Multi-objective optimization of SOFC systems

Xiaojuan Wu¹, Ling He², Danhui Gao³ and Yuanyuan Zhu³

1 Associate professor, School of Automation Engineering, University of Electronic Science and Technology of China, Chengdu, China
2 Student, School of Automation Engineering, University of Electronic Science and Technology of China, Chengdu, China
3 Lecturer, Department of biology and chemical engineering, ZhiXing College of HuBei University, Wuhan, China

Abstract. For solid oxide fuel cell (SOFC) development, maximizing its electrical efficiency and minimizing its cost are two important optimization objects. A new optimization strategy is proposed in this work, which can maximize the SOFC electrical efficiency and minimize the cost in the case of an air leakage fault. The proposed optimization method involves a fault diagnosis module, a switching module and two backup optimizers. The fault diagnosis part is employed to identify the SOFC current fault type, and the switching module is used to select the appropriate backup optimizer. For the efficiency and cost are two conflicting objectives, the multi-objective optimization strategy based on a non-dominated sorting particle swarm optimization algorithm is applied to determine the trade-off solutions. The optimization results show the proposed method can achieve the maximum efficiency and the minimum cost in the case of SOFC normal, and even in the air leakage fault.

1. Introduction
Solid Oxide Fuel Cell (SOFC) is one of the most promising technologies among various new energy resources. However, efficiency and cost are two major hurdles to make SOFC unattractive as an alternative option for electricity users. For the users, they may wish to maximize the SOFC electrical efficiency, but meanwhile to minimize its costs. Efficiency and cost are conflicting to each other, because the higher efficiency would increase the cost. Therefore, to obtain the trade-off solutions, Pareto front has been introduced to the SOFC system, on which all points are potentially an optimum solution for the efficiency and cost optimization. In Ref.[1], by combing the efficiency and cost with different weights, a plurality of Pareto solution was obtained for the SOFC system. In Refs.[2-4], based on genetic algorithm, a series of Pareto solution was acquired for the SOFC efficiency and cost optimization. However, the existing optimization strategies are designed in the normal operation, which can not consider the fault effect on the instantaneous performance of the SOFC system.
For the SOFC system, faults may happen anytime and anywhere, which may further result in the performance losses and even system failure [5]. In the last decades, plenty of fault diagnosis approaches have been advocated to improve the SOFC system stability [6-8]. Even if many optimization techniques and fault diagnosis methods have been developed and implemented on the SOFC system, combining optimization techniques with fault diagnosis technique is still lacking. As far as we know, no literature is to study the maximum efficiency and the minimum cost for the SOFC system under fault state.
Motivated by the above requirement, simultaneous fault diagnosis and online optimization strategy is proposed in this study, which can maximize the efficiency and minimize the cost in the case of SOFC normal operation and the air leakage fault. The proposed tactics contains a fault diagnosis module, a switching part and two backup optimizers. The diagnosis module is used to detect the SOFC system current fault (air leakage faults or normal). The switching module is employed to choose the suitable backup optimizer. A non-dominated sorting particle swarm optimization (NSPSO) algorithm is presented to design the two backup optimizers in the case of air leakage fault and normal operation. The paper hereafter is formed as below. The SOFC models in the case of normal operation and air leakage fault are presented in Section 2. The proposed multi-objective optimization strategy for the SOFC system is explained in Section 3. In Section 4, the optimization results from the concerned SOFC system are given. Section 5 draws the conclusion.

2. SOFC model

A typical SOFC system is considered in this study, which consists of an air compressor, an air heat exchanger, a fuel heat exchanger, a stack and a burner [9]. In the following, the main physical equations have been given above, and further details about the SOFC model can be retrieved from the literature [10-11].

The SOFC electrical efficiency is evaluated by [10]:

$$\eta = \frac{VI - P_o}{W_{fuel,in} \cdot LHV_f}$$  \hspace{1cm} (1)

Where, $V$ is the stack voltage, which is obtained by [12-15]:

$$V = E - \eta_{elec} - \eta_{act} - \eta_{con}$$  \hspace{1cm} (2)

In the normal operation, the cold gas inlet flow rate in the air heat exchanger is given by:

$$W_c = W_{air,in}$$  \hspace{1cm} (3)

Under the air leakage fault, the cold inlet flow rate of the air heat exchanger is substituted by the following equation:

$$W_c = W_{air,in} - W_H$$  \hspace{1cm} (4)

Where, $W_H$ is the air leakage flow rate between the air compressor and the air heat exchanger, which is expressed by [16]:

$$W_H = \begin{cases} \pi C_D D^2 H \left( \frac{P_h}{P_{a,out}} \right)^{\gamma/y} \frac{2\gamma}{\gamma - 1} \left[ 1 - \left( \frac{P_h}{P_{a,out}} \right)^{(y-1)/(\gamma-1)} \right] & \text{if } \frac{P_h}{P_{a,out}} > \left( \frac{2}{\gamma + 1} \right)^{1/(\gamma - 1)} \\ \pi C_D D^2 H \left( \frac{2}{\gamma + 1} \right)^{(y+1)/(2(\gamma-1))} & \text{if } \frac{P_h}{P_{a,out}} \leq \left( \frac{2}{\gamma + 1} \right)^{1/(\gamma - 1)} \end{cases}$$  \hspace{1cm} (5)

For the SOFC system, the cost balance model can be expressed as follows [11]:

$$C_1 \cdot Ex_1 + C_3 \cdot Ex_3 = C_1 \cdot Ex_1 + C_4 \cdot Ex_4 + Z_h$$  \hspace{1cm} (6)

$$C_6 \cdot Ex_6 + C_{10} \cdot Ex_{10} = C_5 \cdot Ex_5 + C_9 \cdot Ex_9 + Z_h$$  \hspace{1cm} (7)

$$C_8 \cdot Ex_8 = C_7 \cdot Ex_7 + C_{12} \cdot Ex_{12} + Z_i$$  \hspace{1cm} (8)

$$C_3 \cdot Ex_3 + C_{11} \cdot Ex_{11} + C_{13} \cdot Ex_{13} = C_2 \cdot Ex_2 + C_{10} \cdot Ex_{10} + Z_i$$  \hspace{1cm} (9)

$$C_4 \cdot Ex_4 = C_3 \cdot Ex_3 + C_{11} \cdot Ex_{11} + Z_b$$  \hspace{1cm} (10)
Where, $Z_h, Z_a, Z_c,$ and $Z_b$ are the cost rates for the fuel heat exchanger, air heat exchanger, compressor, stack and burner respectively, which are calculated by Ref. [10]. $E_{x_k}$ is the total exergy rate for the $k$th stream, which is estimated from Ref.[11]. $C_k$ is the cost per exergy unit for the stream of the SOFC system.

3. Multi-objective optimization strategy for the SOFC system

The proposed optimization strategy for the SOFC system consists of three parts: fault diagnosis module, switching module and optimization part. In the following subsections, each module is described in details.

3.1. Fault diagnosis module

The diagnosis module is presented to classify the current fault type for the SOFC system. For the air in the pipeline linking the air compressor to the air heat exchanger occurs leakage, the inlet gas flow rate of the air heat exchanger will be reduced compared to the normal operation. Thus the air heat exchanger inlet flow rate residual $\delta_w$ is selected as an indicator to diagnose the fault, which is given as below:

$$S = \begin{cases} 
1 & \delta_w = W_{c(N)} - W_e = 0 \\
2 & \delta_w = W_{c(N)} - W_e \neq 0 
\end{cases}$$

(11)

Where, $W_e$ is the real inlet flow rate of the air heat exchanger, and $W_{c(N)}$ is the cold inlet flow rate of the air heat exchanger in the case of normal operation. When the residual $\delta_w$ is zero, the symptom $S$ is 1, which indicates that the SOFC system is in normal running. Otherwise, the symptom $S$ is 2, which shows that the air leakage fault occurs.

3.2. Switching module

Based on the fault diagnosis results, the switching module selects the appropriate backup optimizer to optimize the electrical efficiency and cost for the SOFC system, which is designed as follows:

$$u = \begin{cases} 
    u_N & (S = 1) \\
    u_F & (S = 2) 
\end{cases}$$

(12)

When the Boolean variable $S$ is equal to 1, the optimization law $u_N$ in the case of SOFC normal operation is chosen to optimize the efficiency and cost. While if the Boolean variable $S$ is changed to 2, the optimization law $u_F$ in the case of air leakage fault is designed to optimize the efficiency and cost. How to obtain the optimization law $u_N$ and $u_F$ will be discussed in the following subsection.

3.3. Optimization module based on non-dominated sorting PSO algorithm

The optimization goal is to maximize the electrical efficiency and minimize the cost. Therefore, the following fitness function is formulated:

$$\max \eta$$

(13)

$$\min C_{i3}$$

(14)

To limit the results to a range of feasible points, the following inequality constraints are considered in this study: 1) the burner outlet temperature $T_4 \leq 1400K$; 2) the stack inlet temperature difference $\Delta T \leq 200K$.

Particle swarm optimization (PSO) method is a stochastic optimization technique, which is proposed by Eberhart and Kennedy in 1995. In the PSO algorithm, each particle has a leader which is used to update its position and velocity. However, each particle has a series of various leaders in the NSPSO algorithm. The steps of the non-dominated sorting PSO algorithm is given as below[17]: 1) Generate
an initial population; 2) Generate an offspring population; 3) Update the personal best position; 4) Update the global best position.

4. Optimization results

4.1. Case 1: SOFC normal operation

In the SOFC normal operation, the switching signal $S$ is kept 1, and the optimization law in the normal operation is executed on the SOFC system. To evaluate the proposed method, the non-dominated sorting genetic algorithm (NSGA) is employed in this study to compare with the proposed NSPSO. The parameters of the NSGA are set as follows: population: 150, iteration steps: 200, crossover probability: 0.9, and mutation probability: 0.1. Using the two optimization methods, a series of Pareto optimal solutions is achieved, which is shown in figure 1(a). The blue line indicates the optimization results with the NSPSO algorithm, and the red line depicts the results with the NSGA method. Minimizing the cost and maximizing the electrical efficiency are obviously in conflict with each other. Increasing the efficiency up to about 34% does not significantly increase the unit cost of the SOFC electrical power, while increasing it from 34% to 37% results in a moderate increase in the unit cost of the SOFC electrical power. Increasing the efficiency beyond 37%, leads to a steep rise in the cost. In order to compare the two algorithm, the following four generic metrics are calculated: 1) Number of non-dominated solution (NDS); 2) Spread; 3) Spacing; 4) Maximum spread.

From figure 1(a), the optimization result with the NSPSO method is obviously better than the NSGA algorithm. Further, the metrics previously described are calculated. The number of the NDS in the two algorithm are both 150. The spread metric with the proposed algorithm is 0.4858, however this is 0.7205 with the NSGA method, which implies the uniformity of the solution is better. The maximum spreads are respectively 0.0223 and 0.0211 with the proposed algorithm and the NSGA. The spacing with the proposed algorithm is $7.5388 \times 10^{-5}$, however the spacing with the NSGA method is $8.3082 \times 10^{-5}$. All these metrics indicate that the proposed NSPSO algorithm is superior to the NSGA method.

(a) The Pareto solution under SOFC normal operation (b) The optimal fuel utilization operation
The optimal air inlet flow rate

Figure 1. Optimization results under SOFC normal operation

In the optimization process, the variations of the decision variables ($u_f$, $W_{fuel,in}$, and $I$) are displayed in figure 1(b,c,d). Each point on the horizontal axis directly corresponds to an optimal solution in figure 1(a). For increasing the fuel utilization results in the improvement of efficiency and cost objective functions, the maximum value of the fuel utilization is selected, which is given in figure 1(b). The air inlet flow rate and the current cause a conflict between the defined efficiency and cost objective functions. An increase in the air inlet flow rate shifts the SOFC efficiency to the better optimization result, however, leads to the cost increase. Therefore, the current and the inlet air flow rate are the most widely distributed parameters over their allowable domain values. The current is varied from 10A to 50A, and the inlet air flow rate is changed from 0.1mol/s to 0.55mol/s.

In figure 1(a), each point in the Pareto front is an optimum non-dominated solution. The manufacturer needs to consider many possible “trade-off” solutions and select the optimum one based on their actual needs and interests. In this study, the TOPSIS approach is employed to choose the best optimum solution based on the following steps[18]:

1) The cost and efficiency data in figure 1(a) are presented in a non-dimensionalized form, which is given in figure 2.

Figure 2. The optimal point under SOFC normal operation

2) Find an ideal solution and a non-ideal solution. The ideal solution is an imaginary point where each objective can obtain the optimum value, which is labeled point A in figure 2. Point A represents the lowest cost with 32.59$/GJ as well as the highest efficiency with 41.57%. The non-ideal solution is
also an imaginary point where each objective has its worst value, which is marked point B in figure 2. Point B gives the highest cost with 36.62$/GJ as well as the lowest efficiency with 32.23%.

3) Calculate \( d^- / (d^- + d^+) \). \( d^- \) stands for the distance between any point in the Pareto front and the ideal point A, and \( d^+ \) is the distance between any point in the Pareto front and the non-ideal point B. The best optimum solution is chosen as the point which has the longest distance to the non-ideal solution (point B) and the shortest distance to the ideal solution (point A). Thus, the minimum value of \( d^- / (d^- + d^+) \) is the best optimum solution, which is labeled point C in figure 2. The cost is 34.74$/GJ, and the efficiency is 40.03%.

4.2. Case 2: Air leakage fault

To test the performance of the proposed optimization strategy in the case of air leakage fault, the hole diameter \( D_h \) is increased from 0 to 2mm to simulate the fault.

When the fault diagnosis module detects that the air leakage occurs, the switching signal \( S \) is changed from 1 to 2. The obtained optimization law in the air leakage fault is carried on the SOFC system. In comparison with the normal operation, the optimization results are presented in figure 3.

\[ \text{Figure 3. Optimization results under air leakage fault} \]
In figure 3(a), the blue line reflects the Pareto solution under the air leakage fault, while the red line describes the solution under the normal operation, which is the same with the blue line in figure 1(a). Because of the air leakage, the same efficiency will mean the greater costs compared to the normal operation. The decision variables variations under the air leakage fault are given in figure 3(b,c,d). The fuel utilization still keeps 0.85, for an increase in the fuel utilization brings both the SOFC efficiency and the cost to the better optimization results. The current and the air inlet flow rate are still changed over their acceptable domains, however, are higher than the values under the SOFC normal operation. Based on the TOPSIS method previously introduced, the best optimum solution under the air leakage fault condition is marked point C in the figure 4.

![Figure 4. The optimal point under air leakage fault](image)

The cost is 34.31$/GJ, and the efficiency is 36.04%. The ideal and the non-ideal solutions are respectively labeled Point A and B. Point A represents the lowest cost with 32.97$/GJ as well as the highest efficiency with 37.54%, while Point B gives the highest cost with 37.84$/GJ as well as the lowest efficiency with 31.42%.

5. Conclusions
In this study, the improved multi-objective optimization strategy for the SOFC system has been proposed. The objective is to achieve the maximum efficiency and minimum cost in the air leakage fault state. The model-based fault diagnosis module is firstly employed to classify the current fault type, and then the switching module is used to adjust the backup optimizer. The NSPSO algorithm is presented to carry on the efficiency and cost optimization in the case of SOFC normal and air leakage fault. Compared with the NSGA algorithm, the trade-off curve between the efficiency and cost is better with the NSPSO. Based on the obtained Pareto solution, the TOPSIS method is applied to obtain the best optimum solution under the normal and air leakage fault. The optimization results can offer a help for designing the SOFC system with a high efficiency and a low cost.

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