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Fault Detection and Isolation of PEM Fuel Cell System by Analytical Redundancy

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Abstract—**This paper presents a procedure of fault detection and isolation of proton exchange membrane (PEM) fuel cell based on its mathematic model by analytical redundancy approach. The model is linearized into eight state equations representation. The transient phenomena captured in the model include the compressor dynamics, the flow characteristics, mass and energy conservation and manifold fluidic mechanics. Analytical redundancy relations (ARR) are generated and numerical simulation results are given. Major faults such as flooding, drying within fuel cells, and compressor over-voltage are detected and isolated. The diagnosability of fuel cell system is also obtained.**

Keywords: PEM fuel cell, parity space, analytical redundancy, faults signature, fault detection and isolation, diagnosability

I. Introduction

Fuel cell system is considered as a significant power source with great potential applications in industry [1]. Two major kinds of uses are popular for fuel cells in recent years: stationary and mobile applications. Due to its reliability, flexibility, high efficiency, and low or even no pollution, fuel cell technology is extremely supported by a number of automakers and various government agencies into the development of new energy vehicles [2].

A large number of researchers are currently placing their focus on diagnosis and control of fuel cell system. On the one hand, diagnostic tools can help distinguish the structure–property– performance relationships between a fuel cell and its components. On the other hand, results obtained from diagnosis also provide benchmark-quality data for fundamental models, which further benefit in prediction, control, and optimization of various transport and electrochemical processes occurring within fuel cells [3]. In fuel cell system diagnosis domain, experimental approaches based on knowledge are the most popular utilizations [3,4,5]. Gas pressure is considered as one of the most useful indicators for leakage fault detection. Furthermore, open current voltage (OCV) is also taken into account not only for fault detection but also for localization [6]. Other experimental approaches use characterization of electric components (equivalent electric circuit to electrochemical reaction) based on spectrometric impedance [7]. Model based FDI methods for fuel cell system become more and more important because of its portability and compatibility with other industrial processes. It consists in the generic property of the model and its operating conditions. Usually, analytical redundancy is well considered as a valuable tool to provide information for FDI. In contrast to physical redundancy which is often used as diagnostic tool in non-model FDI approaches, when measurements from parallel sensors are compared to each other, now sensory measurements are compared to analytically computed values of respective variable. Such computations use present and/or previous measurements of other variables, and the mathematical plant model describing their nominal relationship to the measured variable. The idea can be extended to the comparison of two analytically generated quantities, obtained from different sets of variables. In either case, the resulting differences, called residuals, are indicative of the presence of faults in the system. Various approaches exist for redundancy generation, e.g. Bond Graph approach [8], and artificial intelligence [9] etc. One common among those approaches is the characteristic of causality, which is also well developed in fuel cell system diagnosis [8,10]. Since that the complex structure of fuel cell leads to nonlinear mathematical model appearance, diagnosis referring to nonlinear case is also worth to be studied [11]. Another class of model-based methods relies on directly on parameter estimation which is not the focus of this paper.

Parity space approach which is an approach belonging to analytical redundancy methods, specially intended to linear models. Or at least, an extension of this method to nonlinear systems can be made in particular conditions [12,13].

In this paper, fault detection and isolation of fuel cell system based on analytical redundancy in linear case is presented. First, physical model of the whole system with faults specifications is described. Second, residual generation with the method of parity space for the linearized model is presented with faults signature. At last residual evolutions as simulation results are obtained by Matlab/Simulink.

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II. STATE SPACE MODELING OF FUEL CELL SYSTEM

A. *General Model of Fuel Cell System*

Modeling of a fuel cell system concerns multi-physical domains such as electrochemical, thermodynamic, electric and fluid mechanic principles. In this paper, we focus on the studying of the most generally used PEM fuel cell system which contains auxiliary components such as air compressor, hydrogen tank, supply manifold (SM) and return manifold (RM). The fuel cell is a volumetric capacitor including two electrodes named as cathode (ca) and anode (an) which sandwich an electrolyte inside the proton exchange membrane with bipolar plates called as Membrane Electrode Assemblies (MEA) (Fig. 1.). The main function principle can be represented by the electrochemical reaction between oxygen and hydrogen as follow:

$$2H_2 + O_2 \Rightarrow 2H_2O + Heat \tag{1}$$

Hydrogen gas passes over the anode, and with the help of a catalyst, separates into electrons and hydrogen protons. Then the protons flow to the cathode through the electrolyte while the electrons flow through an external circuit, thus creating electricity. In the mean time, the hydrogen protons and electrons combine with oxygen flow through the cathode to produce water. The temperature in operating conditions is 80°C.

Several assumptions are proposed for mathematical modeling procedure:

- Multiple cathode and anode volumes of the multiple identical fuel cells composing a stack are lumped together as a global unit.
- Hydrogen is pressurized in the tank which is not valuable considered in the mathematic model.
- All gases are supposed to satisfy the ideal gas law.
- There is no parasitic reaction considered inside the stack.
- Hydration parameters are constant.
- The stack temperature is uniform.
- The saturation pressure of each component is not varied.
- The variation of canals volume is negligible.
- Hydrogen gas is considered to be completely consumed.

Model developed specially for control and diagnosis studies have certain characteristics. In this paper, we use the mathematical model developed and validated by Jay T. Pukrushpan [14], which includes important characteristics such as dynamics (transient) effects but neglects spatial variation of parameters. From the point of fault detection and isolation, three main faults specifications are proposed, which are related to certain component variations in the model:

- F_1: Flooding inside fuel cell related to stack voltage drop Δv_{st};
- F_2: Drying of fuel cell membrane causing diminution of resistance turning to increase of stack current ΔI_{st};
- F_3: Over-voltage of compressor Δv_{cm}.

Among those three faults, F_1 is the system fault but can be simulated by a sensor fault signal added to the stack voltage output, while F_2 and F_3 which both belong to actuator faults at input level. We suppose that there is only one fault occurring at each time. Multiple faults are not considered in this paper as a general hypothesis.

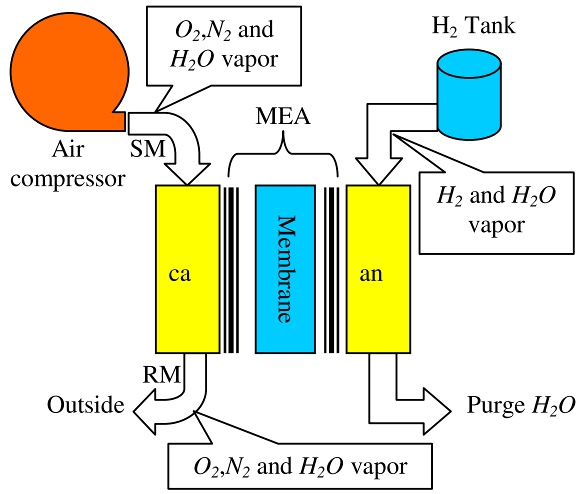

Fig. 1. Scheme of general fuel cell system model

B. *Physical Model*

The dynamics of air supply device is governed by the compressor inertia, J_{cp}:

$$J_{cp}\frac{d\omega_{cp}}{dt} = \tau_{cm} - \tau_{cp} \tag{2}$$

where τ_{cm} and τ_{cp} are the compressor motor torque and the load torque, respectively. A static nonlinear motor equation is used to model the power compressor motor:

$$\tau_{cm} = \eta_{cm}\frac{k_t}{R_{cm}}\left(v_{cm} - k_v\omega_{cp}\right) \tag{3}$$

where the compressor voltage v_{cm} is considered as one of the two inputs of system model due to its contribution to different levels of steady-state performance.

The torque required to drive the compressor is calculated using the thermodynamic equation:

$$\tau_{cp} = \frac{C_p T_{atm}}{\omega_{cp}\eta_{cp}}\left[\left(\frac{p_{sm}}{p_{atm}}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]W_{cp} \tag{4}$$

where k_t, R_{cm} *and* k_v are motor constants and η_{cm} is the motor mechanical efficiency. C_p is the constant-pressure specific heat capacity of air, η_{cp} is compressor efficiency, p_{sm} is the pressure inside the supply manifold, and p_{atm} and T_{atm} are the atmospheric pressure and temperature, respectively. W_{cp} is the compressor output flow rate.

The mass change rate inside the supply manifold, m_{sm}, is governed by the mass conservation principle and the change rate of supply manifold pressure, p_{sm}, is governed by the energy conservation principle:

$$\frac{dm_{sm}}{dt} = W_{cp} - W_{ca,in} \tag{5}$$

$$\frac{dp_{sm}}{dt} = \frac{\gamma R_a}{V_{sm}}\left(W_{cp}T_{cp,out} - W_{ca,in}T_{sm}\right) \tag{6}$$

where $W_{ca,in}$ is the cathode inlet flow rate, $T_{cp,out}$ and T_{sm} are the compressor outlet and supply manifold temperature, respectively. The return manifold pressure is governed by the mass conversation and the ideal gas law under isothermic assumptions:

$$\frac{dp_{rm}}{dt} = \frac{R_a T_{rm}}{V_{rm}}\left(W_{ca,out} - W_{rm,out}\right) \tag{7}$$

where $W_{ca,out}$ and $W_{rm,out}$ are cathode outlet and return manifold outlet flow rate.

According to the gas mass conservation inside the fuel cell, we obtain governing equations, respectively, for oxygen, nitrogen and water vapor inside the cathode.

$$\frac{dm_{O_2}}{dt} = W_{O_2,ca,in} - W_{O_2,ca,out} - W_{O_2,react} \tag{8}$$

$$\frac{dm_{N_2}}{dt} = W_{N_2,ca,in} - W_{N_2,ca,out} \tag{9}$$

Electrochemistry principles are used to calculate the rates of oxygen consumption, $W_{O2,react}$, and water production, $W_{v,gen}$, from the stack current I_{st}:

$$W_{O_2,react} = M_{O_2} \times \frac{nI_{st}}{4F} \tag{10}$$

$$W_{v,gen} = M_v \times \frac{nI_{st}}{2F} \tag{11}$$

The oxygen variation depends on the difference between inlet oxygen (supplied gas) and outlet oxygen with reacted oxygen. Because of no participation of reaction, the nitrogen variation is the unique difference between inlet and outlet. However, the cathode water variation depends solely on the summation of vapor flows, because the liquid water is supposed to stay in the stack and evaporate into the cathode gas if the cathode humidity drops below 100%. Before that the relative humidity of the gas exceeds saturation point at which vapor condenses into liquid water, the mass of water is always in vapor form. Besides of inlet and outlet vapor, the water generated in the reaction will also be vaporized and get through the membrane from anode to cathode. However, part of the vapor gas will recondense into liquid form when temperature is lowered caused by the slow down of reaction. As a consequence, the condensation of water will cause one of the most important faults: flooding in fuel cell.

Similar to the cathode flow model, hydrogen partial pressure and anode flow humidity are determined by balancing the mass flow of hydrogen and water in the anode. Its governing equation deduced from mass conservation is presented as follows:

$$\frac{dm_{H_2}}{dt} = W_{H_2,an,in} - W_{H_2,purge} - W_{H_2,react} \tag{12}$$

$$\frac{dm_{w,an}}{dt} = W_{v,an,in} - W_{v,an,out} - W_{v,mbr} \tag{13}$$

where m_{H2} is the hydrogen mass in the anode;

$m_{w,an}$ is the water vapor mass in the cathode;

$W_{H2,an,in}$ is the hydrogen mass flow rate at the anode inlet;

$W_{H2,purge}$ is hydrogen mass flow rate purged outside which is considered zero according to the last assumption;

$W_{H2,react}$ is the mass flow rate of hydrogen reacted;

$W_{v,an,in}$ is the vapor mass flow rate at the anode inlet;

$W_{v,an,out}$ is the vapor mass flow rate purged at the anode outlet;

The rate of hydrogen consumed in the reaction, $W_{H2,react}$, is a function of the stack current:

$$W_{H_2,react} = M_{H_2} \times \frac{nI_{st}}{2F} \tag{14}$$

Since stack current I_{st} affects both anode state equations and cathode state equations, it is defined as another input variable.

C. *Linearized State Space Model*

From physical model, nonlinear state space representation with nine state variables can be directly deduced [14]. However, unlike the work in [11], the complexity of nonlinear model of the fuel cell system at full size is far beyond the calculate capability of Matlab. It is necessary to linearize the model oriented to diagnosis and control. We have used the LTI systems analysis in Matlab/Simulink in view to linearize our nonlinear model. The water vapor mass $m_{w,ca}$ in the cathode always predicts excessive water flow from anode to cathode which results in fully humidified cathode gas under all nominal conditions. Additionally, the effects of liquid condensation, also known as "flooding", is not included in the model but considered on the fuel cell voltage response. Hence, in this case, we obtain eight state variables without $m_{w,ca}$ defined as follows:

$$x = \left[m_{O_2}, m_{H_2}, m_{N_2}, \omega_{cp}, p_{sm}, m_{sm}, m_{w,an}, p_{rm}\right]^T \tag{15}$$

and three outputs (W_{cp}, p_{sm} and v_{st}) are chosen:

$$y = \left[W_{cp}, p_{sm}, v_{st}\right]^T \tag{16}$$

Two input variables compressor input voltage v_{cm} and stack current I_{st} are decided:

$$u = \left[v_{cm}, I_{st}\right]^T \tag{17}$$

Therefore, state and output equations in standard linear form are presented as follows:

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned} \tag{18}$$

All coefficients in linearized matrix A, B, C and D can be found in APPENDIX with parameters in TABLE II.

III. Generation of ARR by Parity Space Approach

In FDI domain, analytical redundancy relations take an important role both in theory and application. An ARR arises from a causal interpretation of the underlying model primary relations. It only contains observed variables and can hence be evaluated from the observations [15]. Due to the tractability and superposition principle of linear system, parity space approach is also much easier to be integrated in ARRs generation algorithm than nonlinear case. Even if the system and measurement noises are accounted in the global model, the parity space residual can be noise-suppressed [16]. The extension of linear parity space approach to nonlinear one is well developed and applied by [13]. In this paper, eleven constraints including eight state equations and three output equations are over eight unknowns (state variables), which is noted that the system is monitorable. Linear parity space approach has been taken to generate ARRs for our model. The ARRs generation algorithm can be summarized in several steps as follows:

- Determine observability matrix $OBS=[C,CA,\ldots,CA^n]^T$;
- Determine the left null matrix of *OBS* which is called as the parity matrix Ω.
- Determine the dynamically derived observability matrix $ODD=[y,y'-Du,y''-CBu',y^{(3)}-CABu'',\ldots,y^{(n)}-CA^{n-2}Bu^{(n-1)}]$.
- Apply analytical redundancy equation to generate residuals: $R=\Omega\times ODD$, where $R=[r_i]$.
- Select certain residuals in satisfaction of faults specifications.

Through calculation of parity space approach, twenty-two residuals are generated. It is noted that more derivation of inputs u and outputs y, weaker impact of those derivatives to residuals will appear. Therefore, we ignore all derivates higher than one order and all terms with too small value coefficients (<0.01). As a result, we choose two particular residuals which have different sensitivities to different faults defined in section II. Apparently, these three faults can be represented by inputs and outputs of the model in equations (19) and (20):

-Faults F_1 is represented by y_3 i.e. v_{st};

-Faults F_2 is represented by u_2 i.e. I_{st};

-Faults F_3 is represented by u_1 i.e. v_{cm}.

$$r_6 = 0.0157u_1 + 0.0431u_2 + 0.0013(y_2 - y_1) \tag{19}$$

$$r_{17} = -0.0556y_1 - 0.0133y_2 - 0.9896y_3 - 0.0097u_2 \tag{20}$$

We suppose that there is only one fault occurring at each time. Therefore, we obtain the faults signature as shown in TABLE I. The value "1" appearing in the table means that the residual r_i (in column) is sensitive to the fault F_j (in row). From the combination of binary values in the table, it is noted that all faults are detectable (Db) and also isolable (Ib) from each other. Therefore, we can say that the system is diagnosable.

TABLE I
FAULTS SIGNATURE

Faults	Db	Ib	r_6	r_{17}
F_1	1	1	0	1
F_2	1	1	1	1
F_3	1	1	1	0

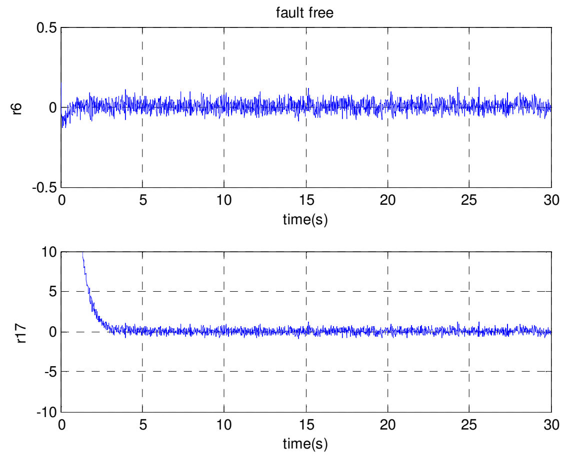

Fig. 2. Residual evolutions of fault free system.

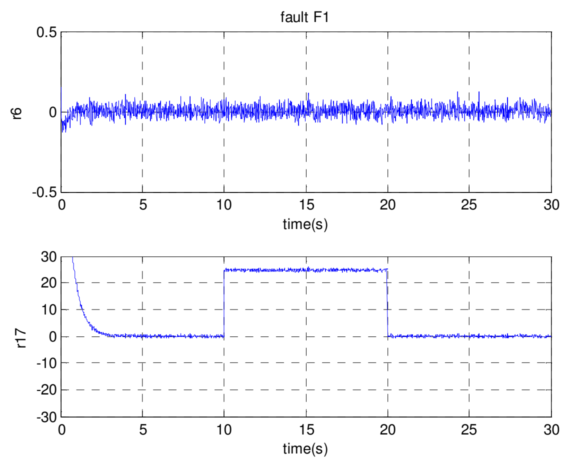

Fig. 3. Residual evolutions of the system with fault F_1.

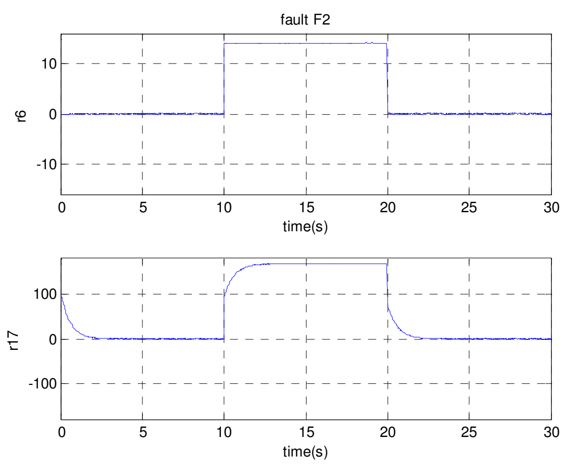

Fig. 4. Residual evolutions of the system with fault F_2.

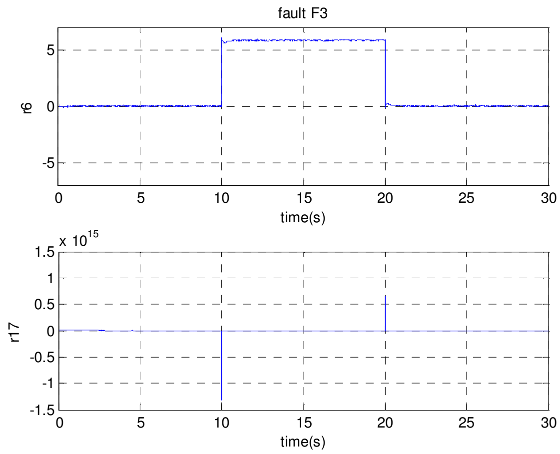

Fig. 5. Residual evolutions of the system with fault F_3.

IV. Simulation

Simulation results are realized in Matlab/Simulink. The algorithm of parity space approach is programmed. Under the approximation of residual expressions, two residual generators working as an FDI integrated system, respectively, corresponding to r_6 and r_{17} are provided with several inputs such as inputs and outputs of the fuel cell system. Through the residuals time evolution (Fig. 2, Fig. 3, Fig. 4 and Fig. 5), the FDI results matching with the faults signature are systematically presented. In Fig. 5, due to derivative effect not considered in (20), the variety of residual r17 at both start and end of the period of fault appearance is not a remarkable indicator. Therefore, it is not used as a fault signature.

The nominal operating point is decided of v_{cm}=164 volt and I_{st}=191 Amp in fault free system (Fig. 2). To simulate fault F_1, a voltage drop of 25 volt is added to the output of y_3. For both of faults F_2 and F_3, two faulty signals with the double value of nominal u_1 and u_2, respectively, are added at the input level of system. All three faulty signals which are square waves appearing between 10 sec and 20 sec during the simulation time of 30 sec. A small oscillation different to zero occurs at initial moment in several plots e.g. r_{17} in figure 2, which can be explained by the transient variation of residual generators' inputs normally considered as disturbance in start-up state performance of the compressor. Two peaks appear in the last plot, which is caused by derivatives of u_1 neglected during the approximation. However, the effective, even if it is too weak to be considerable, will still lead to some undesirable phenomena. Unfortunately, the residual generators in this paper are validated in a particular case with specific values given in APPENDIX. Because of the high dimension of the model, the calculation with symbols is always out of the memory in Matlab. Consequently, the generic of the integrated system is not satisfied. Besides, universal thresholds are difficult to be decided against the variation of parameters.

V. Conclusion

A procedure of fault detection and isolation based on parity space approach applied in a fuel cell system model linearized in state space representation has been presented in this paper. Analytical redundancies are derived as faulty indicators. Two of the twenty-two residuals generated by parity space approach are selected and approximated to the objective of diagnosis. From the faults signature which presents the information concerning sensitivity between faults and residuals, the system is detectable and isolable (diagnosable). Simulation results are provided with specific values. A systematic diagnostic process for an integrated fuel cell system instead of an auxiliary component such as air supply subsystem of fuel cell [11] has been realized, which is a great progress with respect to previous work. However, the particular simulator developed in this paper is short of generic usefulness. The portability of the residual generators is limited. As perspectives, first of all, an algorithm for selection of useful residuals is valuable to be studied and developed. Second, adaptive thresholds are necessary for the system alarm in supervision. Third, the sensitivity of residuals with respect to faults is a valuable work in the future. The fault position and the system complexity will affect the residual sensitivity, since coefficients of fault variables in the model have great influence at properties of residuals. It is certain that different structures of system and various positions of faults will lead to uncertainties of residual sensitivity. Finally, the sensor placement in system level of fuel cell installation will be taken into account as a desirable work for fault diagnosis.

Appendix

Linearized Matrix

$$A=\begin{bmatrix} -6.30908 & 0 & -10.9544 & 0 & 83.74458 & 0 & 0 & 24.05866 \\ 0 & -161.083 & 0 & 0 & 51.52923 & 0 & -18.0261 & 0 \\ -18.7858 & 0 & -46.3136 & 0 & 275.6592 & 0 & 0 & 158.3741 \\ 0 & 0 & 0 & -17.3506 & 193.9373 & 0 & 0 & 0 \\ 1.299576 & 0 & 2.969317 & 0.3977 & -38.7024 & 0.105748 & 0 & 0 \\ 16.64244 & 0 & 38.02522 & 5.066579 & -479.384 & 0 & 0 & 0 \\ 0 & -450.386 & 0 & 0 & 142.2084 & 0 & -80.9472 & 0 \\ 2.02257 & 0 & 4.621237 & 0 & 0 & 0 & 0 & -51.2108 \end{bmatrix}$$

$$B=\begin{bmatrix} 0 & -0.03159 \\ 0 & -0.00398 \\ 0 & 0 \\ 3.946683 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & -0.05242 \\ 0 & 0 \end{bmatrix} \quad D=\begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & -0.29656 \end{bmatrix}$$

$$C=\begin{bmatrix} 0 & 0 & 0 & 5.066579 & -116.446 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 12.96989 & 10.32532 & -0.56926 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

TABLE II
NOMENCLATURE

Symbol	Physical Description
M_v	Vapor molar mass
R_v	Vapor gas constant
R_a	Air gas constant
$W_{ca,out}$	Cathode outlet mass flow rate
$M_{a,ca}$	Cathode air molar mass
R_{O2}	Oxygen gas constant
R_{N2}	Nitrogen gas constant
M_{N2}	Nitrogen molar mass
M_{O2}	Oxygen molar mass
$W_{an,out}$	Anode outlet mass flow rate
M_{H2}	Hydrogen molar mass
R_{H2}	Hydrogen gas constant
A_{fc}	Fuel cell active area
D_w	Membrane water diffusion coefficient
$\rho_{m,dry}$	Membrane dry density
T_{st}	Stack temperature
γ	Ratio of specific heats of air
t_m	Membrane thickness
$M_{m,dry}$	Membrane dry equivalent weight
V_{ca}	Cathode volume
V_{sm}	Supply manifold volume
V_{rm}	Return manifold volume
T_{sm}	Supply manifold temperature
T_{rm}	Return manifold temperature
$p_{sat,ca}(T_{sm})$	Cathode saturation pressure
V_{an}	Anode volume
$p_{sat,an}(T_{an,in})$	Anode saturation pressure
C	Double layer charge capacitor
R_{act}	Activation resistance
R_{conc}	Concentration resistance
$W_{ca,in}$	Cathode inlet mass flow rate
y_{O2}	Oxygen model fraction
ω_{cp}	Rotation velocity of compressor
$\phi_{ca,in}$	Relative humidity of cathode inlet
n	Cell number
F	Faraday constant
R_{ohm}	Ohmic resistance

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