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Multi-Stack Fuel Cell System Stacks Allocation Optimization Based on Genetic Algorithms

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Abstract

High-powered and modularity is the trend for fuel cell systems. Similar to the evolution from single-cylinder to multi-cylinder in conventional internal combustion engines, fuel cell systems shall also follow this developing process. Compared to single-stack fuel cell systems, multi-stack fuel cell systems (MFCS) can enhance the system maximum output power and improve the system performance. To achieve modular design and improve the performance of high-powered MFCS, a MFCS stacks allocation optimization algorithm based on genetic algorithms is proposed in this paper. First, remaining useful life (RUL) and efficiency are choosing as an integrated optimization index, the decision model for MFCS stacks allocation is developed. Then, a heavy-duty commercial vehicle was used as an example to match the vehicle power train parameters. The genetic algorithm is used to solve the global optimal stacks allocation scheme for the vehicle in a specific application scenario. The individual fitness values in the genetic algorithm are solved by the SQP algorithm. The optimized results are analyzed and beneficial conclusions are obtained. Weights of efficiency and RUL and the number of stacks has impacts on the determination of optimal stacks allocation scheme. The overall system efficiency will increase with the efficiency factor weight increase, and the overall RUL will decrease with the efficiency factor weight increase. If the focus is on improving the overall economy of the MFCS, the efficiency/RUL weights shall be taken as 1/0. Finally, the impact of different stacks allocation schemes on the efficiency and RUL of the MFCS is compared.

Introduction

Proton exchange membrane fuel cell (PEMFC) as a kind of electrochemical reaction device could convert the chemical energy in hydrogen into electrical energy quietly and efficiently. With the fuel cell system's maximum power demand increasing, the multi-stack fuel cell system (MFCS) has been investigated and developed. A MFCS could provide a higher power output compared to a single-stack fuel cell system (SFCS). Appropriate control strategies could enhance the performance of the MFCS. MFCS is already applied in the fields of rail transport [1], ships [2], power plants et al. [3].

In recent years, the possibilities of MFCS applications and the special problems of MFCS applications have been studied in various ways. Palma et al. [4] described the disadvantages of increasing the system power by increasing the number of single cells. A modular design approach for the fuel cell system is proposed and an example design of a 150kW MFCS and corresponding DC/DC converter is given. Dépature et al. [5] built a simulation model of MFCS and verified the simulation results through experiments. The results showed that MFCS can improve the system reliability than SFCS. Assabumrungrat et al. [6] investigated the effect of the topology of multi-stack solid oxide fuel cell (SOFC) stacks on the system and found that a multi-stack SOFC tandem topology could improve the performance of the system. Bernardinis et al. [7] proposed a fault-tolerant structure for the MFCS with an anti-parallel bypass diode, which allows current to pass through the bypass when a fault occurs in one of the stacks, ensuring that the system continues to operate. Cardenas et al. [8] studied the degradation mode of the MFCS when a stack is failed. The change in energy management strategy and the impact on the overall system efficiency during different stack failures was also investigated. Zhou et al. [9] studied the stacks allocation schemes for an application with a maximum demand power of 30kW and found that the (10kW, 20kW) stacks allocation scheme is more efficient than the (15kW, 15kW) stacks allocation scheme and can improve the system economy. Garcia et al. [10] proposed a power allocation method for MFCS. Compared to SFCS, it contributes to system efficiency and improves the fault tolerance of the system. Xu et al. [11] proposed an energy management strategy for a dual-stack fuel cell vehicle based on a transient optimization approach. In comparison with SFCS, the dual-stack system can significantly improve efficiency, reduce hydrogen consumption and improve driving mileage. Zhu et al. [12] proposed an MFCS control strategy with real-time power distribution, which can improve the efficiency of the system with identical parameters of each stack. Macias et al. [13] optimized the daisy chain allocation strategy by identifying the maximum efficiency point and the maximum output power of each stack, adaptively changing the order of turn-on of different stacks to avoid the overall durability of the system being affected by the rapid aging of a stack. Liu et al. [14] proposed an adaptive power distribution method that integrates the stack operation performance to control the output power of different DC/DC converters through communication-free droop control. In summary, the related works on MFCS were conducted based on average allocation as the stacks allocation scheme. However, average allocation is not the optimal scheme in available stacks allocation schemes. We need to investigate the MFCS stacks allocation method to determine the optimal stacks allocation for a specific application scenario and a specific vehicle.

In this work, we proposed a mathematical model for the optimization of the MFCS stacks allocation. MFCS stacks allocation optimization solution method based on genetic algorithms is proposed. A heavy-duty commercial vehicle was used as the research object to match vehicle power train parameters and study the optimal stacks allocations in vehicle application scenarios. This paper uses a PEMFC stack as the research object for the research of stacks allocation methods. However, the solution methods may also be adapted to other types of fuel cells similarly.

Mathematical Model Description

When the MFCS is in a normal and stable working condition, the stack may be idealized and abstracted as a direct current "power source" as long as an external circuit is looped, according to the PEMFC operating principle. For a multiple power source system, there are many maximum power allocation and power management schemes. As a result, there is an optimal power allocation and power management schemes for improved efficiency and longer RUL at various loads. For MFCS, the ideal stacks allocation scheme may be established by comparing the optimal output powers scheme for all power demands for the various stacks allocation schemes. To obtain the optimal stack allocation solution, a mathematical model for the MFCS stacks allocation problem needs to be developed and solved [15].

Description of optimization index

System efficiency and RUL are considered as the key index to evaluate the performance of fuel cell systems. To obtain better MFCS efficiency and RUL, system efficiency and RUL are used as the index to evaluate the performance of MFCS in the stacks allocation optimization problem. The global optimization objective function is defined as:

$$S^* = \arg\max \; J(S) \tag{1}$$

where S is one of the available stacks allocation schemes; $J(S)$is the global optimum solution result at a certain stacks allocation scheme S; S^* is the global optimal stacks allocation.

The magnitude of the efficiency and the RUL of MFCS is not only related to the maximum power of each stack but also influenced by the power demands of MFCS at each moment and the actual output power of different stacks. To solve the global optimization problem, it is necessary to find the optimal objective value at each moment, where the transient optimization objective function is defined as:

$$J(S) = \max \sum_{l=1}^{L} k\left(P_l^{\mathrm{d}}\right)\left(\alpha \eta_{\mathrm{MFCS}}\left(P_l^{\mathrm{d}}\right) + \beta \delta_{\mathrm{MFCS}}\left(P_l^{\mathrm{d}}\right)\right) \tag{2}$$

where P_l^{d} is one of the power demands in specific application scenarios; $k\left(P_l^{\mathrm{d}}\right)$ is the power demands rate at P_l^{d}; $\eta_{\mathrm{MFCS}}\left(P_l^{\mathrm{d}}\right)$ is the MFCS efficiency at P_l^{d}; $\delta_{\mathrm{MFCS}}\left(P_l^{\mathrm{d}}\right)$ is the MFCS RUL at P_l^{d}; α, β is the weights of the MFCS efficiency and RUL. The variables of optimization are the output power magnitude of different stacks at each moment. The goal of the optimization is to obtain the global optimum value under this stacks allocation scheme.

Description of Constraints

MFCS Efficiency Characteristics Fuel cell stack efficiency is an important economical index, indicating the conversion rate from chemical energy to electrical energy at different output powers. To describe the efficiency characteristics of a PEMFC stack, a polynomial was chosen to be used to fit the power and efficiency points of a 70kW PEMFC stack. In this work, the output power to maximum power ratio is used as the independent variable to fit the stack efficiency characteristic curves, thus expressing the efficiency characteristics of different stacks using a polynomial function. The efficiency characteristic curve can be described as:

$$\begin{aligned} \eta_i\left(x_i\right) &= 1.8503x_i^5 - 8.5011x_i^4 + 14.0855x_i^3 - 10.8165x_i^2 \\ &+ 3.7845x_i + 0.09976, x_i = P_{i,l}^{\mathrm{out}} / P_i^{\max}, i = 1,2,\ldots n, \end{aligned} \tag{3}$$

where $P_{i,l}^{\mathrm{out}}$ is the output power of the i-th stack at P_l^{d}; $P_i^{\max}$ is the maximum output power of the i-th stack; MFCS efficiency is determined by a combination of the efficiency of each stack and the output power of each stack. Based on the efficiency characteristics of the PEMFC stack, the MFCS efficiency can be defined as:

$$\eta_{\mathrm{MFCS}}\left(P_l^{\mathrm{d}}\right)=\frac{\sum_{i=1}^{n} P_{i,l}^{\mathrm{out}}}{\sum_{i=1}^{n}\frac{P_{i,l}^{\mathrm{out}}}{\eta_i\left(P_{i,l}^{\mathrm{out}}/P_i^{\mathrm{max}}\right)}}. \tag{4}$$

MFCS RUL Characteristics

Many factors will affect the RUL of a fuel cell stack, such as material properties, load variation, and control strategies of key components, etc. At present, the RUL of fuel cell systems can only be predicted and estimated by experimental, where the effect of operating conditions (start-stop, power fluctuation rate, etc.) on the fuel cell RUL is not clear. In this work, it is assumed that each stack is kept on during MFCS operation, the effect of start-stop on stack RUL is ignored. Meanwhile, in practical engineering applications, the part of the load fluctuation is compensated by the battery, the effect of load power fluctuation on fuel cell stack RUL is ignored in this study. Therefore, this paper will focus on the effect of the different MFCS stack output power magnitudes on the MFCS RUL, and establish the corresponding descriptive function.

A simplified model for describing the relationship between the fuel cell output power and RUL proposed by Nathalie Herr [16] was referenced and his proposed RUL model was normalized to express the impact degree of different stack output power to maximum power on RUL. Similar to the efficiency characteristic curve, the RUL characteristic curve can be described as:

$$\begin{aligned}\delta_i\left(x_i\right)=&-0.1685x_i^{4}-2.1721x_i^{3}+1.3973x_i^{2}\\&+0.8638x_i+0.2447,\ x_i=P_{i,l}^{\mathrm{out}}/P_i^{\mathrm{max}},\ i=1,2,\ldots n.\end{aligned} \tag{5}$$

From the above RUL characteristics, a functional equation for evaluating the MFCS RUL is established, and the RUL of each stack is considered based on the magnitude of the system average RUL. The RUL of MFCS can be defined as:

$$\delta_{\mathrm{MFCS}}\left(P_l^{\mathrm{d}}\right)=\frac{\sum_{i=1}^{n}\delta_i\left(P_{i,l}^{\mathrm{out}}/P_i^{\mathrm{max}}\right)}{n} \tag{6}$$

Furthermore, the optimization problem needs to meet the following constraints:

$$\sum_{i=1}^{n} P_{i,l}^{\mathrm{out}}=P_l^{\mathrm{d}} \tag{7}$$

$$\sum_{l=1}^{L} k\left(P_l^{\mathrm{d}}\right)=1 \tag{8}$$

$$\Delta P_{\mathrm{low}}<\sum_{i=1}^{n} P_i^{\mathrm{max}}-P_{\mathrm{d}}^{\mathrm{max}}<\Delta P_{\mathrm{high}} \tag{9}$$

$$0.1P_i^{\mathrm{max}} \leq P_{i,l}^{\mathrm{out}} \leq P_i^{\mathrm{max}} \tag{10}$$

$$P_{\mathrm{fc\,min}} \leq P_i^{\mathrm{max}} \leq P_{\mathrm{fc\,max}} \tag{11}$$

$$\alpha+\beta=1 \tag{12}$$

where ΔP_{low} and ΔP_{high} are the upper and lower limits of the maximum power of the MFCS, the purpose is to limit the maximum power of the MFCS to a certain range while meeting the design requirements, taking ΔP_{low} as 0kW and ΔP_{high} as 20kW; P_{fcmin} and P_{fcmax} are the minimum and maximum available fuel cell stack maximum power, take P_{fcmin} as 10kW, P_{fcmax} as 120kW; $P_{\mathrm{d}}^{\mathrm{max}}$ is the maximum output power of the MFCS, which is taken as 240kW according to the results of parameter matching.

In summary, the mathematical model of MFCS optimal stacks allocation is shown as:

$$S^{*}=\arg\max\ J(S),\ P_i^{\mathrm{max}}\in M,\left(P_l^{\mathrm{d}},k\left(P_l^{\mathrm{d}}\right)\right)\in K$$

$$s.t.\begin{cases}\alpha+\beta=1\\ J(S)=\left[\begin{array}{l}\max\ \sum_{l=1}^{L}k\left(P_l^{\mathrm{d}}\right)\left(\alpha\eta_{\mathrm{MFCS}}\left(P_l^{\mathrm{d}}\right)+\beta\delta_{\mathrm{MFCS}}\left(P_l^{\mathrm{d}}\right)\right)\\ s.t.\begin{cases}\eta_{\mathrm{MFCS}}\left(P_l^{\mathrm{d}}\right)=\dfrac{\sum_{i=1}^{n}P_{i,l}^{\mathrm{out}}}{\sum_{i=1}^{n}\dfrac{P_{i,l}^{\mathrm{out}}}{\eta_i\left(P_{i,l}^{\mathrm{out}}/P_i^{\mathrm{max}}\right)}}\\ \delta_{\mathrm{MFCS}}\left(P_l^{\mathrm{d}}\right)=\dfrac{\sum_{i=1}^{n}\delta_i\left(P_{i,l}^{\mathrm{out}}/P_i^{\mathrm{max}}\right)}{n}\\ \sum_{i=1}^{n}P_{i,l}^{\mathrm{out}}=P_l^{\mathrm{d}}\\ 0.1P_i^{\mathrm{max}}\leq P_{i,l}^{\mathrm{out}}\leq P_i^{\mathrm{max}}\\ \sum_{l=1}^{L}k\left(P_l^{\mathrm{d}}\right)=1\end{cases}\end{array}\right.\\ P_{\mathrm{fcmin}}\leq P_i^{\mathrm{max}}\leq P_{\mathrm{fcmax}}\\ \Delta P_{\mathrm{low}}<\sum_{i=1}^{n}P_i^{\mathrm{max}}-P_{\mathrm{d}}^{\mathrm{max}}<\Delta P_{\mathrm{high}}\end{cases} \tag{13}$$

where K is a matrix that contains power demands and power distribution information in a certain application scenario; M is available mature stacks set in market.

Vehicle Power Train Parameters

In the road transport field, MFCS is more suitable for heavy-duty, high-powered commercial vehicles. To obtain the power demands of a MFCS for heavy-duty commercial vehicles, the vehicle power train parameters need to be matched first. In this work, a heavy-duty commercial vehicle is used as an example to solve the MFCS stacks allocation optimization model, and the vehicle parameters and dynamics indexes s are shown in Table 1.

TABLE 1 Vehicle parameters and dynamics indexes.

Parameters	Value
Type	Heavy-duty commercial vehicle
MFCS maximum power (kW)	240
Curb weight (ton)	21.5
Full load weight (ton)	40
Drag area (m^2)	6.95
Coefficient of air resistance	0.75
Maximum speed (km/h)	100
Climbing capacity (%)	>20
0-50 km/h acceleration time	<15s
Rolling resistance coefficient	0.01
Rotation mass coefficient	1.1

Using the vehicle parameters and dynamics indexes in Table 1, according to the vehicle power balance equation, we can determine the maximum power demand of the vehicle, hence the MFCS maximum demand power can be determined. The peak and rated power of the motor are determined by the vehicle's dynamics index including maximum speed, maximum climbing capacity, and acceleration performance. The maximum output power of the motor is determined by the maximum value of the power demand under the three power indexes. The maximum output power of the MFCS can be determined from the equation (14).

$$\alpha_{\mathrm{MFCS}} \leq \frac{P_{\mathrm{MFCS}} P_{\mathrm{d}}^{\max} \eta_{\mathrm{DCF}}}{\left(P_{\mathrm{m}} + P_{\mathrm{amax}}\right)} \tag{14}$$

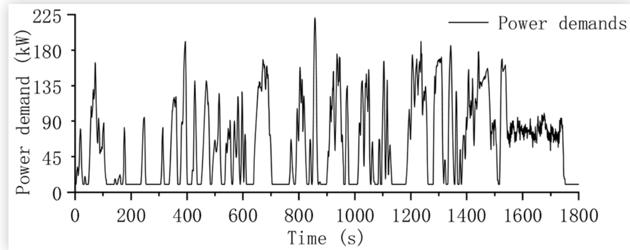
Where P_{m} is the peak power of the motor; P_{amax} is the maximum power of the auxiliary plant; η_{DCF} is the power conversion efficiency; α_{MFCS} is the MFCS supply ratio (the ratio of the MFCS output powers to the power demanded by the load). Most fuel cell commercial vehicle powertrains available on the market currently use weak hybrid solutions (α_{FC}<0.6). Therefore, the maximum power of the MFCS was chosen between 240kW and 260kW, taking into account the actual requirements and the parameters of the prototype vehicle.

By splitting the high-powered fuel cell stack, individual power control of the small stacks helps to improve the overall system efficiency and RUL. At the same time, there is a limit to the number of stacks, and the excessive stacks will increase the difficulty of system control and the cost of MFCS. The maximum power of the mature stack products on the market is concentrated between 10kW and 120kW. Based on the results of vehicle parameter matching, it is determined that the fuel cell system of 240-260kW is split into 3 to 4 stacks, and the effects of different stacks allocation schemes on the economy and durability of the fuel cell system are investigated. The optimal stacks allocation scheme is calculated and selected for a specific operating condition.

MFCS Power Demands Matching

Vehicle driving conditions describe the relationship between speed and time in the process of vehicle driving under the certain road and traffic conditions, reflecting the kinematic characteristics of vehicle driving. If the parameters of the vehicle are determined, the different working conditions will lead to different MFCS power demands, and the difference in power demands will affect the selection of the optimal stacks allocation scheme. Heavy-duty commercial vehicles are characterized by fixed driving routes and single road condition information, and the randomness of their working condition changes is not obvious. Using the China heavy-duty commercial test cycle (C-WTVC) as an example of a typical working condition, the power demands of the vehicle in the working condition can be calculated by using the vehicle driving equation. The power demands of MFCS are obtained by subtracting the battery power demands from the vehicle power demands, and different energy management strategies have different MFCS power demands. The power demands of MFCS vary with time. The continuous-time of the working condition is discretized as Δt , and Δt is taken as 1s here, assuming that the power demand of the fuel cell is equal in each Δt interval and the time range of the whole working condition is t_1~t_2, then in a certain working condition. Here, the sliding filter algorithm equation is used to obtain the power demands of the MFCS, which aims to mitigate the fluctuation of the output power of the MFCS, the equation as shown in:

FIGURE 1 MFCS power demands in C-WTVC scenarios.



$$P_{\mathrm{MFCS}(t)} = k * \frac{P_{\mathrm{MFCS}(t-N+1)} + P_{\mathrm{MFCS}(t-N+2)} + \ldots + P_{e(t)}}{N} + P_a \tag{15}$$

where the sliding window size N=5; the scale factor k=0.7; the parasitic power of MFCS P_a=10kW; $P_{\mathrm{MFCS}(t)}$ and $P_{e(t)}$ are the magnitude of the MFCS power demand and the total power train power demand at a moment t respectively. The MFCS power demands in C-WTVC is shown in Figure 1.

Solution and Discussion

To obtain the global optimal solution, the instantaneous optimization problem needs to be solved first. The optimization problem is based on Sequential Quadratic Programming (SQP) [17] to solve. The global optimum value is obtained by integrating the instantaneous optimal values, and the genetic algorithm [18] is used to iteratively calculate the global optimum value until the algorithm converges to the optimal stacks allocation solution.

Genetic Algorithm-Based Solution

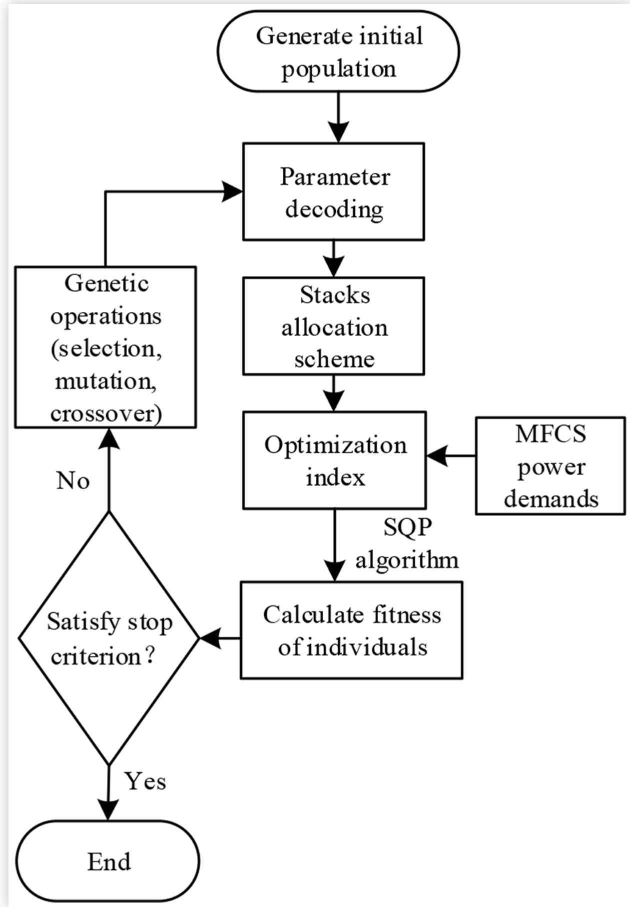
The solution of the optimal stacks allocation mathematical model is a multivariate, nonlinear optimization search process with constraints, and traditional optimization algorithms such as the gradient descent method, Lagrange multiplier method, and linear programming algorithm are difficult to obtain the global optimal solution. In this work, the Genetic Algorithm (GA), a classical intelligent optimization algorithm, is used to solve the problem. Genetic algorithms are based on the theory of population evolution, in which each individual in a population is specially coded, such as 0-1 coding or real number coding, to represent the chromosomes of each individual, after which individual fitness is calculated for each individual. Individual fitness represents the degree of adaptation of an individual in the population, i.e., an individual with a greater individual fitness is considered to have better genes (chromosomes) and has a greater probability of retaining its genes to the next generation. Then, the fitness of each individual in the population is compared, and the population is judged to be evolutionary complete by certain conditions, such as the error between the average fitness and the maximum fitness of the population is below a certain limit. If the evolution is completed, the solution is finished. Otherwise, the population is genetically manipulated for the next round of iterations. The process of solving the optimal stacking scheme based on the genetic algorithm is shown in Figure 2 and is summarized in the following steps:

1. The population is initialized, where the population represents a set consisting of m different stacks allocation schemes, the number of stacks is taken as n, it constitutes an $m \times n$matrix, the population size m is taken as 100, n is taken as 3 or 4, and the random generation of each individual in the population is in the form of binary (0-1) encoding.
2. Parameter decoding is performed, i.e., binary is converted to decimal, and the fitness of each individual is calculated, where the fitness is the reciprocal of the global objective values, and the instantaneous optimization algorithm (SQP algorithm) is called to calculate the optimal objective values at each moment, and the global objective value is obtained by integrating the values, and the fitness value is denoted as $\xi_{i+1}^1, \xi_{i+1}^2 \ldots \xi_{i+1}^m$, where ξ_i^j is denoted as the fitness of the j-th individual in the i-th generation.
3. To determine whether the population meets the termination condition, it is defined here that when the error rate of the mean of individual fitness of two adjacent generations of the population is less than 5%, the termination condition is considered to be met and the solution is finished, as shown in the equation (16), where k is taken as 5%.

$$\left| \frac{ave\left\{\xi_{i+1}^1, \xi_{i+1}^2 \ldots \xi_{i+1}^m\right\} - ave\left\{\xi_i^1, \xi_i^2 \ldots \xi_i^m\right\}}{ave\left\{\xi_i^1, \xi_i^2 \ldots \xi_i^m\right\}} \right| \times 100\% < n \quad (16)$$

4. If the solution is not completed, the individuals of the population are ranked according to their fitness, and the individuals with greater fitness in the population are selected to enter the next generation, and new offspring are generated and combined into the next generation population by crossover, mutation and other operations.
5. Parameter decoding is performed again to calculate the fitness of individuals in the new generation population, and the termination condition is judged, after which iterations are repeated until the algorithm converges to satisfy the termination condition.

FIGURE 2 Genetic algorithm solving process.

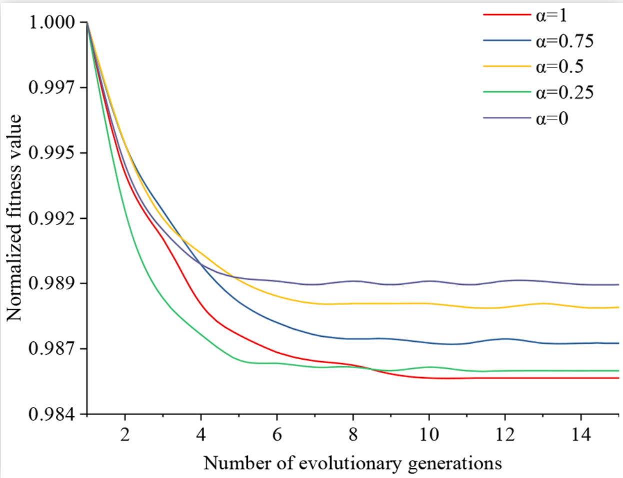


The boundary and constraints in performing the optimal solution are as follows, the sum of the instantaneous output power of each stack is equal to the desired power of the objective condition at that moment, while the respective output power should be less than the maximum power size of the stack, regarding the parameters in the genetic algorithm, the number of populations is set here as 100, and the probabilities of crossover and variation are 0.8 and 0.02, respectively.

Comparison and Analysis of Optimization Results

With the number of stacks of 3, the optimal stacks allocation scheme obtained with different efficiency weights α is calculated, where the efficiency weights are from 0-1 with a step

FIGURE 3 Genetic algorithm convergence diagram.



size of 0.25. The normalized fitness values with evolutionary generations under different weights are shown in Figure 3, and the normalization equation is:

$$J_i^{'} = \frac{1}{J_i^*} / \max\left(\frac{1}{J_1^*}, \frac{1}{J_2^*} \cdots \frac{1}{J_m^*}\right), \ i = 1,2 \ldots m, \tag{17}$$

where J_i^* is the optimal target value for the i-th generation. With different weights, the fitness values generally converge when the number of evolutionary generations reaches 10.

The optimized calculated stacks allocation scheme and the corresponding performance indexes are shown in Table 2. It is seen that the optimization results corresponding to different weights are different for C-WTVC conditions. The choice of the optimal stacks allocation scheme is related to the weights of the RUL and efficiency factors. The maximum power of stack 1 (the largest stack) is unaffected by the weight change and all reach the upper limit of 120kW of the maximum power of a single stack; The maximum power of stack 2 (the second largest stack) tends to decrease and then increase as the weight of the RUL factor increases; The maximum power of stack 3 (the smallest stack) decreases with increasing weight of the RUL factor. The average system efficiency will increase with the increase of the efficiency factor, and the average RUL will decrease with the increase of the efficiency factor. If the focus is on improving the overall economy of the fuel cell system, the weighted efficiency/RUL shall be taken as 1/0.

Assuming that the maximum power range of commercially available stacks is 10kW-120kW, and the maximum power interval between adjacent stacks is 10kW. The weights of the RUL and efficiency were set as 0.5. The objective values of all the stacks allocation schemes were calculated by the enumeration method. The top ten stack allocation schemes with the largest objective values were selected as shown in Table 3. It can be seen that the objective value of (120kW, 100kW, 20kW) stacks allocation schemes is the best, and the optimal objective value is 56.446%, which is the closest to the genetic algorithm optimized stacks allocation scheme. On the other hand, the accuracy of the results obtained by the stacks allocation optimization algorithm is verified. After that, with the number of stacks of 4 and the weights of RUL and efficiency terms of 0.5, the same solution process was carried out. The optimization stacks allocation scheme (120kW, 100kW, 10kW, 10kW) is 4.40% higher than the objective value of the optimal stacks allocation scheme (120kW, 100kW, 20kW).

Figure 4 is a comparison of the objective values of the optimal stacks allocation scheme for different power demands with the number of stacks of 3 and 4, respectively. The figure

TABLE 3 Comparison of optimal objective values for top 10 in 3 stacks allocation schemes.

No.	Stack 1(kW)	Stack 2(kW)	Stack 3(kW)	Objective value(%)
1	120	100	20	56.446
2	110	110	20	56.341
3	120	110	20	56.234
4	120	110	10	56.058
5	120	120	20	56.015
6	120	120	10	55.836

FIGURE 4 Comparison of objective values for two different stacks allocation schemes (α=0.5, β=0.5).

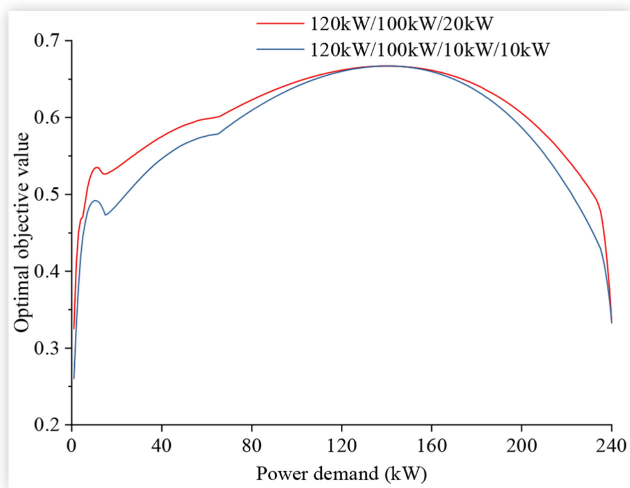


TABLE 2 Optimization results with different weights.

Weights (Efficiency/RUL)	1/0	0.75/0.25	0.5/0.5	0.25/0.75	0/1
Stack 1 (kW)	120	120	120	120	120
Stack 2 (kW)	102	96	102	110	110
Stack 3(kW)	28	24	18	10	10
Objective value (%)	57.736	56.723	56.465	56.771	57.529
Average efficiency (%)	57.736	57.312	56.343	54.547	54.414
Average RUL (%)	50.316	54.956	56.587	57.512	57.529

shows that the objective values corresponding to scheme 2 (120kW, 100kW, 10kW, 10kW) are better in the low power range than those of scheme 1 (120kW, 100kW, 20kW). When the demand power reaches a certain Power, the objective values of the two schemes are equal, and when the demand power is higher, the objective value of the scheme 2 is higher than that the scheme 1. Therefore, it can be concluded that when the fuel cell system often operates in the middle power range, the effect of the number of stacks on the RUL and efficiency of the fuel cell is not significant, and when it often operates in the low power and high power range, increasing the number of stacks will help to improve the system performance index.

Conclusions

High-powered systems is one of the development trends of fuel cell systems. SFCS has disadvantages such as poor single-unit consistency, poor maintainability, and limited efficiency, which limit the application of fuel cell systems in high-powered scenarios. MFCS has the advantages of modular design, high-powered, fault tolerance, and increases the freedom of parameter matching and control strategy design. In this work, the MFCS stacks allocation optimization algorithm are proposed with specific application scenarios by considering efficiency and RUL as the integrated optimization index, and the optimization problem is solved by genetic algorithms, and some beneficial results are obtained. The main conclusions of this paper are shown below:

1. Based on efficiency and RUL integration optimization index and objective constraints, a mathematical model can be established for the MFCS stacks allocation problem, and the optimal stacks allocation scheme can be determined using the genetic algorithm and SQP algorithm.
2. The stacks allocation optimization can help to improve the MFCS fuel economy and system durability.
3. The optimal MFCS stacks allocation scheme is related to the efficiency and RUL weights, number of stacks etc. The optimal MFCS stacks allocation scheme for this application scenario can be determined by considering these influencing factors.

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Definitions/Abbreviations

MFCS - multi-stack fuel cell system
SFCS - single-stack fuel cell system
ICE - internal combustion engine
PEMFC - proton exchange membrane fuel cell
C-WTVC - China heavy-duty commercial test cycle
WTVC - World Transient Vehicle Cycle
RUL - remaining useful life

Symbols

α weight of efficiency
β weight of RUL
η the efficiency of the MFCS, %
δ the RUL factor of the MFCS, %
Δ denotes change in quantity

Subscripts and Superscripts

d demand
max maximum
min minimum
out output
a auxiliary plant
m motor

Nomenclature

P - power demand, kW
N - window size
k - scale factor
J - optimization index
n - number of stacks
L - number of different P_l^{d}