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Maximum Power Point Tracking Control of Direct Methanol Fuel Cell

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Abstract

The performance of direct methanol fuel cell (DMFC) is closely related to its operating conditions, and there exists a specific combination of operating conditions at which the DMFC output maximum power to the driven load. Working at maximum power point (MPP) can lower the methanol crossover and ancillary power consumption so as to improve the global efficiency of the system. The fuzzy controller proposed in this paper provides a simple and robust way to keep the DMFC working at MPP by adjusting the operating conditions followed by the variation of driven load in real time. Simulation shows that the fuzzy control approach can yield satisfactory results.

Keywords: *direct methanol fuel cell, fuzzy control, maximum power point tracking*

1. Introduction

Nowadays, the direct methanol fuel cell (DMFC) is becoming a highly promising alternative power source with its most attractive feature of liquid methanol fuel. But for the lower efficiency and power density, the application of DMFC is still limited greatly [1]. To achieve a better performance, many researchers have investigated the DMFC by experimental or numerical simulation methods [2-16]. The findings showed that a number of operating conditions can affect the performance of DMFC, and the DMFC performance can be improved significantly by tuning the operating conditions which are further closely related to methanol crossover and efficiency.

The power produced by the DMFC varies with the driven load under the same operation conditions, and there always exists an operating point where the DMFC can produce the maximum power, such operating point is called maximum power point (MPP), which corresponds to the different condition combinations. Though the fuel efficiency is at best 50% at MPP, it is still beneficial in applications where power density is more important than the fuel efficiency [17]. Zhong et al [17] designed an adaptive extremum-seeking controller to trace MPPs of fuel cell power plants. Chun et al [18] proposed a novel approach of combination of radial basis function neural network and particle swarm to achieve the MPP of a small wind power generator system. Though MPP tracking (MPPT) methods have been wildly used in photovoltaic, wind and PEMFC applications [17-21], few literatures about DMFC MPPT have been reported so far.

This paper studied the relationship between operating conditions and MPPs based on a DMFC model to determine suitable control variables and to find an effective optimum operating strategy. It also proposed a design of the controller to force the DMFC work at MPPs in order to improve the performance and efficiency of DMFC by adjusting operating conditions.

The paper is organized as follows. In Section 2, the relationship between MPP and operating conditions is discussed. A fuzzy controller for controlling of current density and concentration is introduced in Section 3, and finally the simulation results are discussed in detail in Section 4.

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2. The Relationship between Operating Conditions and MPPs

In this work, three easily controlled operating conditions are selected as control variants, namely, current density, methanol concentration and flow rate to study the performance based on a DMFC model described in [9]. Others main operate conditions are defined as following:

1. The fuel cell stack temperature is kept at 353K.
2. The pressure in anode and cathode is 0.1MPa and 0.3MPa respectively.
3. The oxygen partial pressure in cathode is 20%.
4. The air flow rate is proportional to the methanol concentration that fed into the anode and the stoichiometry of methanol and air is controlled at a best value and kept constant, thus the DMFC will be provided with enough but not excess oxygen.

To determine the MPPs of DMFC, we selected various combinations of methanol concentration and flow rate first, and then adjusted the current density manually to obtain the maxim power density and the corresponding methanol crossover. Table 1 presents the simulation results of maxim power density, voltage, current density and crossover under different combinations of concentration (0.1M~2M) and flow rate (2ml min^{-1}~30 ml min^{-1}).

As different operating condition cause different effect on the performance of DMFC, to determine the suitable control variables, we analyzed correlation between operating conditions and the performance by SPSS (IBM software) based on the data shown in Table 1. The analysis result is presented in Table 2.

Table 1. The Performance of MPP and the Corresponed Operating Conditions

	Flow rate (mL min^{-1})	Concentration (M)	Current (mA cm^{-2})	Max power (mW cm^{-2})	Crossover (mol cm^{-2}s^{-1})
1	2	0.5	113	61.16	6.42E-05
2	5	0.5	120	65.06	7.14E-05
3	10	0.5	125	66.48	6.43E-05
4	20	0.5	125	67.23	7.10E-05
5	30	0.5	127	67.47	6.53E-05
6	2	0.8	180	94.36	1.06E-04
7	5	0.8	195	100	1.02E-04
8	10	0.8	200	102	1.03E-04
9	20	0.8	200	103.3	1.13E-04
10	30	0.8	205	103.4	9.71E-05
11	2	1	227	115	1.23E-04
12	5	1	240	122	1.42E-04
13	10	1	250	124.2	1.28E-04
14	20	1	250	125.7	1.41E-04
15	30	1	250	126.2	1.46E-04
16	2	1.2	270	134.9	1.58E-04
17	5	1.2	280	142.7	2.03E-04
18	10	1.2	295	145.5	1.73E-04
19	20	1.2	300	146.9	1.69E-04
20	30	1.2	295	147.6	1.94E-04
21	2	1.5	330	163.2	2.29E-04
22	5	1.5	355	172.1	2.33E-04
23	10	1.5	365	175.3	2.31E-04
24	20	1.5	370	177	2.31E-04
25	30	1.5	375	177.3	2.18E-04
26	2	2	430	206	3.47E-04
27	5	2	450	216.6	4.04E-04
28	10	2	470	220	3.73E-04
29	20	2	486	222	3.35E-04
30	30	2	485	223	3.48E-04

Table 2. Correlation Analysis between Operating Conditions and Performance

		Max power	Crossover
Current	Pearson correlation	.997**	.967**
	Significance	.000	.000
Concentration	Pearson correlation	.893**	.912**
	Significance	.000	.000
Flow rate	Pearson correlation	.214	.128
	Significance	.057	.257

2.1. The Relationship between Current Density and Max Power Density

The correlation parameter of current density to max power density and to crossover is 0.997 and 0.967 separately while p-value<0.001, which means the current density is significantly related to the max power density and crossover. Based on data listed in table 1, a fitting model of current density and maxim power density is created by MATLAB, and the model can be defined as follows:

$$I_{Ref}=0.002*P^2+1.688*P+0.336 \quad (1)$$

Where i_{Ref} (mA cm^{-2}) is the fitting current density which is the most appropriate to the driven load, P(mW cm^{-2}) is the power density calculated by Equation (2).

$$P = P_{Load} / A \quad (2)$$

Where P_{Load} (mW) is the power of driven load, A(cm^2) is the cross-sectional electrode area of DMFC.

Figure 1 plots the current density as a function of maxim power density, and compares the fitted values with MPPs listed in Table 1. It is obvious that the fitting model can precisely describe the relation of current density and max power density. Now, if the driven load is determined, we can calculate a corresponding current density which can keep the DMFC operate at an appropriate MPP.

2.2. The Relationship between Flow Rate and Max Power Density

The correlation parameter of flow rate to max power density is only 0.214 while p is 0.057; this means the flow rate is an unconsidered factor to the power density. From data in table 1, we can find that the change of flow rate can affect the max power density greatly only when it is below 20ml min^{-1}. According to the principle of DMFC, the methanol can be converted into electricity when diffusing from anode to catalytic layer. When the methanol supply rate is below the diffusion rate, increase of flow rate can provide more fuel to sustain higher power output. Once the supply rate is beyond the diffusion rate, the excess methanol will flow out of DMFC stack rather than diffuse into the catalytic layer, which can be proven indirectly by the correlation parameter of flow rate to crossover. Thus, simply increasing the flow rate is no good to improve the DMFC performance.

Data in Table 1 also shows that concentration and flow rate are coupled operating conditions. Actually, the lack of fuel caused by the reduction of methanol concentration can be offset by the increase of flow rate within the threshold of flow rate, for both of them can influence the supply of fuel, and vice versa. Figure 2 illustrates the effect of flow rate on the methanol concentration and crossover under different constant power density. The current density is calculated by Equation (1) to keep the DMFC work at MPPs.

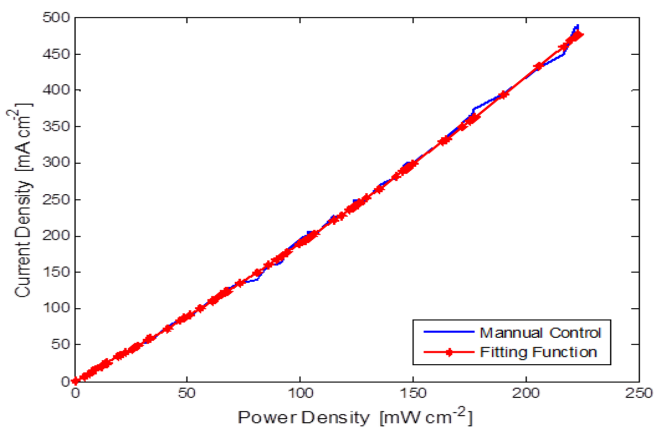
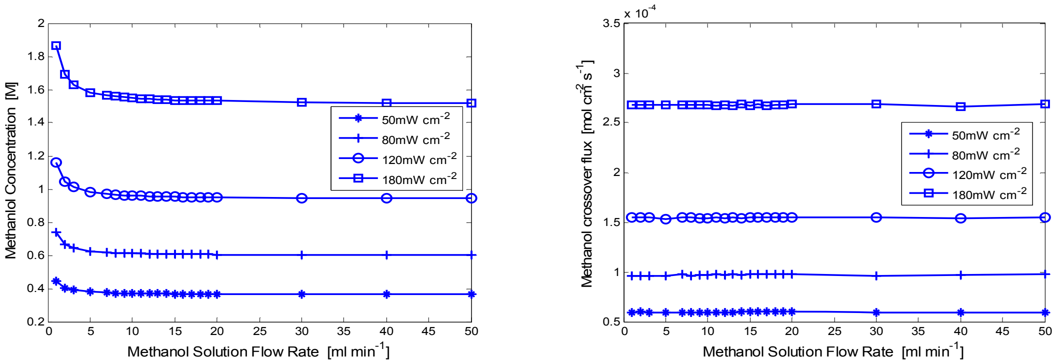


Figure 1. Comparison of Simulation Results and Fitting Values



(a) The relationship between concentration and flow rate

(b) The relationship between crossover and flow rate

Figure 2. Effect of Flow Rate under Constant Power Density

Figure 2(a) shows the concentration decreases with the increase of flow rate under 4 different power densities, and the concentration is almost constant when the flow rate exceeds 20ml min^{-1}. Actually, the decrease in concentration is less than 0.7% when the flow rate increases from 20ml min^{-1} to 50ml min^{-1} under arbitrary constant power density, which means the upper limit of flow rate should be 20ml min^{-1}. We also notice the increase of flow rate cause a significant drop in concentration when the flow rate is below 5ml min^{-1}. In this region, small fluctuation of flow rate will cause the fluctuation of concentration, which would lead to the unstable state of the control system easily. In addition, data in Table 1 indicate that lower flow rate limits the maxim power density clearly for the mass transport limitations of methanol in the anode [5]. So the lower limit of flow rate should be 5ml min^{-1}.

From Figure 2(b) we can find the crossover fluctuates slightly with the increase of flow rate, and the maximum fluctuation ratio is only 1.6% at the range of flow rate from 1ml min^{-1} to 50ml min^{-1}. This means the effect of flow rate on crossover under constant power density can be neglected. Ancillary power consumption and the stability of control system are becoming main factors to the determination of flow rate. Though lower flow rate leads to less ancillary power consumption, the flow rate should be higher than 10ml min^{-1} in consideration of the effect of carbon dioxide in the anode on the performance of DMFC [5].

Now we can conclude that the suitable flow rate ranges from 10ml min^{-1} to 20ml min^{-1}, and it is clear that the determination of flow rate is independent of power density from the Figure 2. So the flow rate can be a fixed value between 10ml min^{-1} and 20ml min^{-1} in a DMFC MPPT system. In this paper, the flow rate of 12ml min^{-1} is selected in view of less power consumption.

2.3. The Relationship between Methanol Concentration and Max Power Density

The correlation parameter of concentration to max power density and crossover is 0.893 and 0.912 separately while p-value<0.001, which means concentration is also a significant relevant factor to both the power density and methanol crossover.

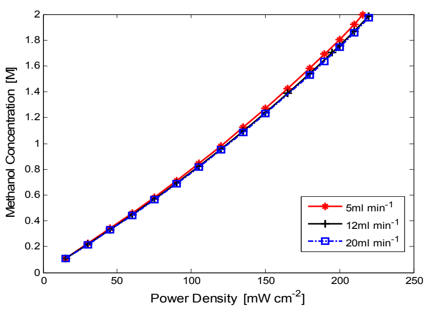


Figure 3. The Relationship between the Concentration and Max Power Density

Figure 3 illustrates the relationship between the concentration and max power density under different flow rates. From the figure, we can find that there exists a one to one correspondence between the concentration and the max power density when the flow rate is fixed. It is noticed that the increase of flow rate has almost no effect on the max power density when it exceeds 12 ml min^{-1}, and lower flow rate results in lower max power density under the same concentration especially when the driven load is greater than 100mW cm^{-2}.

3. Construction of Controller

The controller is proposed to trace the MPP of DMFC stacks by adjusting the operating conditions according to the driven load. The flow rate is kept 12 ml min^{-1} in the following simulation according to the aforementioned discussion.

The tasks of the controller include: 1) calculating the work current density by means of Equation (1) so as to shift the operate point of the stack. 2) selecting suitable methanol concentration to keep the DMFC working at MPP.

Figure 4 shows the schematic of the proposed controller.

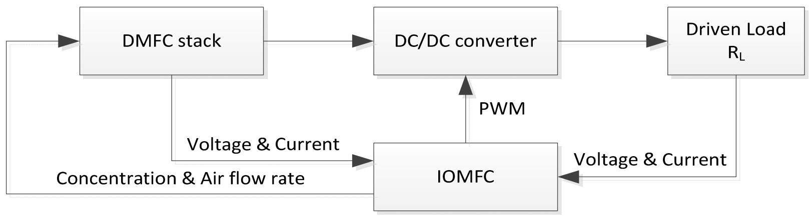


Figure 4. Schematic of the Controller of DMFC

3.1. Increment Output Mode Fuzzy Controller

Fuzzy control method is widely used in Fuel Cell system [23, 24].Considering that the DMFC is a large time-delay and complex system, an improved fuzzy controller-increment output mode fuzzy controller (IOMFC) [25] is introduced to control the work current density and methanol concentration.

Same with the basic fuzzy controller, IOMFC uses error and error change rate of the controlled variable as input, and process the input variables based on the general fuzzy sets and rule base [26] aims to eliminate the error. Different from that basic fuzzy controller, the result of fuzzy processor is processed as follows before applied to the controlled object.

$$u_{c(i)} = u_{c(i-1)} + K_{c1}(f_{(i)}(e_{(i)}, ec_{(i)}) - f_{(i-1)}(e_{(i-1)}, ec_{(i-1)})) + K_e e_{(i)} \quad \left|e_{(i)}\right| < \delta \tag{3}$$

$$u_{c(i)} = u_{c(i-1)} + K_{c2} f_{(i)}(e_{(i)}, ec_{(i)}) \quad \left|e_{(i)}\right| > \delta \tag{4}$$

To keep the control process smoothly and fast, the IOMFC select different control mode according to the error: when the absolute error is bigger than the threshold δ, Equation (4) is selected; when the absolute error is less than the threshold δ, Equation (3) is selected.

The IOMFC can make the controlled signals gradually approaching the expectation by tuning the control signal continuously based on fuzzy operation, which draws on the human control behavior. The introduction of IOMFC can simplify the control process while ensuring the accuracy even for the large time-delay complex systems.

3.2. Control of the Current Density

To keep the DMFC work at MPPs, it is necessary to regulate the work current density when variations in driven load occur. In this paper, a DC/DC converter, which is located between the DMFC stack and the driven load as shown in Figure 4, is used to shift the work point so as to control the current density of DMFC [16, 17], and the current density is given by the following equation.

$$I_{FC} = V_{FC} / (1-d)^2 R_L A \quad (5)$$

Where I_{FC} (mA cm^{-2}) and V_{FC}(V) is the output current density and voltage of the DMFC respectively, d is the duty cycle of PWM signal, R_L(KΩ) is the resistance of driven load, A(cm^2) is the cross-sectional electrode area of DMFC.

To force the DMFC always work at MPPs, The IOMFC iteratively calculates the reference current density by Equation (1), and regulates the duty cycle of PWM signal of the converter based on the error and error change rate of the reference current density and the work current density followed by the change of driven load. When the work current density coincides with the reference value, the operate point of DMFC will be a MPP corresponding to the driven load.

3.3. Control of the Concentration

From Figure 5, it is clear that the same power density Pc (such as point A, B, C and D) can be produced under different concentrations and the concentration corresponding to the point C, which is a MPP, is the lowest. The DMFC can't produce enough power to drive the load when the concentration is lower than point C (such as point G), while when the concentration is higher than point C (such as point A, B and D), the DMFC produce higher power density than the load needed at the giving work current density calculated by Equation (1). Thus, keeping the DMFC work current density equal to the result of Equation (1), we can keep the DMFC work at an appropriate MPP by adjusting the concentration to ensure the DMFC output power and the driven load the same.

When the driven load increase (from P_c to P_e), the DMFC work current density will be forced to increase until it shifts from I_c to I_e. Only by increasing the concentration, the output power density can approach the driven load, and once the output is equal to the driven load, the shift of MPP is completed (from point C to point E). In the same way, the DMFC can shift its work point from point E to point C by decreasing the concentration when the driven load drops down. Thus, the work point of DMFC can be shifted between different MPPs by adjusting concentration.

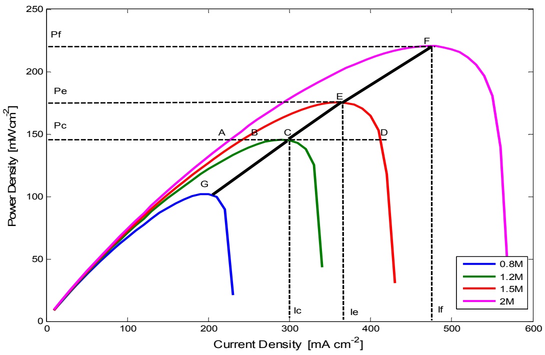


Figure 5. Example of MPPs shift of DMFC (Flow rate=12ml min-1, T=353K)

So, based on the error and error change rate between driven load and real output of DMFC, the IOMFC can adjust the concentration constantly followed by the variation in driven load to keep the DMFC always operating at an appropriate MPP.

4. Simulation Results and Discussion

Figure 6 shows the power density can follow the step change of the driven load and enter into the steady state after a large regulation time (about 200~500s). We also notice that the existence of power density overshoots when rapid driven load change occurs. As can be seen from Figure 7, there always exist lag time between the change of concentration and power density no matter how the driven load changes for the slow electrochemical kinetics of methanol oxidation and the slow methanol diffusion and convective transport mechanism, and it is the existence of large time-delay that increases difficulties of control process greatly and cause the power density overshoots and fluctuations.

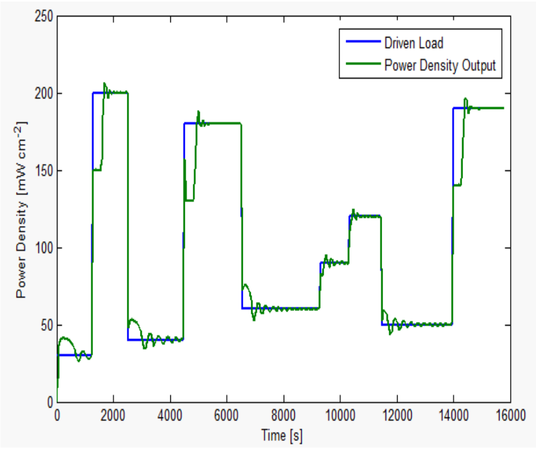


Figure 6. Power Density Responses to Step Change in Driven Load

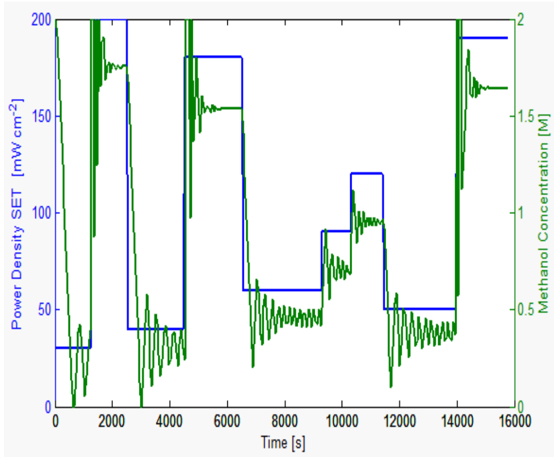
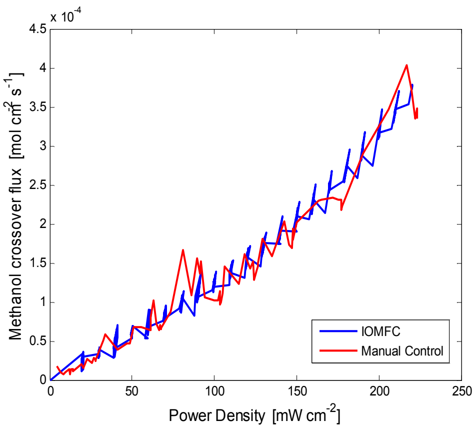
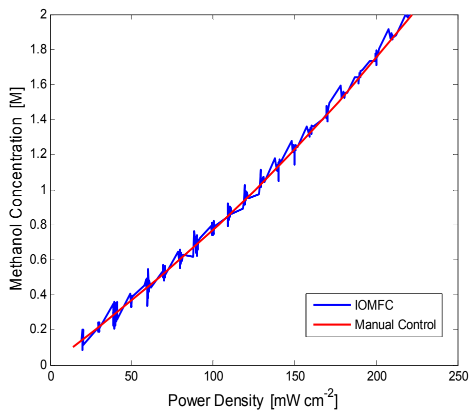


Figure 7. Concentration Responses to Step Change in Driven Load

Figure 8 compares the methanol crossover flux and the concentration of the selected MPPs with the IOMFC control results under different power densities. The results show the crossover and concentration characteristic curves are almost same except the fluctuation caused by the controller, which can prove that the controller can keep the DMFC operating at MPPs by adjusting the work current density and methanol concentration dynamically followed by the change of driven load. According to the previous analysis, with the help of the fuzzy controller, the concentration is always the lowest corresponding to the output power density, and the air flow rate is proportional to the methanol concentration, so the ancillary power consumption will be the lowest too.



(a) Comparison of crossover under different power density



(b) Comparison of methanol concentration under different power density

Figure 8. Comparison of IOMF Control and Manual Control

5. Conclusion

In this paper, the effect of concentration, methanol solution flow rate and current density on the performance of DMFC was analyzed based on a simulation model. The result showed that increase of flow rate can't affect the max power density and methanol crossover when it is beyond a specific threshold. Low flow rate can reduce the power consumption of recirculation pump, but higher concentration is needed to keep the power output, and higher concentration will cause higher crossover and increase power consumption of air pump, so lower flow rate is not a suitable choice.

In this paper, a fuzzy controller is introduced to adjust the work current density and concentration of DMFC dynamically following the driven load. The simulation results show that the controller can keep the DMFC working at MPPs. With the aid of the fuzzy controller, the methanol concentration and crossover are always the lowest corresponding to the driven load. For the air flow rate is proportional to the concentration, the lowest concentration also leads to the lowest power consumption of air pump.

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