Temperature Maintenance of Proton Exchange Membrane Fuel Cell System Based on Genetic Algorithm

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Abstract. Temperature is one of the main factors affecting proton exchange membrane fuel cells(PEMFC). In severe cold conditions, when equipment with PEMFCs is shut down for a short period of time, the battery temperature will drop to below zero degrees Celsius. Under this condition, the generation of ice will increase the battery start-up time, and cold start of PEMFC often requires additional heat sources. At the same time, repeated cold starts will seriously reduce the lifespan of proton exchange membrane fuel cells. Aiming at this problem, a temperature maintenance strategy is proposed for short-term low-power output of PEMFCs in severe cold conditions based on the temperature dynamic model of PEMFCs, which reduces energy loss through genetic algorithm effectively.

Keywords: PEMFC; Temperature Dynamic Model; Genetic Algorithm.

1. Introduction

Proton exchange membrane fuel cells (PEMFCs) have the characteristics of being environmentally friendly and conducive to sustainable development as a type of hydrogen fuel cell. At the same time, PEMFCs have advantages such as high energy density, low-temperature operation, and rapid start-up[1], which make them widely applicable in the field of transportation. As the core of fuel cell vehicles, PEMFC must withstand various complex working conditions and severe environments[2].

Appropriate temperature condition is crucial for the successful operation of PEMFC, as excessively high temperatures can damage the proton exchange membrane, while excessively low temperatures can reduce the electrochemical reaction rate. Maintaining the temperature of PEMFCs under low temperature conditions or achieving cold start of PEMFC has been widely studied. The generation of ice is an important factor affecting the success of cold start. K. Jiao and M. Oszcipok's experiments both failed in cold start under the initial condition of minus 20 degrees Celsius, both of which pointed out that the cold start load level and blowing speed must be high to prevent water from condensing into ice inside the battery[3,4]. In response to the cold start problem of PEMFC, Min et al. designed a new cold start mode that takes the volume of ice on the membrane and the absorbed heat as inputs for fuzzy control, and the current density as output. Compared with traditional start modes, this mode shortens the start time, reduces the generation of ice, and successfully achieves cold start at minus 20 degrees Celsius[5]. Liu et al. designed PEMFC cold start experiments under various load currents, which show that increasing the initial water content can alleviate the problem of startup failure under high current density, but it will delay the success time of cold start[6]. Wang et al. studied the rapid cold start of a PEMFC system with a rated power of 70kW without auxiliary heating, achieving rapid cold start at minus 20 degrees Celsius and minus 30 degrees Celsius. However, after 30 experiments, the rated performance of the battery decreased by 1%[7]. Frequent temperature changes of PEMFC can also reduce its lifespan[8]， frequent constant pressure cold starts will cause aggregation of platinum catalysts and decomposition of membrane polymer structures, causing irreversible damage to platinum catalysts and proton exchange membranes[9], Yang et al. point out that the output performance of PEMFC significantly decreases after repeated cold starts, due to the high current density and low voltage startup method leading to the decomposition of the membrane polymer structure[10].

In the field of transportation, PEMFCs are generally used as vehicle power batteries which require frequent power switching leading to a decline in the lifespan of PEMFC. At the same time, the temperature of PEMFC in the shutdown state will drop to the ambient temperature. In severe cold areas, cold start of PEMFC needs to consider issues such as water freezing inside the battery and energy consumption of external facilities preheating. In extremely cold environments, PEMFC startup will take a long time or even fail to start successfully. Meanwhile, cold start under low temperature conditions can significantly reduce the lifespan of PEMFC. Therefore, it should be discussed to maintain the temperature of PEMFC when it is in standby mode in severe cold environments.

This paper focuses on the temperature maintenance problem of PEMFC in severe cold environments, establishes a temperature dynamic model of PEMFC, proposes a PEMFC temperature maintenance scheme, and optimizes the current density of the battery through genetic algorithm, effectively reducing the energy loss of the battery.

2. Model Description

PEMFC system is a complex nonlinear system. To simplify modeling, this paper makes the following assumptions: the pressure and temperature inside the fuel cell stack are uniform, the stack is heated as a solid block, and the gases involved in the reflection are in an ideal state.

2.1 Stack Voltage Model

The output voltage V_{cell} of a single battery in a PEMFC stack consists of four parts: Nernst voltage E_n, activation loss V_{act}, ohmic loss V_{ohmic} and concentration loss V_{conc}.

$$V_{cell} = E_n - V_{act} - V_{ohmic} - V_{conc} \tag{1}$$

The Nernst voltage is related to the stack temperature T_{fc}, anode hydrogen gas partial pressure P_{H_2}, and cathode oxygen gas partial pressure P_{O_2}:

$$E_n = 1.299 - 0.85 \times 10^{-3}\left(T_{fc} - 298.15\right) + 4.31 \times 10^{-5} \times T_{fc} \times \ln\left(P_{H_2} P_{O_2}^{\frac{1}{2}}\right) \tag{2}$$

The activation loss can be expressed using an empirical formula:

$$V_{act} = -\left[\xi_1 + \xi_2 T_{fc} + \xi_3 T_{fc} \ln\left(C_{O_2}\right) + \xi_3 T_{fc} \ln\left(I_{fc}\right)\right] \tag{3}$$

where I_{fc} and C_{O_2} represent the output current of the battery and the oxygen concentration in the cathode catalyst layer. ξ_1、ξ_2、ξ_3、ξ_4 are empirical parameters: $\xi_1 = -0.948$，$\xi_3 = 7.6 \times 10^{-5}$，$\xi_4 = -1.93 \times 10^{-4}$，$\xi_2$ can be obtained from the following equation:

$$\xi_2 = \left[286 + 20 \times \ln(A) + 4.3 \times \ln\left(C_{H_2}\right)\right] \times 10^{-5} \tag{4}$$

where A is the activation area and C_{H_2} is described by Eqs.(5) as follows:

$$C_{H_2} = \frac{P_{O_2}}{5.08 \times 10^6 \times e^{-\frac{498}{T_{fc}}}} \tag{5}$$

The Ohmic loss is related to the membrane resistance R_m and the electrode plate resistance R_c:

$$V_{ohmic} = I_{fc}(R_m + R_c) \tag{6}$$

the electrode plate resistance is a constant value. The membrane resistance is affected by current density and temperature which can be obtained using Eqs.(7) as follows:

$$R_m = \frac{\rho_M l}{A} \tag{7}$$

where l is the thickness of membrane, ρ_M is the membrane resistivity：

$$\rho_M = 181.6 \times \left[1 + 0.03\frac{I_{fc}}{A} + 0.063\left(\frac{T_{fc}}{303}\right)^2\left(\frac{I_{fc}}{A}\right)^{2.5}\right] \Big/ \left[\left(\lambda - 0.634 - \frac{3I_{fc}}{A}\right) e^{4.18\times\frac{T_{fc}-303}{303}}\right] \tag{8}$$

where λ is an adjustable parameter with a value range between 14 and 23.

The concentration loss is expressed as follows:

$$V_{conc} = Bln\left(\frac{I_{max}}{I_{max} - I_L}\right) \tag{9}$$

where B is an empirical constant， $I_{max}$is the theoretical maximum current density, and $I_L$is the actual current density.

The output power of the stack $P_{fc} = nI_{fc}V_{cell}$, where n is the number of cells in the stack.

2.2 PEMFC Dynamic Temperature Model

According to the specific heat capacity formula $Q = cm\Delta T$, the relationship between battery heat generation, heat dissipation, and battery temperature per unit time can be expressed as:

$$C_{fc}M_{fc}\frac{dT_{fc}}{dt} = Q_{gen} - Q_{dis} = \left(Q_{react} - P_{fc}\right) - \left(Q_{gas} + Q_{rad} + Q_{cool}\right) \tag{10}$$

where C_{fc} is the specific heat capacity of the fuel cell, M_{fc} is the mass of the fuel cell, Q_{react} is the total electrochemical energy released by the fuel cell reaction per unit time, P_{fc} is the output power of the fuel cell, Q_{gas} is the difference in heat brought in and out by the fuel cell reaction gas per unit time, Q_{amb} is the radiation heat from the fuel cell to the outside per unit time, and Q_{cool} is the heat dissipation of the fuel cell radiator per unit time.

The energy generated per unit time by a stack depends on the chemical reactions that occur in the stack, and the reaction equation is:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$$

all the energy generated by this reaction can be obtained through $\Delta H = 285.8kJ/mol.$

The hydrogen consumption per unit time of the fuel cell stack is expressed as follows:

$$N_{H_2}^{react} = \frac{nI_{fc}}{2F} \tag{11}$$

where n, I_{fc} and F represent the number of cells in the stack and the output current of the battery. The total chemical energy released by the reaction per unit time can be expressed as:

$$Q_{gen} = \Delta H\frac{nI_{fc}}{2F} \tag{12}$$

Q_{gas} is related to the input airflow energy Q_{in} and output airflow energy Q_{out}. This model considers the low-power output state of FC, assuming that the input and output airflow rates are not large and their differences remain constant.

Q_{rad} is related to the surface area A_{fc}, ambient temperature T_{atm} and stack temperature, calculated using the Stefan-Boltzmann law::

$$Q_{rad} = \varepsilon\sigma A_{fc}\left(T_{fc}^4 - T_{atm}^4\right) \tag{13}$$

Q_{cool} is caused through forced air cooling heat exchange:

$$Q_{cool} = CAv_{air}\left(T_{fc} - T_{air}\right) \tag{14}$$

where v_{air}, C, A represent the heat transfer wind speed, the gas correlation coefficient, and the air-cooled heat dissipation area.

3. Genetic Algorithm

Genetic algorithm originated from computer simulation of biological systems, which has been widely applied in fields such as function optimization, production scheduling, and adaptive control, improving the efficiency of solving certain problems. It simulates the replication, crossover, and mutation that occur in nature. Starting from any initial population, it generates the next generation of population that is more adaptable to the environment through random selection, crossover, and mutation, thereby obtaining the optimal solution of the problem. It is a global search optimization method[11]. The specific steps are shown in Fig. 1.

The initial population is generated by generating binary codes, and the basic characteristics of a population in genetic algorithms are the number of individuals in the population and the chromosome coding of individuals in the population. There are various ways to encode individuals, and commonly used methods include binary encoding, gray code encoding, floating-point encoding, etc. The algorithms operate the chromosome encoding of individuals and the optimal solution is obtained through decoding.

The fitness value of an individual is used to evaluate the quality of the solution to the problem, and an appropriate fitness value calculation function can improve the competitive relationship among individuals in the population, which can effectively improve algorithm efficiency.

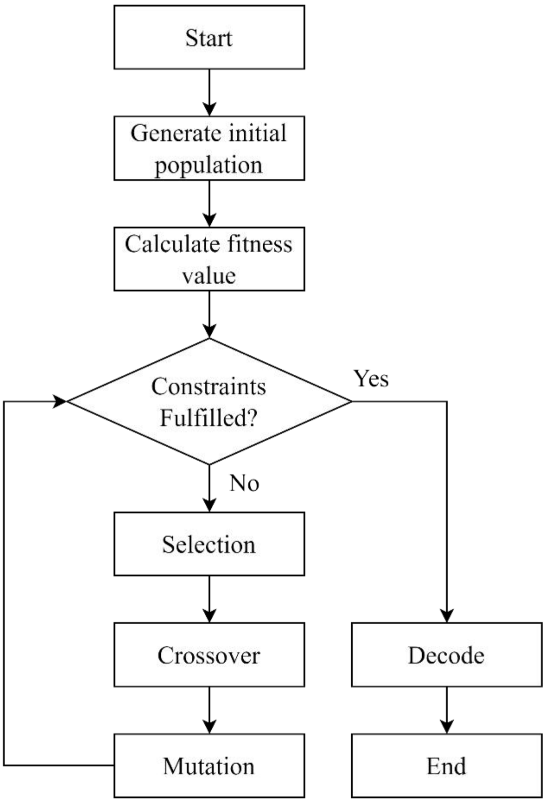

Fig. 1 Genetic Algorithm

Roulette is used in selection operation. The proportion of a certain individual's fitness to the total fitness of all individuals is the probability of that individual being selected, that is, the probability of a certain individual being selected can be expressed by Eqs.(10) as follows:

$$P_i = \frac{f(x_i)}{\sum_{j=1}^{N} f(x_j)} \tag{15}$$

The crossover operation is similar to the crossover of biological chromosomes. It randomly selects a position in the paternal chromosome, and then crosses the chromosomes of two paternal individuals at that position. Crossover ensures the inheritance of the good characteristics of the paternal population to the next generation, thereby producing new better individuals.

The mutation operation changes the genetic information of a certain point or points on a chromosome. It is mainly used to prevent algorithms from getting stuck in local optima during the process.

4. Experimental Result

A temperature dynamic model of FC was constructed based on Eqs.(1) to Eqs.(14). Considering the regular operation temperature of FC, the initial temperature of the system is set to 70 degrees Celsius (343K), and the ambient temperature is set to minus 20 degrees Celsius(253K). The expected final temperature is 20 degrees Celsius(293K), and the minimum temperature of the battery should not be lower than 0 degrees Celsius(273K) to prevent icing. Considering actual situations, there are delays in the changes of each variable in the model. Fig. 2 shows the relationship between battery temperature and genetic algebra under this condition. Fig. 3 shows the relationship between energy loss and genetic algebra. Some generations' data with distinct characteristics are shown in Table 1.

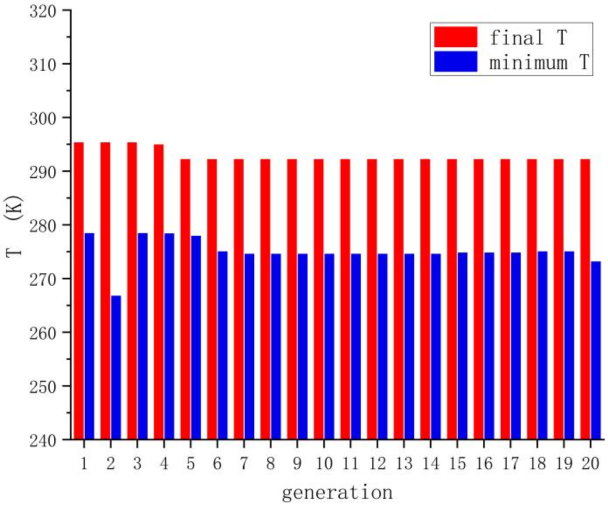

Fig. 2 Final Temperature and Minimum Temperature

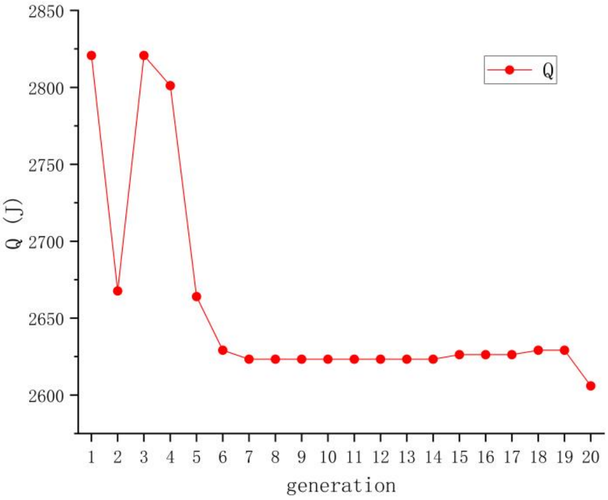

Fig. 3 Energy Loss

The algorithm meets the termination condition in the 20th generation, with a final temperature of 292.3K and a relative error within 0.25%. The minimum temperature is related to the optimization of energy loss, reaching 273.3K in the 20th generation, meeting the constraint of higher than 273K. In the 20th generation, the energy loss of the system is 2606J, which is 7.6% less than the first generation(2821K) and 54% less than the situation of maintaining the original battery temperature without changing the current(5665K). The algorithm has a significant optimization effect on the energy loss.

Table 1. Experimental Data of Generation 1, 2, 10, 11, 19 and 20

Generation	Final T / K	Minimum T / K	Energy loss / J
1	295.5	278.6	2821
2	295.4	266.9	2668
10	292.3	274.7	2623
11	292.3	274.7	2623
19	292.3	275.2	2629
20	292.3	273.3	2606

It can be obtained from Fig. 2 and Fig. 3 that the energy loss of the second generation is significantly lower than that of the first generation, and its lowest temperature is the lowest among all generations. This is due to some individuals choosing to not work for a long time during the optimization process, resulting in the inability of the fuel cell stack to produce energy. Meanwhile, its energy loss is significantly higher than that of generations after 5, due to the fact that the optimization process of the final temperature in the second generation has not yet ended. The final temperature in the second generation is higher than that of its descendants, because the optimization is not yet completed and this operation at this time will lead to more energy generation. This situation does not occur again in the third generation because the algorithm imposes penalty on individuals with a minimum temperature below 273K, reducing their fitness value to prevent such genes from being passed to the next generation.

The seventh to nineteenth generations show little difference, but a breakthrough is made in the twentieth generation because the algorithm continuously monitors the fitness value of ten consecutive generations. When the fitness value of ten consecutive generations remains unchanged, the algorithm increases the mutation rate of individuals, introducing new genotypes to jump out of local optima.

5. Experimental Result

In this paper, an energy optimization algorithm based on genetic algorithm for FC in low-temperature environments is proposed. Firstly, an output power model and a dynamic temperature model for FC stacks are established. Secondly, considering energy loss, a genetic algorithm is designed to select reasonable operation under target conditions. Finally, a FC system model is built on simulation platform and the optimization scheme is verified. The experimental results show that the scheme can effectively reduce energy loss during the maintenance of FC temperature in low-temperature environments, while avoiding battery degradation caused by cold start.

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