A Novel Method for Parameter Identification of Fuel Cell Equivalent Circuit Model

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Abstract. In order to monitor the running state of fuel cell and prolong its service life, fault diagnosis technology has been widely researched. The fuel cell equivalent circuit model (ECM) can easily characterize the water content and membrane drying of the cells which has attracted the attention of scholars. Usually ECM is obtained by electrochemical impedance spectroscopy (EIS), and uses an electronic load for impedance excitation test, then achieves parameter identification through algorithms for fault diagnosis. This paper proposes a novel fuel cell ECM model parameter identification method by constructing a new combined network that the fuel cell ECM is included. It doesn’t require an electronic load to provide an excitation, meanwhile it relies on the DC/DC converter’s input voltage and inductor current, without voltage and current sensors on the fuel cell side. It uses the least square method to identify this new combined network’s parameter. This method reduces the cost of system components and achieves a good test performance.

1. Introduction
With the increasing shortage of fossil energy, hydrogen energy has received more research and application as a kind of renewable energy. Fuel cell is an efficient way to apply hydrogen energy which has advantages of no pollution, low noise and high specific power. It shows a good application prospect of replacing internal combustion engines [1].

For better promotion, the service life of fuel cells needs to be prolonged. In order to maintain the stable running of fuel cells, a lot of research has been done on fault diagnosis. Common faults such as flooding and membrane drying can be intuitively characterized by fuel cell ECM [2]. Fuel cell ECM identifications generally rely on the EIS test [3], which creates excitation on the fuel cell by electronic loads, causing stack current and voltage disturbances. The excitation signal sweeps from low frequency to high frequency, and the electrochemical impedance spectrum of the fuel cell can be obtained at each frequency. Usually traditional method requires high equipment cost and time cost.

Some scholars choose the voltage reference signal of the DC/DC converter as an excitation injection entrance to realize disturbances of the fuel cell stack, and get rid of expensive detection equipments [4], such as electronic loads. Ordinarily EIS tests rely on fuel cell voltage and current signals, this paper proposes a new design that does not require fuel cell current sensors. By combining a part of components of the DC/DC converter and the fuel cell ECM into a new port network, we can use the input capacitor voltage and inductor current data of DC/DC converter to identify this port network’s parameter by nonlinear least square method. This method can ensure the recognition accuracy of ECM parameters while reducing system sensors.
2. Principle and design of EIS test system
Proton exchange membrane fuel cell (PEMFC) is a common type of fuel cell, it has soft output characteristics and achieves desired power output through a boost DC/DC converter [5]. This paper boosts the BALLARD company’s Nexa 1.2 kW PEMFC to a 110V DC bus through a BOOST converter, as shown in Figure 1. The converter works at a switching frequency of 20kHz and adopts a voltage and current double closed-loop control strategy. In addition, boost inductor $L=1500\mu\text{H}$, input filter capacitor $C_{\text{in}}=4.7\mu\text{F}$, output capacitor $C=330\mu\text{F}$. The excitation signal of fuel cell’s voltage and current within the range of 0.05-2000 Hz, injects into the reference signals of the DC/DC converter, causes ripples on the fuel cell working circuit for obtaining impedance information at various frequency points. In order to stable fuel cell’s running status, we adjust the amplitude of the excitation signal to make the ripples of the current signal within 5%.

3. Parameter identification method
3.1 Fuel cell ECM
As a single-chip cell’s voltage is about 1.1V, a fuel cell stack is closely stacked with tens of single-chip cells, so it is difficult to directly obtain the health status of the fuel cell through technical ways [6]. When we desire to know the water content of fuel cells, it is often indirectly characterized by the equivalent circuit model ECM.

The most common ECM model is the Randles model [7], which can characterize the difficulty of proton and electron transport in the fuel cell electrode. It is composed of a charge transfer resistance $R_{\text{ct}}$, a double-layer capacitance $C_{\text{dl}}$, and a resistance $R_{\text{el}}$ of the electrolyte.

Figure 2. ECM of Nexa 1.2 kW PEMFC.
This article uses BALLARD company's Nexa 1.2 kW PEMFC. The output current range is 0 to 46A. The output voltage is 26V at full-load, and 43V at no-load. When the output current > 5A, the ECM model is shown in Figure 2 [8], consisting of a ohm resistance \( R_{\text{ohm}} \), a Warburg element that characterizes the mass transfer impedance of the reactant and a low-frequency induction effect inductance \( L \), a double-layer capacitance \( C_{\text{dl,A}} \) and a charge transfer resistance \( R_{\text{ct,A}} \) of the anode, a double-layer capacitance \( C_{\text{dl,C}} \) and a charge transfer resistance \( R_{\text{ct,C}} \) of the cathode. The values of the equivalent current parameters are listed in Table 1.

### Table 1. The parameters of ECM.

| Parameter                                      | Value |
|-----------------------------------------------|-------|
| Ohm resistance \( R_{\text{ohm}} \)/mΩ        | 35.8  |
| Anode charge transfer resistance \( R_{\text{ct,A}} \)/mΩ | 36.6  |
| Anode double layer capacitor \( C_{\text{dl,A}} \)/mF | 25.66 |
| Cathode charge transfer resistance \( R_{\text{ct,C}} \)/mΩ | 133.9 |
| Cathode double layer capacitor \( C_{\text{dl,C}} \)/mF | 97.38 |
| Mass transfer impedance Warburg element equivalent capacitance \( C_w \)/F | 1.014 |
| Mass transfer impedance Warburg element equivalent resistance \( R_w \)/mΩ | 170.61 |
| Low-frequency induction effect inductance \( L \)/mH | 79    |

The fuel cell ECM impedance formula is as follows:

\[
Z_{\text{ECM}} = R_{\text{ohm}} + \frac{R_{\text{ct,A}}}{1 + j\omega R_{\text{ct,A}} C_{\text{dl,A}}} + \frac{R_{\text{ct,C}}}{1 + j\omega R_{\text{ct,C}} C_{\text{dl,C}}} + \frac{R_w L_w}{R_w + L_w + j\omega R_w L_w C_w} \tag{1}
\]

Where the angular frequency

\[
\omega = \frac{f}{2\pi} \tag{2}
\]

#### 3.2 Port equivalent circuit

When using the DC/DC converter input capacitor voltage and inductor current signals for parameter identification, the fuel cell ECM and the DC/DC converter front-end circuit should be combined into a new port network, as shown in Figure 3.

![Figure 3. Diagram of Port Network.](image)

When focusing on the impedance information, the ECM’s voltage source should be regarded as a short circuit state, as shown in Figure 4. Without a fuel cell stack current sensor, the input capacitor voltage and the inductor current of the DC/DC circuit can also effectively identify the parameters of the port equivalent circuit containing the fuel cell ECM.
The overall equivalent impedance formula is as follows:

\[ Z = \frac{Z_{ECM}}{1 + j \omega C_{in} Z_{ECM}} \]  

(3)

\( Z_{ECM} \) is the impedance of the stack ECM, and \( C_{in} \) is the input filter capacitor parameter. Since the input filter capacitor \( C_{in} \) is a known parameter determined by design, the number of parameters that need to be identified is not increased.

Suppose the fuel cell ECM parameter identification object is an array containing eight unknown parameters \( h_m, \omega_c, \alpha, \beta, R_C, \omega_L \). When inputting the corresponding excitation frequency \( f_k \) (the angular frequency \( \omega_k \)), the ideal impedance of the fuel cell ECM is as follows:

\[ Z_{ECM}(\omega_k, c) = R_{hm} + \frac{R_{ct,A}}{1 + j \omega_k R_{ct,A} C_{dl,A}} + \frac{R_{ct,C}}{1 + j \omega_k R_{ct,C} C_{dl,C}} + \frac{R_w L_w}{R_w + \omega_L + j \omega_k R_w L_w C_w} \]  

(4)

3.3 Identification of nonlinear least squares

This paper uses the nonlinear least squares algorithm for parameter identification. Through the FFT analysis of the input capacitor voltage \( U_{cin} \) and inductor current \( I_l \) of the DC/DC converter, the ripple components of \( U_{cin,k} \) and \( I_{l,k} \) at the excitation frequency \( f_k \) can be obtained, which are used to calculate the actual impedance \( Z_k \) of the port equivalent circuit. The amplitude and phase angle are as follows:

\[ |Z_k| = \left| \frac{U_{cin,k}}{I_{l,k}} \right| \]  

(5)

\[ \angle Z_k = \angle U_{cin,k} - \angle I_{l,k} \]  

(6)

The basic idea of nonlinear least squares fitting [5] is based on minimizing the sum of errors’ squares. Since the impedance is a complex number, the real part and the imaginary part need to be considered separately. We can set the objective function (also called loss function) of the actual impedance and the ideal impedance for parameter identification as:

\[ F(\omega) = \sum_{i=1}^{n} (Z_{ECM,RE}(\omega_k,c) - Z'_{k,RE})^2 + \sum_{i=1}^{n} (Z_{ECM,IM}(\omega_k,c) - Z'_{k,IM})^2 \]  

(7)

The smaller the objective function, the more accurate the parameter identification. This paper adopts an iterative algorithm, which requires us to start from an initial value of the identification parameter and continuously iterative for optimization, at last the objective function can obtain a minimum value.

The Levenberg-Marquardt algorithm is a widely used nonlinear least squares algorithm currently. It is improved on the Gauss-Newton method and has the advantages of both the gradient method and the Gauss-Newton method. This paper uses the Levenberg-Marquardt method [5] to find the parameter array that minimizes the value of the objective function.

We set the objective function as:

\[ F(x) = \sum_{i=1}^{m} J_f(x) \]  

(8)

\( J_f(x) \) is the Jacobian matrix of \( f(x) \). In the Gauss-Newton method, we expand \( F(x) \) by Taylor formula,
a second-order approximate expression of the objective function is obtained

\[ F(x + h) \approx L(h) = F(x) + G_F h + \frac{1}{2} h^T H_F h \]  

(9)

\( G_F \) is the gradient of \( F(x) \),

\[ G_F = \frac{dF}{dx} = J_f^T(x)f(x) \]  

(10)

\( H_F \) is the Hessian matrix which can be approximated by \( 2J_f^T(x)J_f(x) \). When \( x = x_k \), mark \( L(h) \) as \( L_k(h) \). If \( L_k(h) \) needs to get the minimum value, we need \( L_k(h) = 0 \). That is

\[ \left[ J_f^T(x_k)J_f(x_k) \right] h_k = -G_F(x_k) = -J_f^T(x_k)f(x) \]  

(11)

In order to prevent the iterative matrix from being singular and failing, the Levenberg-Marquardt method adds a damping coefficient greater than zero to the diagonal elements of the matrix, as follows

\[ \left[ J_f^T(x_k)J_f(x_k) + \mu I \right] h_k = -G_F(x_k) = -J_f^T(x_k)f(x) \]  

(12)

When the value of \( \mu \) is large enough, it can always make \( \left[ J_f^T(x_k)J_f(x_k) + \mu I \right] \) positive definite.

4. Experiment

This paper runs the designed modeling simulation in MATLAB/SIMULINK, and then relies on the NIPXie-1071 hardware-in-the-loop test system for experimental verification. The host computer program of the hardware-in-the-loop test system uses Shanghai Yuankuan Starsim HIL. This paper uses TMS320F28335 DSP for control, and uses Code Composer Studio to debug and load the control program. The experimental platform is shown in Figure 5.

![Figure 5. Hardware in the loop experiment.](image)

We use DSP controller to select 30 discrete frequency points as excitation signals from 0.05-2000Hz, and apply disturbances to the chassis model. Under the excitation of each frequency, FFT analysis is performed on the input capacitor voltage and inductor current signal of the DC/DC converter circuit to obtain a complete impedance spectrum composed of impedance at each frequency.

The experimental input capacitor voltage and inductor current’s oscilloscope waveforms are shown in Figure 6, their amplitude from HIL output has been shrunk ten times.
Figure 6. Oscilloscope waveform (At 1Hz disturbance).

Use impedance spectrum data and nonlinear least square method to identify ECM parameters. The result is listed in Table 2.

Table 2. The parameters of ECM.

| Parameter                                    | Identification result | Relative error |
|----------------------------------------------|-----------------------|----------------|
| Ohm resistance $R_{ohm}$/mΩ                 | 35.678                | 0.34%          |
| Anode charge transfer resistance $R_{ct,A}$/mΩ | 35.89                 | 1.94%          |
| Anode double layer capacitor $C_{dl,a}$/mF   | 25.482                | 0.69%          |
| Cathode charge transfer resistance $R_{ct,C}$/mΩ | 141.86               | 5.94%          |
| Cathode double layer capacitor $C_{dl,c}$/mF | 95.701                | 1.72%          |
| Mass transfer impedance Warburg element     |                       |                |
| equivalent capacitance $C_w$/F              | 1.056                 | 4.14%          |
| Mass transfer impedance Warburg element     |                       |                |
| equivalent resistance $R_w$/mΩ              | 170.02                | 0.35%          |
| Low-frequency induction effect inductance    |                       |                |
| $L$/mH                                       | 81.551                | 3.23%          |

The impedance spectrum (discrete points) obtained in the experiment and the fitted impedance spectrum (curve) by the ECM parameter identification are illustrated in Figure 7.

Figure 7. Experimental and fitted electrochemical impedance spectra.

Then, we calculate the error index of the ECM parameter identification: the Mean Absolute Percentage Error (MAPE) relative to the theoretical value and the coefficient of determination to measure the goodness of fit (R-Square).

$$MAPE = \frac{1}{N} \sum_{n=1}^{N} \left| \frac{\hat{y}_n - y_n}{y_n} \right| \times 100\%$$ (13)
\[ R - \text{Square} = 1 - \frac{\sum_{i=1}^{N} (\hat{y}_i - y_i)^2}{\sum_{i=1}^{N} (y_i - \bar{y})^2} \] (14)

The error results are shown in Table 3:

| Index         | Number value |
|---------------|--------------|
| MAPE          | 2.295%       |
| R-Square      | 0.9976       |

The MAPE is 2.295% and the R-Square is 0.9976, which shows a good test effect.

5. Conclusion

In this paper, a port network containing fuel cell ECM is constructed based on fuel cell system, meanwhile a method for identifying the ECM parameters by using the input capacitance voltage and inductance current signals of DC/DC converter is proposed. The system simulation has been constructed in MATLAB/SIMULINK, and the hardware-in-the-loop system (HIL) is used for verification. It shows that this method has a good identification of ECM Parameters. This paper also provides an approach for reducing the use of sensors in fuel cell diagnosis system, which delivers an enlightening idea for scholars and further research.

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