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Fault detection for PEM fuel cell using kalman filter

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Abstract: Fault detection plays a key role in high cost and safe-critical systems to avoid the occurrence of an abnormal event. This work presents a model-based fault detection in the water management system of proton-exchange membrane (PEM) fuel cell stack using Kalman filter (KF). The KF is a model-based FD method relies on analytical redundancy to predict the related fault disturbed by some noise. Then, it corrected the faults with its mathematical model to minimize the error covariance between the normal and faulty scenarios by a repetitive process. Two faulty scenarios; flooding and drying which happen at anode and cathode side of PEM fuel cell are investigated. The proposed FD method using KF has successfully detected flooding and drying faults in PEMFC.

1. Introduction

Most research and development in fault detection was limited to critical safety systems such as nuclear power plants, aircraft and national defence. However, today, fault detection is established in many industries where most applications are electrical motors, manufacturing, automotive and chemical processes systems. Enormous demands on reliability and safety of industrial plants need early detection of faults in order to avoid abnormal event progression and productivity loss. The fault is defined as is an unpermitted deviation of the system's feature from a common condition where it can lead to the system's malfunction or failure. The fault in a system can be categorised into three kinds, which are actuator, plant and sensor faults. Actuator fault usually occurs in the actuator part of the system, for example, in servo motor such as lock-in-place or freezing, float, hard-over-failure and loss of effectiveness. Plant fault will occur in the system, for example, power source failure such as battery and solar arrays failures in satellites, tank leakage in chemical systems, wing damage in aerial vehicles and bearing faults in rotational equipment of aircraft engines, while sensor fault occurs in the output interface of a system. Typical sensor fault happen such as bias, drift, performance degradation, sensor freezing and calibration error [1].

In PEM fuel cell, hydrogen with low content of carbon monoxide is an ideal fuel for PEM fuel cell to avoid fuel cell poisoning. Henceforth, the PEM fuel cell can obtain efficiency up to 60% higher compared to an internal combustion engine which efficiency around 20-35% [2]. However, due to specific faults take place in reactant system, water management system, cooling system, and air supply system of the PEM fuel cell, the process to achieve the high performance of that system is quite impossible. Some of the wide range of phenomena involved in operating the fuel cell is the normal source fault such as irregular management of water such as flooding and drying, degradation of catalyst and contamination of membrane electrode assembly. The fault such as flooding often occurs at cathode side while drying at the anode side of the fuel cell stack. The mentioned faults cause the voltage to fall and lower the lifespan of fuel cell. The cell voltage either increase or decrease due to the presence of a fault [3]. Thus, the fault detection in PEM fuel cell is proposed using the Kalman filter. Four parameters, exchange current density, mass transport constant, temperature and air

pressure, are the faulty parameters to vary for three different scenarios; normal, flooding and drying scenarios in PEM fuel cell [2].

2. Kalman Filter Method

The Kalman Filter (KF) is a recursive predictive filter which depends on the use of state-space techniques and recursive algorithms. It estimates the condition of a dynamic system in which the system can be disturbed by some noise. The prediction is the initial step of KF. The predicted condition is calculated through disregarding the differential equations and dynamic noise which represent a dynamic model to be solved [4,5]. The discrete-time nonlinear dynamic system is given as

$$x_{k+1} = F(x_k, u_k, w_k) \quad (1)$$

$$y_k = H(x_k, v_k) \quad (2)$$

The state-space of the system in equations (1) and (2) is represented by

$$x_k = Ax_{k-1} + Bu_{k-1} + w_{k-1} \quad (3)$$

$$z_k = Hx_k + v_k \quad (4)$$

where w and v represent the process and measurement noises, and these noises are zero-mean Gaussian white noise vector. The vector x represents the states of the system and z represents the state of the measurements and u is the input vector of the system. In this work, \hat{x}_k^- is defined as prior status estimation derived from status transition equation at the moment of $k-1$, and \hat{x}_k is the posterior status estimation combines the measurements at the moment of k . Hence, the deviations are given as

$$e_k^- = x_k - \hat{x}_k^- \quad (5)$$

$$e_k = x_k - \hat{x}_k \quad (6)$$

The following prediction and update equations from the Kalman filter theory are obtained. The prediction equations are given as

$$\hat{x}_k^- = A\hat{x}_{k-1} + Bu_{k-1} \quad (7)$$

$$P_k^- = AP_{k-1}A^T + Q \quad (8)$$

and the update equations are

$$K_k = P_k^- H^T (HP_k^- H^T + R)^{-1} \quad (9)$$

$$\hat{x}_k = \hat{x}_k^- + K(z_k - H\hat{x}_k^-) \quad (10)$$

$$P_k = (I - K_k H) P_k^- \quad (11)$$

where Q represents the covariance of the process noise, R represents the estimated error covariance of

the measurement noise and K_k represents the Kalman gain. Equation (10) is given as residual of differences between prediction and actual measurements [4,5].

3. Proton-exchange membrane (PEM) fuel cell

PEMFC [2] is a kind of electrolyte which is a polymer membrane with high conductivity of proton if the membrane is in excellent hydration. In single-cell structure, a voltage is dependent on working conditions such as temperature, applied load, and fuel or oxidant flow rates. As the electrical energy is drawn from the fuel cell, the measured cell voltage falls from the theoretical voltage due to several irreversible loss mechanisms. The loss is a variation of the cell voltage, V_{irrev} from an assumption voltage, V_{rev} . The formulation of voltage losses is given

$$V(i) = V_{rev} - V_{irrev} \quad (12)$$

where V_{rev} is the maximum (reversible) voltage of fuel cell while V_{irrev} is the irreversible voltage loss (over potential) occur in the cell. The irreversible formula is

$$V_{irrev} = V_{act} + V_{ohmic} + V_{conv} \quad (13)$$

where V_{act} is the activation potential, V_{ohmic} is the ohmic over potential and V_{conv} is the concentration overpotential. The saturation pressure of water is given as

$$\log P_{HO} = -2.179 + (0.02953 \times T_c) - (9.1837 \times 10^{-5} \times T_c^2) + (1.4454 \times 10^{-7} \times T_c^3) \quad (14)$$

where T is the cell operating temperature in °C.

Performance of PEMFC

The first procedure is the calculation of Nernst voltage and voltage loss using below formula equation [2]. The corresponding Nernst Equation is given as

$$E = E^0 - (RT \ln(P_{H_2} P_{O_2}^{1/2} / P_{H_2O})) / 4F \quad (15)$$

Where R is universal gas constant, T is absolute temperature, P_{H_2} , P_{O_2} , and P_{H_2O} are the partial pressure of hydrogen, oxygen, and water. The E^0 is standard electrode potential and F is Faraday's constant. The operating voltage of the cell can be represented as the exits from the ideal voltage created by these polarizations

$$V_{actual} = E^0 - V_{activation} - V_{con} - V_{ohmic} \quad (16)$$

Where V_{actual} is actual cell potential, $V_{activation}$ is activation polarisation, V_{con} is concentrated polarisation, and V_{ohmic} is ohmic polarisation. The activation losses, the concentration polarization and the ohmic polarisation is given in following equations

$$V_{activation} = (RT) / (2F \alpha_a \ln(i / i_a)) + (RT) / (4F \alpha_c \ln(i / i_c)) \quad (17)$$

$$V_{ohmic} = j \times ASR \quad (18)$$

$$V_{con} = RT(\ln(P_{H_2} / P_\alpha) + 0.5\ln(P_{O_2} / P_c)) / 2F \quad (19)$$

where i is current density, α is transfer coefficient, j is current density, ASR is area specific resistance. Moreover, the partial pressure of water, hydrogen and oxygen formula is utilized to calculate Nernst voltage. From the calculation of the saturation pressure of water, it explains that when current increases, the cell voltage drops rapidly because of the various non-equilibrium effects. For example, the most straightforward effect is the drop in voltage because of internal resistance in fuel cell. The drop of cell voltage is equivalent to the multiplication of flowing current and resistance based on Ohm's law. Table 1 shows the parameter for PEM fuel cell [2].

Table 1. Parameters of PEM Fuel Cell [2]

Parameter	Value	Description	Parameter	Value	Description
R	8.314 J molK ⁻¹	Ideal Gas Constant	r	0.19 Ω cm ²	Internal Resistance
F	96487 Coulombs	Faraday's Constant	α	0.5	Transfer Coefficient
T_c	80 °C	Temperature	A_{cell}	100 m ²	Area of Cell
P_{air}	3 atm	Air Pressure	P_{H_2}	3 atm	Hydrogen Pressure
N_{cell}	90	Number of Cells	α_1	0.085	Amplification Constant
Gf_{liq}	-228170 J mol ⁻¹	Gibbs Function in Liquid Form	i_o	10 ^{-6.912} A cm ⁻²	Exchange Current Density
k	1.1	Mass Transport Constant	i_l	1.4 A cm ⁻²	Limiting Current Density

4. Result and discussion

The performance of PEMFC is represented by a polarization curve and is shown in figure 1 for normal polarization. In this figure, cell voltage dropped with the increase of the current density. The fuel cell has no load and considers as an open circuit. The cell voltage is approximately less than 1.2 V due to some unavoidable loss generated in the fuel cell such as internal current and resistance, activation and concentration losses and reactants crossover.

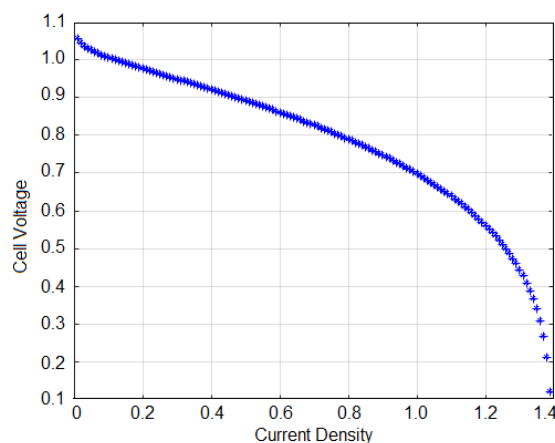


Figure 1. The polarization curve of normal PEMFC

In this paper, the flooding and drying detection of PEM fuel cells is investigated. Four related parameters, exchange current density, mass transport constant, temperature and air pressure, are chosen to vary for three different scenarios; normal, flooding and drying scenarios. Those parameters of three different scenarios are shown in Table 2 to be changed based on assumption during these scenarios while other parameters are kept constant.

Table 2. Parameters of PEMFC during three conditions

Condition	Parameters			
	Exchange Current Density	Mass Transport Constant	Temperature	Air Pressure
Normal	$10^{-6.912}$ A cm ⁻²	1.1	80 °C	3 atm
Flooding	$5^{-6.912}$ A cm ⁻²	1.0	80 °C	3 atm
Drying	$10^{-6.912}$ A cm ⁻²	1.1	140 °C	6 atm

Figure 2 shows the flooding polarisation curve compared with normal by varying the parameters in Table 2. The polarization curve for flooding scenario is higher than the fault-free. Figures 3 and 4 shows the KF detection result for exchange current density and mass transport constant parameters in flooding scenarios. In these figures, we can see that the exchange current density and mass transport constant is decreased compared to the fault-free scenario. The consequences of flooding will damage the lifespan and robustness of PEMFC in prolonged duration. The presence of water for the long term will lead to corrosion in electrodes, exchange membrane and gas diffusion media. Thus, ohmic losses will increase and the performance of PEMFC will decrease.

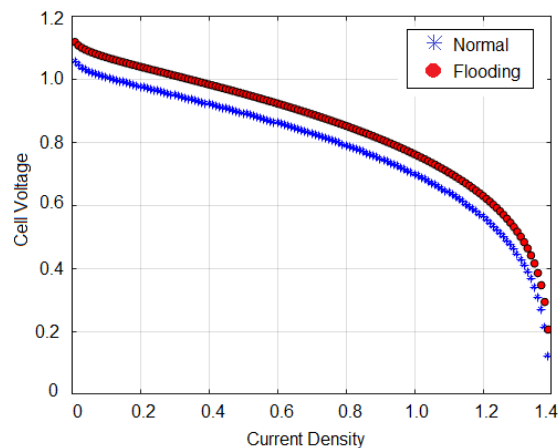


Figure 2. The polarization curve for the flooding scenario

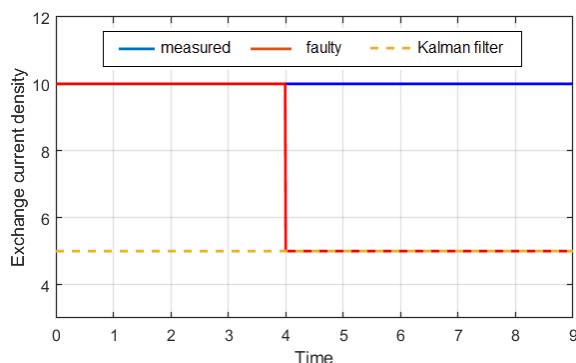


Figure 3. Fault diagnosis in exchange current density

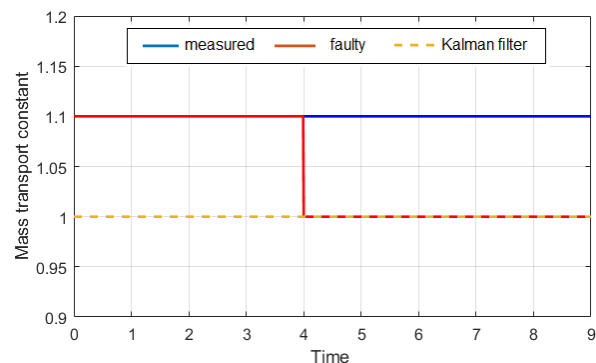


Figure 4. Fault diagnosis in mass transport constant

Figure 5 shows the drying polarisation curves with comparison to the normal scenario and it is shown that that the curve for drying situation is lower compared to the normal scenario. In Figures 6 and 7, the KF method successfully detects an increase in temperature and air pressure in the drying scenario. The drying will create holes in the membrane and the lifespan of the PEMFC will be decreased. The feeding inlet gases without sufficient humidification, electro-osmosis particular at high current and increase of cell temperature which enhances evaporation are the main factors for drying scenario in PEM fuel cell.

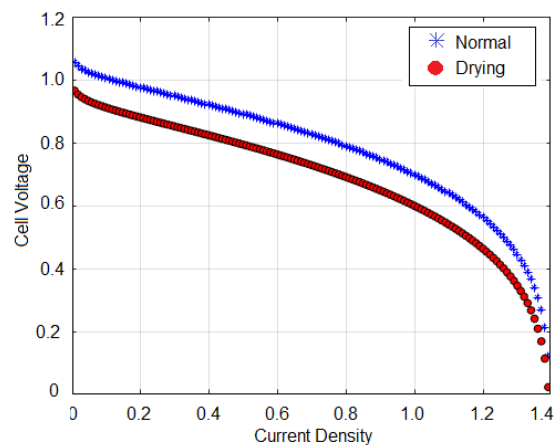


Figure 5. The polarization curve for drying scenario

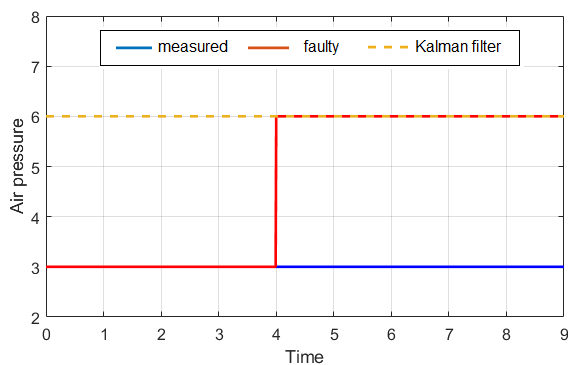


Figure 6. Fault diagnosis in air pressure

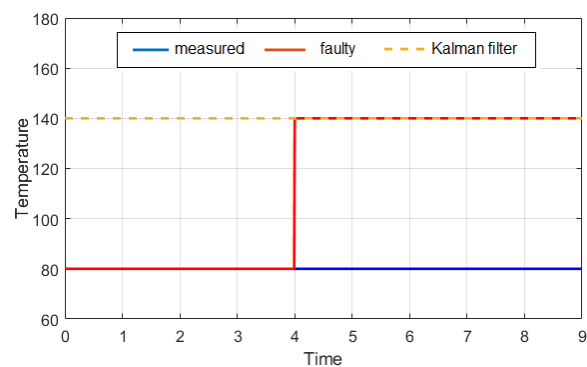


Figure 7. Fault diagnosis in temperature

5. Conclusion

In this work, the fault detection in PEM fuel cell is detected using Kalman filter method. The Kalman filter method successfully evaluated faulty signals in the flooding and drying scenarios by evaluation the differences in faulty parameters such as exchange current density, mass transport constant, temperature, and air pressure.

Acknowledgements

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