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Short communication

An impedance-based predictive control strategy for the state-of-health of PEM fuel cell stacks

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ABSTRACT

This work presents a control strategy for PEM fuel cell systems based on simultaneous impedance measurements on single cells. This control strategy distinguishes between flooding and drying of the cells in a stack and helps to run the stack at an optimal operating point. In the presented experiments, it has been found that impedance measurements can detect flooding phenomena in single cells minutes before they can be seen in related polarisation curves. It is shown that impedance measurements at two specific frequencies, one high and one low frequency impedance, are sufficient to predict voltage drops caused by flooding and drying. In flooding mode, the imaginary part of the low frequency impedance changes while the high frequency impedance remains stable and vice versa in drying mode. This technique reduces measuring time compared to the measurement of whole impedance spectra, without losing important information for the control of the system.

1. Introduction

Polymer electrolyte fuel cells represent a promising technology for portable power applications. Studies predict that portable applications will form the first mass market for commercial fuel cell systems due to the fact that high costs and low lifetime are accepted in favour of high energy densities [1,2]. In contrast to batteries, fuel cell systems need an actively controlled supply of reaction gases. Normally, they also need active heat management [3]. One of the most important problems in PEM fuel cell system control is the complex water management in the stack. In excess water conditions, water vapour in the cells can condense and block the gas transport in the electrodes, gas diffusion layers (GDL) and gas channels. Especially at high current densities, at the cells' maximum power point, it produces a large amount of water which blocks the gas channels. This can lead to unstable cell voltages [4–7]. PEM fuel cell stacks are often operated at a current density below their maximum power point to avoid flooding and to keep the voltages stable. At high voltage and temperature, the cell membranes tend to dry out and their protonic conductivity and mechanical stability decreases [8]. These different failure mechanisms cannot be distinguished in detail by polarisation curves.

Electrochemical Impedance Spectroscopy (EIS) is established as a powerful characterisation tool to detect different failure mechanisms occurring in a fuel cell. Impedance spectra can help to characterise a cell in a much more sophisticated manner than just analysing the polarisation curves. They allow separation between membrane conductivity, kinetic and mass transport limitations [9–12]. Several models exist to examine the current response of fuel cell electrodes and entire fuel cells [13–15]. Fouquet et al. [16] present a fitted impedance model to monitor the state-of-health (flooded, dry and nominal) of PEM stacks.

For the control of a PEM fuel cell system, the cell voltage is commonly used in addition to the stack temperature and the gas fluxes as the main input parameter. As described above, such control strategies often cannot differentiate between drying and flooding of the cell. Furthermore, a voltage drop can only be measured but not predicted, so the control algorithm has to react very rapidly to prevent conditions that lead to power loss or can cause damage to the fuel cell. Thus, model-based control strategies have been developed to acquire more information about the fuel cell conditions so that unfavourable conditions can be prevented and voltages drops can be avoided [17–19].

Mérida et al. [20] show that flooding and dehydration – the two extreme failure modes – can be distinguished by impedance measurements in different frequency bands. They present only impedance measurements of the whole stack and do not detect flooding of single cells. Le Canut et al. [21] present impedance spectra of one cell in a stack during drying and flooding operation.

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Hakenjos et al. [22,23] showed that impedance spectra can detect flooding of single cells in a stack minutes before the cell power decreases. He suggests this measurements to be used in a control strategy.

The present paper develops these approaches one step further by showing impedance measurements on single cells during operation in flooding and drying modes. It also describes how to reduce measuring time by measuring and analysing impedances only at specific frequencies. Finally, a control strategy that uses these measurements to operate a stack by preventing cell flooding and drying is presented and analysed.

2. Experimental

The measurements were carried out using a six-cell stack (described in detail by [24]) with graphite compound bipolar plates. Each cell has an active area of 30 cm^2. Cooling ribs are attached to the two endplates. A controllable fan cools these ribs evenly. The heat of the inner cells is conducted through the stack to reach the cooling ribs. Additionally, this stack contains a humidifying unit located between one of the endplates and the first cell. Thus, an asymmetrical temperature distribution inside the stack is expected. The stack temperature was measured with a Pt-100 resistance temperature device on the surface of the bipolar plate in the middle of the stack.

Large manifolds deliver the feed gases (hydrogen/air) to the single cells to obtain a homogeneous gas supply. On the anode side, hydrogen was fed with a maximum pressure of 200 mbar and recirculated with a pump in a closed loop. This loop can be opened in optional intervals by a purge valve to discharge water and residual gases. In the following, the interval between purge actions is defined as Δt_{purge}, the length of the purge action itself as t_{open}. The open cathode side was supplied with air under realistic humidity and temperature conditions (see Section 3.1). The nominal power output of this stack is 30 W at about 7 A.

For the EIS measurements, a multichannel test bench (described in detail by [22,25]) was used. Temperature and relative humidity of the inlet gases are controllable. Impedance spectra of up to 19 channels can be recorded by using a Solartron 1254 Frequency Response Analyser (FRA) and a Kepco BOP 20-20 M load. To measure the cell impedances, the stack was operated in galvanostatic mode and an ac signal of ±200 mA was impressed on the load current (7 A). This amplitude was chosen to obtain a linear answer of the system (voltage change of $< \pm 10$ mV). The FRA recorded the cell voltages and the ac current signal simultaneously and calculated the resulting impedances.

3. Results and discussion

The following sections describe the procedure from measurement of impedance spectra to stack control design based on impedance values at single frequencies. Firstly, impedance spectra during flooding events are measured. From these spectra, characteristic data are extracted that can predict voltage drops. Secondly, a control concept is presented that uses these values to control a PEM fuel cell stack and prevent voltage drops.

3.1. Impedance spectra during cell flooding

In the standard control approach for the fuel cell system described in [24], single cell voltages in the stack are monitored. In nominal operation, the air stoichiometry is set to a constant level that keeps the stack well humidified ($\lambda = 2.5$, based on empirical data). When one cell voltage drops caused by flooding, the cathode stoichiometry is set to a maximum value limited by the air pump power (λ = approximately 4 . . . 5) until the voltage drop has disappeared.

Table 1
Operating conditions during measurement

Stack temperature (T_{stack})	60 °C
Load current (I)	7 A
Dew point of air (τ_{air})	30 °C
Dew point of hydrogen (τ_{H_2})	−100 °C
Interval between purge time (Δt_{purge})	140 s
Purge time (purge valve open) (t_{open})	3 s
Stoichiometry of air (λ_{air})	2–4
AC amplitude for EIS (ΔI_{EIS})	200 mA
Measurement frequencies (f_{EIS})	75 mHz–1 kHz

The aim of our experiments described below is to operate the stack without this control and to observe what happens before and during these voltage drops. The operating conditions in the following measurements are listed in Table 1. Fig. 1 shows two typical voltage drops occurring in different cells due to cell flooding under the described operating conditions. The air stoichiometry is set to 3. After 233 min, it is decreased to 2 to provoke cell flooding. Immediately, all cell voltages begin to fall slightly, but only cell 6 voltage drops strongly. It reaches a minimum at 241 min. During the following minutes, the voltage rises again, but remains unstable. At 254 min, the air stoichiometry is reset from 2 to 3. After this increase, the voltage rises immediately, indicating that the higher air flux has removed the liquid water from the gas channels and a higher oxygen concentration is available on the catalyst layer.

Cell 5 shows a similar but later and even clearer voltage drop: after 245 min, the voltage begins to decrease significantly. It falls to nearly 0.1 V at 254 min and rises again after the stoichiometry increase, similarly to cell 6.

After the voltage drops, both cell voltages 5 and 6 jump to a higher value than at the beginning, as the cells still profit from their good membrane humidification that reduces protonic conductivity. In comparison, cell 4 shows a nearly constant characteristic during the entire period. This cell in the middle of the stack is not affected by flooding because it is slightly warmer than the outer cells.

In the shown period, impedance spectra of the cells were recorded (measuring 11 points between 75 mHz and 1 kHz). Figs. 2 and 3 display the impedances of cells 5 and 6 at different times during the flooding event (Z0 – Z20). In contrast to Mérida et al. [20], the impedance was measured every 2 min during the whole flooding period.

The impedance spectrum Z0 in Fig. 3(cell 6) still consists of nearly one arc, it represents a well-working cell without mass

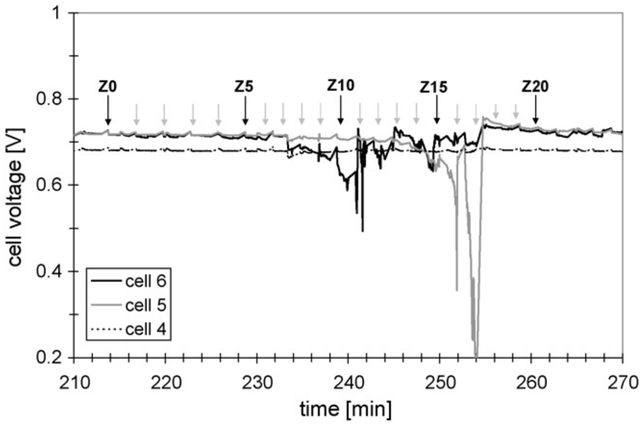

Fig. 1. Cell voltages of three cells during cell flooding events of cells 5 and 6.