INTRODUCTION

Many scientists are currently seeking to identify alternatives to internal combustion engines with the hope that these alternatives can positively impact the environment.\(^1-3\) The PEMFC has become an important research topic because it exhibits a higher efficiency (approximately 60%) than internal combustion engines. In theory, the open circuit voltage (OCV) of a single fuel cell can reach 1.229 V.\(^4,5\) However, due to energy loss during the electrochemical reactions of the anode and cathode sides, the OCV of a single cell is approximately 1.0 V. The polarization phenomena mainly include activation, ohmic and concentration difference polarizations. The efficiency of a PEMFC is easier to control by operating within the ohmic polarization region, where the resistance of the fuel cell is considered the ohmic resistance. For every single PEM, the internal resistance of the fuel cell mainly includes the bulk resistance of the components and the contact...
The structure of a single proton exchange membrane fuel cell is shown in Figure 1. The fuel cell ohmic impedance is mainly composed of the electronic conduction resistance and the proton conduction resistance. The resistance of the catalyst layer and the PEM are considered the proton conduction resistance. The resistance of the other parts and the contact resistance among the parts are considered the electronic conduction resistance because of the electron conduction. The proton conduction resistance is the main part of the operational resistance. As the technology improves, the contact resistance cannot be considered. The resistance of the bipolar plate and the GDL can also be neglected because they are smaller. However, it is still more difficult to directly measure the internal resistance of a fuel cell.

The established research methods to monitor the ohmic resistance of the fuel cell include the current interruption method, electrochemical impedance spectroscopy (EIS) and alternating current (AC) frequency, and variable amplitude method. Tuomas et al.\textsuperscript{5} adopted the current interruption method to investigate the PEMFC internal resistance. They performed experiments to interrupt the current and observe every transient voltage of the single fuel cell. By comparing the different current densities and two types of air supply methods, the researchers concluded that the current interrupting method and a digital oscilloscope, which shows the voltage curves of the fuel cell, enabled the separation of the ohmic polarization from three voltage losses. Moreover, free convection may affect the conductivity by maintaining the ability of the PEM to transform protons. Rui and his team studied an online monitoring system of the PEMFC resistance using EIS.\textsuperscript{6} In the experiments, they combined an AC power source with a stack. The results show that it is useful to estimate the PEMFC internal operating resistance.

The data of every single-cell voltage can be obtained, and the resistance of the entire fuel cell is solved by the online measuring system. Qihong et al.\textsuperscript{7} utilized the AC frequency and variable amplitude method to measure a PEMFC internal resistance. This method and EIS are identical because the high frequency AC perturbation signals are used to collect the AC voltage and AC current data in two methods. Using the acquired data, the researchers calculated the ohmic impedance of fuel cell based on Ohms law. However, there are clear disadvantages to these three methods. The impedance of the PEMFC cannot be constantly monitored using the current interruption method. With this measuring method, the accuracy of capturing the voltage and current is unsatisfactory, especially in high current density conditions. The PEMFC internal ohmic resistance can be obtained in real time using the current interruption method. The PEMFC internal ohmic resistance can be measured in real time utilizing the EIS method and AC frequency and variable amplitude method. However, these two methods are more appropriate for the single fuel cells or a small stack. In addition, the complexity of the fuel cell testing system will increase if either of the latter two methods is used to estimate the fuel cell resistance. The latter two methods are obviously not very appropriate to predict and calculate the internal ohmic resistance of higher-power PEMFC. Kalman filter method is a better algorithm to estimate some important parameters indirectly measured. Those optimal algorithms (extended Kalman filter, double Kalman filter, etc.) based upon the Kalman filter are also suitable to obtain these parameters and for real-time system.\textsuperscript{8,9} But there are some disadvantages about the application of Kalman filter method. The main point is that the Kalman filter method is only suitable to predict one parameter. This disadvantage can be avoided by using the DKF method. The complexity of the PEMFC system structure does not be increased when these algorithms are used. The fuel cell can also be simplified as the equivalent circuit model by setting the output current density in the ohmic polarization region. This equivalent model has an extremely high linear output, which is more suitable to adopt the double Kalman filter.
(DKF) algorithm to estimate the PEMFC internal resistance. This optimal algorithm is more beneficial to obtain accurate data than the traditional Kalman filter algorithm.

In this research, the ohmic impedance of a fuel cell can be investigated by employing the DKF method and setting the ohmic region. The estimation model of PEMFC ohmic internal resistance is built based on the PEMFC equivalent model. The PEMFC can be assumed an equivalent model by setting the output current density at the ohmic region. First, the polarization curve of single cell should be obtained. Second, the estimation model is added into the fuel cell control unit (FCU). The feasibility of the ohmic resistance prediction model is verified by simulating two different working conditions in the experimental test bench. In the progress of simulating working conditions, the internal ohmic resistance is estimated and stored. The PEMFC output voltage is also monitored and compared with the simulation output voltage using MATLAB/Simulink to verify the feasibility of this designed algorithm. The experimental results show that it is more useful to estimate the PEMFC internal resistance using the designed algorithm. This research can extend the methods of measuring and exploring the PEMFC operation progress.

1.1 | Polarization curves

The relationship between the output voltage and the current density is extremely nonlinear.\textsuperscript{10,11} The single fuel cell output voltage can be expressed as:

\[ U = E - b \log(I) - m \exp(nI) - R_Ω I \]  

(1)

where \( E \) is the ideal OCV of the single fuel cell, \( I \) is the output current of the single fuel cell, \( b \) is the Tafel slope, \( m \) and \( n \) are the correctional coefficients, and \( R_Ω \) is the ohmic resistance of a single fuel cell.

**TABLE 1** Main PEMFC system operating parameters in the experimental process

| Parameter                                | Unit   | Value/numerical range |
|------------------------------------------|--------|-----------------------|
| Hydrogen stoichiometry                   | -      | 1.5                   |
| Hydrogen flow rate                       | g/s    | 0.16-0.76             |
| Hydrogen input pressure (relative pressure) | psi    | 16.15-20.50           |
| Air stoichiometry                        | -      | 2                     |
| Air flow rate (standard condition)       | g/s    | 6.85-34.27            |
| Air input pressure (relative pressure)   | psi    | 15.42-18.18           |
| Air humidity                             | %      | 95                    |
| Coolant temperature                      | °C     | 46-73                 |

**FIGURE 2** The single fuel cell polarization curve
The PEMFC polarization curve should be obtained to identify ohmic region. The output voltage of a single fuel cell is obtained by using the cell voltage monitor (CVM) system and setting many different output current densities. By operating the PEMFC in the experiment test bench, the final polarization curve of the single cell is determined. The operational parameters are shown in Table 1. A single-cell polarization curve is shown in Figure 2.

1.2 Equivalent circuit model

Most scientists assume that every single cell works in the ohmic area because the relationship between the output voltage and the output current density is approximately linear, and the entire output voltage of fuel cell can be more easily controlled. The demand power cannot be adequately satisfied if the fuel cell works in the activation polarization region. The output voltage should be lower than the voltage shown in Figure 2 in the activation area because the single-cell voltage should also be maintained within 0.8 V in the idle condition. Additionally, the fuel cell operation becomes dangerous due to the sharp drop in output voltage in the concentration difference region. Therefore, it is more reasonable to make the PEMFC work in the ohmic polarization region. Figure 3 shows an equivalent circuit model to depict the output characteristics of a fuel cell that works in the linear area. This model is called Randles equivalent circuit model.\textsuperscript{12-14}

In this model, $R_p$ is the sum of the activation impedance and concentration difference resistance, $C_p$ is the porous characteristics of the anode electrode, $R_\Omega$ is the ohmic impedance of the single cell, and $U$ is the output voltage of the single cell.\textsuperscript{15-17} The PEMFC equivalent circuit model is very suitable for the linear system. What’s more, the output performance of the PEMFC is approximately linear during operating the ohmic region. Therefore, the output performance of every single cell can be expressed by this equivalent circuit when the output current density is controlled in the ohmic area. The key point is the setting of the PEMFC output current density. The activation and concentration resistance, which are assumed to further illustrate the polarization of the fuel cell, do not exist. Additionally, a close relationship between the ohmic impedance and PEM moisture is analyzed.

1.3 DKF structure

The DKF method is a more convenient method to estimate some parameters that cannot be directly measured by utilizing both measured data and finite data. The adoption of this method can provide an understanding of the fuel cell real-time operation status. In addition, the concept of state space is added to the random estimation theory in the DKF method. Because the collection of the fuel cell system parameters is discrete, this property can be applied in the DKF method. The structure of the DKF method is depicted in Figure 4. There are two main contents about the processes of estimating internal resistance using the DKF algorithm. First, the voltage of $C_p$ will be estimated based on the state equations of equivalent circuit model. Second, the fuel cell internal impedance will be estimated based on this estimating voltage.

In the DKF method, the state transition equation and predictive equation can be taken advantage of to eliminate the white noise and optimize the parameter estimations. In addition, it is important to discretize the state equation to accomplish the recursion equations. There is one more estimation process compared with the usual Kalman filter method.

1.4 DKF algorithm

Generally, the discrete state transition equation of a dynamic system is like

$$X(i+1) = \Phi X(i) + \Theta Z(i) + \Gamma W(i)$$  \hspace{1cm} (2)

$$Y(i) = H X(i) + V(i)$$  \hspace{1cm} (3)

where $i$ is the iterative sequence number, $X$ is the state variable, $Y$ is the observed variable, $\Phi$ is the state transition matrix, $\Gamma$ is the noise driving matrix, $H$ is the observed matrix, $W$ is the white noise of the input, $V$ is the observed white noise, $\Theta$ is the control transition matrix, and $Z$ is the external control variable.

Assuming that the two kinds of white noise are uncorrelated random signals with a zero mean, the formula can be written as

$$E[W(n) W(n)^T] = \begin{cases} Q, & n = i \\ 0, & n \neq i \end{cases}, \quad E[V(n) V(n)^T] = \begin{cases} Q_1, & n = i \\ 0, & n \neq i \end{cases}$$  \hspace{1cm} (4)

where $E[\bullet]$ is the mean value, $Q$ is the variance in the input with noise, and $Q_1$ is the variance in the observed white noise.
There are five steps in the optimal estimation process if the measured system is linear. Step (i) entails the progress of the prior estimate about the state variable:

\[ X_p(i) = X_n(i-1) \Phi + Z(i) \Theta \]  

where \( X_p \) is the predicted random variable and \( X_n \) is the optimal random variable. In step (ii), the optimal estimate can be calculated by the following equation:

\[ X_n(i) = X_p(i) + K(i) \left[ Y(i) - H X_p(i) \right] \]  

where \( K \) is the weighting variable to observe the optimal estimation, which is a very important parameter in the Kalman filter method. In steps (iii) and (iv), the \( K \) parameter can be expressed as Equations (7) and (8):

\[ P_p(i) = \Phi P_n(i-1) + \Gamma Q \Gamma^T \]  

where \( P_{now} \) and \( P_{pre} \) are the predicted covariance matrix and the optimal covariance matrix, respectively, for the estimate error.

\[ K(i) = P_p(i) H^T \left[ H P_p(i) H^T + Q \right]^{-1} \]  

In step (v), the optimized covariance matrix is given by

\[ P_n(i) = P_p(i) \left[ I_1 - H K(i) \right] \]  

where \( I_1 \) is the identity matrix.

The PEMFC can be considered a linear system, as shown in Figure 3, if the fuel cell works in the ohmic area. Therefore, the state equations of the equivalent circuit are determined by

\[ du_p/dt = -C_p^{-1} R_p^{-1} u_p + C_p^{-1} I \]  

\[ U_0 = -u_p - I R_\Omega + U_{OCV} \]  

where \( u_p, C_p, R_p, \) and \( I \) are the voltage between the two ends of \( C_p \), the capacitance value, the impedance value of \( R_p \), and the output current density of the stack, respectively. Additionally, \( U_r, R_\Omega, \) and \( U_{OCV} \) are the output voltage of the fuel cell, ohmic resistance of the fuel cell and the OCV of the fuel cell, respectively. In the next step, it is necessary to discretize the equivalent circuit state equations. The discrete equations can be written as

\[ u_p(i + 1) = A u_p(i) + B I(i) + W(i) \]  

\[ U_0(i) = -u_p(i) - I(i) R_\Omega(i) + U_{OCV}(i) + V(i) \]

where

\[ A = \exp \left( -T_0 R_p^{-1} C_p^{-1} \right) \]

\[ B = R_p (1 - A) \]

In these equations, \( T_0 \) is the sampling instant.

First, the computational process for one part of the internal voltage of the fuel cell can be expressed as

\[ u_p(i) = A u_p(i - 1) + B I(i) \]  

\[ P_p(i) = A P_n(i - 1) A^T + Q_p \]  

\[ K_p(i) = P_p(i) H_p \left[ H_p P_p(i) H_p^T + D_u \right] \]

\[ u_n(i) = u_p(i) + K_p(i) \left[ U_0(i) + u_p(i) + R_\Omega(i) I(i) - U_{OCV}(i) \right] \]

\[ P_n(i) = P_p(i) \left[ 1 - K_p(i) H_p \right] \]

where

\[ H_p = -1 \]

In these relations, \( u_p, P_n \), and \( K_p \) are the predicted values of the voltage between the two ends of \( C_p \), predicted covariance variable and the DKF weighting, respectively. \( Q_p \) and \( D_u \) are the state variance and measured variance, respectively. \( u_p \) is the optimal estimation of the voltage of \( C_p \). \( P_n \) is the optimized covariance. Thus, the optimal estimation of \( u_p \) can be accomplished by the Equations (16)-(20). Then, the following recursion equations can be applied to estimate the internal ohmic impedance of the fuel cell:

\[ R_\Omega(i) = R_\Omega(i - 1) \]  

\[ P_\Omega(i) = P_\Omega(i - 1) + Q_\Omega \]

\[ K_\Omega(i) = P_\Omega(i) H_\Omega(i) \left[ H_\Omega(i) P_\Omega(i) H_\Omega^T(i) + D_\Omega \right] \]
From these recursive equations, two variables are obtained within a sampling period in this algorithm. The estimation process includes forecasting the state variable of the next moment by utilizing the optimal estimate of the last moment and optimizing the prediction variable. In this PEMFC ohmic internal resistance prediction model, $R_p$ and $C_p$ are 0.001 and 200, respectively, based on the PEMFC parameters manual. At the same time, the PEMFC output
performance is approximately linear. The value of $C_p$ is considered the stable parameter. The values of $Q_p$ and $D_u$ are 0.5 and 2, respectively. The values of $Q_D$ and $D_D$ are 1 and 2, respectively.

2 | EXPERIMENTAL

2.1 | PEMFC system

In this study, a PEMFC system is constructed in the laboratory to simulate the PEMFC working conditions in an actual fuel cell vehicle. The FCU, including the fuel cell ohmic resistance estimation part, is independently studied. The structure of the PEMFC system is illustrated in Figure 5A.

This stack is a series of 240 membrane electrode assemblies that comprises 50-μm Nafion 112 membranes. The commercial stack is shown in Figure 5B and was made by Elring Klinger (E. K) company. The rated output power is 60 kW. The core of the air supply was a centrifugal air compressor with a rated power of 5 kW. The operation of the water pump involved self-suction, and the rated power is 7.5 kW. The rated power of the hydrogen pump is 8 kW. The maximum pressure of hydrogen tank is 15 MPa (absolute pressure).

The data transferring mode employs a controller area network (CAN) bus. The received instructions for the working equipment from the FCU are also provided by the CAN bus. The up-level computer utilizes LabVIEW to display the main parameters and enable interaction with the FCU via a CAN converter. A boost DC converter is the linking device between the fuel cell output terminals and the load. Because of the polarization characteristics of the fuel cell, the PEMFC output voltage decreases with an increase in output current density. The poor energy management of the electric automobile can be adequately improved by adding the DC converter. The output voltage range of DC converter is 10-420 V. This converter boosts the voltage of the fuel cell to the set point and maintains this voltage in a small wave range. In this study, the PEMFC output voltage and current density is logged with the DC equipment. The messages from the DC converter can be simultaneously transmitted by the CAN network. By simulating the working conditions in this experimental bench, the PEMFC internal resistance was obtained. This progress can validate the feasibility of the stack and verify the proposed DKF method, early experimental procedures should be performed as follows:

A PEMFC system is a multiple-input, multiple-output, and time-varied system. The fuel cell system should be operated in stable conditions to obtain appropriate monitoring data. Thus, it is important to ensure that the main parameters are in the usual range, such as air mass flow and hydrogen mass flow. Moreover, the Urban Dynamometer Driving Schedule (UDDS) and Federal Test Procedure (FTP) working conditions are adopted to simulate the power demand of an actual automobile and collect the output voltage and current density. Based on the two simulation conditions, the fuel cell automobile speed should be converted to the fuel cell output power by using the related electric motor parameters and standard tire parameters. The fuel cell output power is calculated by Equations (28) and (29). According to the calculated fuel cell output power, it is important to set the PEMFC output current density and simulate the actual working conditions of a PEMFC.

$$u_a = 0.337 \times (n \times r_0) \times (i_g \times i_0)^{-1}$$ \hspace{1cm} (28)

where $u_a$ is the automobile speed, $n$ is the motor speed, $r_0$ is the static loaded tire radius, and $i_g$ and $i_0$ are the transmission rear and the final driver ratio, respectively.

$$P_F = \eta_f^{-1} \left( mgf/ua + CA_Dua^3/21.15 \right)/3600$$ \hspace{1cm} (29)

where $P_F$ is the fuel cell output power, $m$ is the PEMFC automobile simulation mass, $g$, $A_D$, and $f$ are the rolling resistance coefficient, gravity acceleration, and windward area, respectively. $C$ is the wind resistance coefficient. $\eta_f$ is the PEMFC automobile simulation transmission coefficient.

In the next step, the monitor data are transferred to the FCU, and the fuel cell ohmic resistance is calculated by the designed algorithm based on the DKF. To verify the feasibility of this method, the output voltage of the fuel cell is calculated utilizing the estimated resistance. The error between the calculation and the experimental measurement is compared and is critical to this research. The monitor parameters can reflect the operating performance of the PEMFC. Controlling the parameters will guarantee that the fuel cell system works smoothly. The values and numerical ranges of the parameters are shown in Table 1.

The experimental procedures are described as follows: (i) The first progress of this experiment is the fuel cell system starting. The stack should be allowed to reach a stable operating condition, especially regarding the temperature, and
FIGURE 6  (A) Changes in fuel cell output current density in the UDDS conditions. (B) Changes in ohmic internal resistance of the fuel cell in the UDDS conditions. (C) Curves of the ohmic resistance of the fuel cell ohmic resistance and the output current density of the fuel cell in the UDDS conditions. (D) Partial enlargement of the curves for the ohmic resistance and output current density of the fuel cell in the UDDS conditions.
each current density level can be set. (ii) The power demands are transmitted to the FCU from the upper computer. After receiving the instructions, many operating parameters are regulated by the FCU to satisfy the power demands. (iii) In the process of simulating two working conditions, the fuel cell output current density and voltage are monitored by Hall sensors and transferred to the FCU. The fuel cell ohmic resistance is estimated by the designed module based on the DKF method. The fuel cell ohmic resistance will be saved by LabVIEW. The fuel cell simulation voltage is calculated and compared using MATLAB/Simulink based on the estimating fuel cell ohmic impedance.

3 | RESULTS AND DISCUSSION

Using the DKF method to estimate the ohmic impedance, it is necessary to set the initial values of some parameters, such as the fuel cell OCV and the internal ohmic resistance of the fuel cell. When there is no output current density from the PEMFC, $U_{OCV}$ appears to be the value of the intersection between the $y$-axis and the extended line of the ohmic polarization curve in Figure 2. Due to no power generation, the value of $I_x$ is 0. The initial ohmic impedance can also be calculated by the ohmic polarization curve of the fuel cell, which is the slope of the polarization curve.

With the UDDS conditions, the curve of the PEMFC working current density is shown in Figure 6A. The rate of current density change is 0.1 A cm$^{-2}$ per second, and the change in current density is 0.2-1 A cm$^{-2}$. The aim is to study the ohmic region resistance. Meanwhile, limiting the range of output current density is beneficial for the fuel cell performance because it is easier to obtain a high operating performance of the PEMFC. In this polarization region, the change in PEMFC output performance is more stable. The initial current in this experiment is 0.505 A cm$^{-2}$.

The calculated ohmic resistance is depicted in Figure 6B. The ohmic impedance ranges from 0.336 to 0.402 $\Omega$ within the normal range. At the same time, the variation range is smaller. According to the figure, the varying frequency of the estimated resistance is very high, which can illustrate the PEMFC operating dynamic characteristics. In this figure, the PEMFC ohmic resistance is not stable because the supply of hydrogen and oxygen is not relatively stable. The pressure and flow rate of reactants are always fluctuating. The PEMFC output and operation performance are changing. However, the variation range of ohmic resistance decreases.

Figure 6C shows the relationship between the output current density and the ohmic impedance of the fuel cell. This figure reveals that the ohmic resistance decreases when the fuel cell current increases. Figure 6D shows enlarged curves of the partially simulated working conditions. When the output current density changes, the change in ohmic resistance exhibits hysteresis. The small change in output current density causes a sharp fluctuation in the internal resistance. The reasons for this phenomenon can be obtained by analyzing the chemical reactions follows:

(i). When the current increases, the required reactants must be increasingly fed to satisfy the operating conditions of the PEMFC. Because of the large amounts of hydrogen and oxygen, a considerable amount of water is generated on the cathode side according to Equation (30). In addition, water permeation is observed from the cathode to the anode due to the difference in water concentration. Thus, the amount of moisture in the PEM will increase, which can increase membrane conduction. A proton can be successfully transferred from the anode side to the cathode side, and the ohmic resistance of the fuel cell can be determined by the amount of moisture in the PEM:

\[
m_{\text{water}} = 9.34 \times 10^{-5} N_{\text{cells}} I_d A_a \tag{30}
\]

\[
R_{\Omega} = m_{\text{water}} \times L_{\text{PEM}} \tag{31}
\]

where $N_{\text{cells}}$ is the number of single cells, $m_{\text{water}}$ is the generation rate of water in the cathode (g/s), $I_d$ is the PEMFC output current density, $A_a$ is the PEMFC active area, and $L_{\text{PEM}}$ is the proton exchange membrane thickness.

(ii). When the fuel cell is operated in low current density conditions, both the water generation and the internal temperature are lower than those in high current density conditions. The internal reactant rate is also relatively slow which caused the difficulty of the proton transfer. The PEMFC estimated resistance increases.

The use of the DKF method to obtain the ohmic impedance can reduce the effect of noise and enhance the designed accuracy. Therefore, in the iteration process, the setting of the state variable and measured variance variable has a relative role in the estimation. Compared to the measured variance, the state variance value has a larger effect on this algorithm. If the state variance is set to an excessively small value, the method cannot accurately reflect the actual working condition of the fuel cell. However, if this variable is set to an excessively large value,
large deviations in the fluctuation of ohmic impedance may occur. The range of measured variance is commonly 1-2. This range is based on the experimental system.

The experimental verification is accomplished by calculating the output voltage of the fuel cell based on the evaluated results. It is significant to compare the measured output voltages. Thus, the relative error can be obtained from Equation (32).

\[
\varepsilon = \left| U_{\text{ver}} - U_m \right| \times U_m^{-1} \times 100\% \quad (32)
\]

In this relation, \( U_{\text{ver}} \) and \( U_m \) are the simulation and experimentally measured voltages, respectively.

The calculated output voltage of the fuel cell and the experimentally measured voltage of the fuel cell are depicted in Figure 7A.

**FIGURE 7** (A) Similarity of the experimentally measured output voltage of the fuel cell and the simulated voltage in the UDDS conditions. (B) Changes in relative error between the experimentally measured output voltage of the fuel cell and the simulated voltage in the UDDS conditions.
Figure 7A shows the correlation between the simulated value and the monitored values. From this figure, the similarity is very high, which illustrates the validity of the DKF method. Utilizing Equation (32), the relative error is shown in Figure 7B. The range of relative error is notably small, which indicates the feasibility of this algorithm. Furthermore, the deviation between the calculated and the experimentally measured voltages increases when there is a high current density output. If the wave range for the output current density and output voltage is stable, the relative error is low. However, in the step voltage process, the deviations become larger than their original values, and the relative error values of the first few iterations are also larger than their original values. The initial experiment error has been filtered because the initial input of designed algorithm is set the measured data.

The change in the output current density of the fuel cell in the simulation in the FTP working conditions is shown in Figure 8A.

In Figure 8A, the change in the output current density of the fuel cell is 0.2-1 A cm\(^{-2}\). The change rate of the current density is identical to the current change in the UDDS conditions. Figure 8B shows the change curve of the ohmic resistance of the fuel cell in the FTP conditions. The change in ohmic impedance is 0.340-0.406 Ω. Because of the variation in the ohmic impedance is different from the last condition. However, the ohmic internal resistance has very similar ranges for the two conditions, and the deviation between two estimated internal resistance values is lower.

Figure 8C shows the relationship between the output current density and the ohmic resistance of the fuel cell. As demonstrated in the previous analysis, the change in fuel cell current density strongly affects the ohmic resistance of the fuel cell. The ohmic resistance of the fuel cell decreases when the output current density of the fuel cell increases. The enlarged curves are shown in Figure 8D, which illustrates that a very large fluctuation exists in the ohmic impedance of the fuel cell when the output current density of the fuel cell quickly changes.

Figure 9 shows the simulation value of the output voltage of the fuel cell and the relative error between the experimentally measured output voltage of the fuel cell and the simulated value. Figure 9A shows the similarity between these two voltage values, which is very high.

4 | CONCLUSIONS

The PEMFC polarization characteristics and equivalent circuit model have been presented for the ohmic resistance estimation progress in this paper. The monitoring data are obtained by simulating the UDDS and FTP conditions in a custom-built platform. The PEMFC ohmic resistance is estimated using the proposed DKF mathematical algorithm. The feasibility of this method is verified by comparing the simulated voltage with the experimentally measured voltage. The following specific conclusions can be obtained:

(i). The experimental results show that it is useful to estimate the internal ohmic impedance by using the DKF method when the fuel cell is operated in the ohmic region. The designed DKF algorithm is appropriate for the indirectly measured parameters. It is also beneficial to avoid the measured and system noises. The frequent variation of PEMFC ohmic resistance cannot be reflected by the polarization curve alone. By employing this prediction model, the frequency of PEMFC resistance variation can be shown. The variation range of the ohmic resistance is smaller. However, the designed DKF algorithm is not suitable to estimate the internal resistance of the PEMFC when the PEMFC operates in the other polarization regions. One of the reasons is that the OCV is different when the PEMFC is operated in the other polarization regions. In addition, the equivalent circuit model of the PEMFC is not suitable. The estimated internal resistance of the PEMFC based on this internal resistance estimation model is not reliable.

(ii). Setting the PEMFC output current density range at approximately the normal fuel cell working periods, which can make the fuel cell internal resistance smaller than other regions, is beneficial to the fuel cell system operation performance and exploration of the fuel cell resistance. This method can be combined with a fuel cell control system to achieve the aim of monitoring the operational performance of a PEMFC in real time. In addition, the change in fuel cell current density has a large effect on the fuel cell resistance change. The ohmic resistance decreases when the fuel cell current density increases. According to estimating the fuel cell internal resistance, the key to obtaining better fuel cell operation performance is to set a well current density range. Additionally, the level of fuel cell internal resistance could give a reflection of the moisture in the PEM and could serve as the basis for adequately controlling the fuel cell operating process.

(iii). From the perspective of chemical reactions, the water contents of the PEM influence the internal resistance and operating performance of the fuel cell. Especially, the greater is the quantity of water that is generated in the larger current density region, the larger is the effect on the fuel cell resistance, which is smaller. In the step current or step voltage regions, the relative error is larger.

(iv). Regarding the expectations about the ohmic resistance estimation, there are many extended research contents
FIGURE 8  (A) Changes in output current density of the fuel cell in the FTP conditions. (B) Curves of the ohmic resistance of the fuel cell in the FTP conditions. (C) Curves of the ohmic resistance and the output current density of the fuel cell in the FTP conditions. (D) Partial enlargement of the curves for the ohmic resistance and output current density of the fuel cell in the FTP conditions.
about the PEMFC operation performance. In the future, the humidity of air can be adjusted in real time by calculating the moisture of PEM based on the estimating resistance. The experiment about the PEMFC thermal management can also be carried out based upon this ohmic resistance estimation algorithm.

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