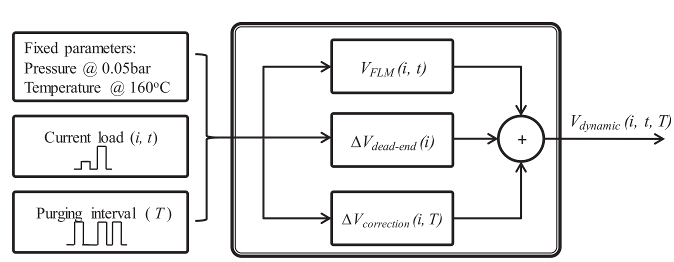

Fig. 1. Schematic of the model structure.