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FUEL CELL STACK CONFIGURATION USING HARMONY SEARCH ALGORITHM

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Abstract

This paper deals with the application of harmony search (HS) algorithm to find the optimum configuration of a fuel cell-based stand alone power supply system. The optimization process includes finding the optimum number of cells in series, number of cells in parallel, and cell's surface area by which the system delivers its maximum output power at the load's operating voltage. Due to the nonlinearity and complexity of proton exchange membrane fuel cells (PEMFCs), conventional optimization techniques are unable to efficiently solve the problem. HS is a metaheuristic optimization algorithm which tries to simulate the improvisation process of musicians. Easy implementation, simple concept, and high search power have made HS as a popular optimization algorithm to tackle complex optimization problems. In this paper, a HS-based stack configuration process is proposed to provide dc electricity for a single dwelling in a remote area of a developing country. Promising simulation results accentuate that HS can be a good candidate to solve fuel cell optimization problems.

Keywords: Fuel cell, Stack configuration, Optimization, Harmony search algorithm.

1. Introduction

Due to the growing demand of energy, resulting in the increase in greenhouse gas emissions and fuel prices, the efforts to utilize renewable energy sources have been increased remarkably. It seems that fuel cells with many advantages like high efficiency, trivial pollution, good dynamic response, and low noise are promising devices to become primary source of energy in the coming years, especially in distributed power generation and portable electronic applications. Owing to its high power density, low operating temperature allowing a fast start up, and zero emission if it is run with pure hydrogen, proton exchange membrane fuel cell (PEMFC) has been the most popular kind of fuel cells.

To work efficiently, a fuel cell-based stand alone power supply system must be able to deliver its maximum output power at load's operating voltage. As a result, optimization of stack configuration in terms of number of cells in series and parallel and cell's surface area is essential. The nonlinearity and complexity of PEMFC system make traditional optimization techniques unable to capably solve optimization problems. As a result, a powerful optimization technique is needed.

Harmony search (HS), originally proposed in [1], is a metaheuristic optimization technique which tries to simulate the improvisation process of musicians. As a powerful technique, HS has been successfully applied in various areas [2-7]. It has simple concept, is easy to implement, imposes fewer mathematical requirements in comparison with conventional methods, and produces a new solution after considering all the existing solutions. Results in [7] indicate that HS has a competitive performance to the other optimization techniques in solving fuel cell optimization problems. This paper attempts to find the optimum configuration of a fuel cell-based stand alone power supply system using HS algorithm.

2. Description of PEMFC stack model

When a PEMFC is working hydrogen gas is fed to anode side and oxygen, usually from air, is supplied to cathode side. In the anode hydrogen gas releases electrons and H^+ ions (or protons). Polymer electrolyte only allows the protons to pass through it, and not the electrons. Via an external circuit, the electrons move from the anode to the cathode and accordingly an electrical current flows through the circuit. At the cathode, oxygen reacts with the electrons taken from the external circuit and the protons from the polymer electrolyte and produces water. Total reaction can be represented by:

$$H_2 + \frac{1}{2}O_2 \longrightarrow H_2O + Electricity + \text{Heat} \quad (1)$$

In the literature various models have been developed to simulate PEMFC behavior [8]. The one used in this paper has been adopted from [9]. This model illustrates cell voltage as a function of cell current which can be helpful for electrical engineering aims. Based on this model output voltage can be obtained by:

$$V = n_s \times (E_0 - \eta_{ohm} - \eta_{act} - \eta_{con}) \quad (2)$$

where V is the output voltage, n_s is number of fuel cells connected in series, E_0 is the ideal standard voltage, and η_{ohm}, η_{act}, and η_{con} are ohmic, activation, and concentration voltage drops, respectively.
The ohmic loss which is linearly proportional to the current is due to electrolyte resistance to the flow of ions across it, and the resistance of the electrode material to the flow of electrons. It is given by:

$$\eta_{ohm} = ri \quad (3)$$

where r is the area specific resistance of fuel cell and i denotes current density.
The activation loss that is more important at low currents is due to voltage lost in activating the chemical reactions to take place at the fuel cell electrodes. It is expressed by:

$$\eta_{act} = A\ln\left(\frac{i}{i_0}\right) \quad (4)$$

where A is called Tafel slop and i_0 denotes the exchange current density.
The concentration loss is related to the consumption of reactants by fuel cell. As the reactants are used, their concentration changes at the surface of the cell electrodes causing a drop in operating voltage. The concentration loss is given by:

$$\eta_{con} = -B\ln\left(1 - \frac{i}{i_L}\right) \quad (5)$$

where B is a concentration loss constant and i_L denotes the limiting current density at which the cell voltage will fall quickly.

Crossover and internal currents are other causes for fuel cell voltage drop. Reasons for this are the waste of fuel that passes directly through the electrolyte producing no electrons and electron conduction through the electrolyte and not passing through the electrodes. This results in an increasing effect on the current withdrawn from the cell by value of i_n.
By combining the described voltage drops, the voltage versus current (V-I) characteristic of the system including n_s fuel cells connected in series is expressed by:

$$V = n_s \times \left(E_0 - r(i + i_n) - A\ln\left(\frac{i + i_n}{i_0}\right) + B\ln\left(1 - \frac{i + i_n}{i_L}\right)\right) \tag{6}$$

To produce more electrical power fuel cells have to be connected in parallel, too, forming a stack. The voltage versus current (V-I) characteristic of a stack can be represented by:

$$V_s = n_s \times \left(E_0 - r\left(\frac{I_s}{n_p s} + i_n\right) - A\ln\left(\frac{\frac{I_s}{n_p s} + i_n}{i_0}\right) + B\ln\left(1 - \frac{\frac{I_s}{n_p s} + i_n}{i_L}\right)\right) \tag{7}$$

where I_s is the stack current, V_s is the stack voltage, s denotes the cell's surface area, and n_p in the number of cells in parallel. A typical PEMFC stack system has been indicated in Fig.1.

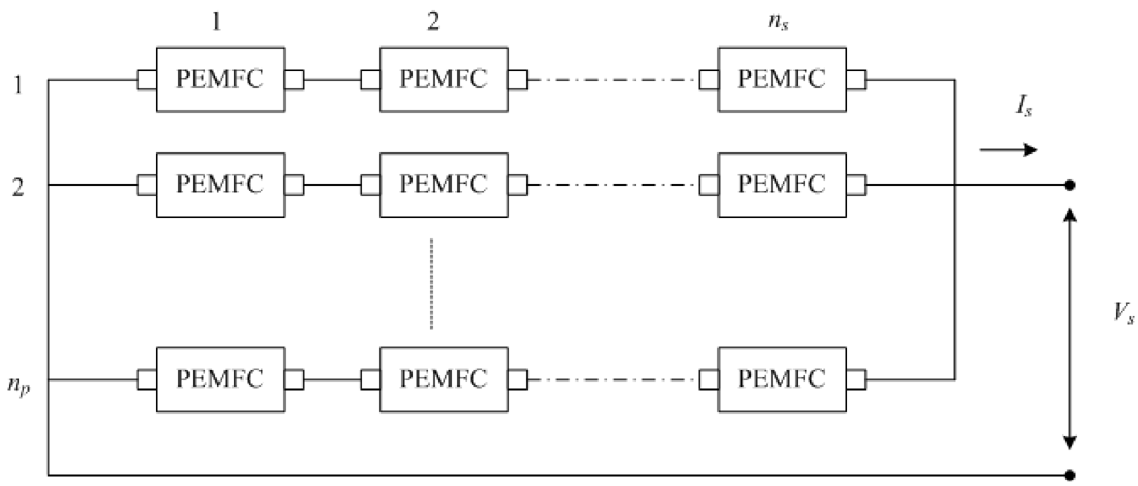

Fig. 1. Schematic of a PEMFC stack system

3. Optimization problem

The aim of this paper is to provide dc electricity for a single dwelling in a remote area of a developing country. The system load is estimated to be 730 kW h per year on 12 V dc. A fuel cell stack is used to convert hydrogen into dc electricity. To perform more efficiently, the stack system has to deliver its maximum output power at the load's operating voltage. This task can be accomplished by the help of an optimization technique by finding optimum configuration of PEMFC stack including number of cells in series n_s, number of cells in parallel n_p, and cell's surface area s. In order to conquer this problem harmony search algorithm is proposed.

In order to evaluate the quality of harmonies in HS algorithm, the objective function is defined by Eq. (8). The value of the objective function will specify how good a harmony's quality is. In this case, the lower the objective function value, the better the harmony is.

$$F = \alpha_1 \left(1 - \frac{P_{\max}}{P_{ref}}\right)^2 + \alpha_2 \left(1 - \frac{V_s(P_{\max})}{V_{ref}}\right)^2 \quad (8)$$

where P_{max} is the maximum output power, $V_s(P_{max})$ is the stack voltage at the maximum output power, P_{ref} is the load's power, V_{ref} is the load's operating voltage, and α_1 and α_2 are used to control the weighting of each term.
The basic form of HS can only handle continuous variables. However, n_s and n_p are integer variables. To handle integer variables without any effect on the implementation of HS, harmonies will search in a continuous space regardless of the variable type, and then truncating the real-values to integers is only performed in evaluating the objective function.

4. Harmony search algorithm

HS, devised in an analogy with music improvisation process where musicians improvise the pitches of their instruments to achieve better harmony, is a high-performance meta-heuristic algorithm that uses stochastic random search instead of a gradient search. Simple concept, few parameters to adjust, and easy implementation make the HS as the main rival of other evolutionary algorithms. Based on natural musical performance processes, music players seek to find pleasing harmony which is evaluated by an aesthetic standard so that the pitch of each musical instrument determines the aesthetic quality. Similarly, the optimization process seeks to discover a global optimum which the evaluation of a solution is carried out in putting values of decision variables into the objective function. In music improvisation, each player sounds any pitch within the possible range, jointly making one harmony vector. If all the pitches compose a fine harmony, the player memorizes that experience, and the opportunity to compose a fine harmony increases next time. In the same way in engineering optimization problems, decision variables at first are given a value within the possible range, jointly making one solution vector. If the solution vector makes a good result, that experience is memorized, and the opportunity to make a good solution is also increased next time.
In general, when musicians want to improvise a pitch, they utilize one of the following three rules: (1) playing a pitch from the memory, (2) playing a pitch close to a pitch from the memory, and (3) playing a pitch from possible range randomly [10]. In the HS algorithm, each solution is called harmony and cast in a *d*-dimensional vector including decision variables. At the beginning of the algorithm, a population of harmony vectors are randomly generated in the search space and stored in the harmony memory (HM). Then, a new harmony is improvised. Each decision variable is adjusted by one of the three rules: (1) selecting a value from the HM, (2) selecting a value close to one value from the HM, and (3) selecting a value from possible range randomly. Accordingly, the worst harmony of the HM is eliminated and replaced by the new harmony if the quality of the new harmony is better than that of the worst harmony. The key parameters which play an important role in the convergence of the HS algorithm are harmony memory considering rate (*HMCR*), pitch adjusting rate (*PAR*), and bandwidth of generation (*bw*). These parameters can be potentially useful in adjusting convergence rate of the algorithm to the optimal solution. The *HMCR* is the rate of choosing one value from the HM varying between 0 and 1. *PAR* and *bw* are defined as [11],

$$PAR(t) = PAR_{\min} + \frac{PAR_{\max} - PAR_{\min}}{t_{\max}} \times t \tag{9}$$

$$bw(t) = bw_{\max} \exp(c \cdot t) \tag{10}$$

$$c = \frac{Ln\left(\frac{bw_{\min}}{bw_{\max}}\right)}{t_{\max}} \tag{11}$$

where PAR_{max} and PAR_{min} are the maximum and minimum pitch adjusting rates, respectively, t denotes the iteration index, t_{max} is the maximum number of iterations, and bw_{max}, bw_{min} are the maximum and minimum bandwidths, respectively.

The steps of the HS algorithm are as follows:

Step 1. Firstly, harmony memory size (HMS), *HMCR*, PAR_{max}, PAR_{min}, t_{max}, bw_{max}, and bw_{min} are specified.

Step 2. The HM is initialized with HMS randomly generated solution vectors in the search space using Eq. (12).

$$x_i(j) = l(j) + \alpha \times (u(j) - l(j)) \tag{12}$$

where $i=1,2,\ldots,HMS$ is harmony's index, $j=1,2,\ldots,d$ denotes the decision variable's index, α is a random number uniformly distributed from the interval [0, 1], and $l(j)$, $u(j)$ are, respectively, the lower and upper bounds of j^{th} decision variable. So, the HM is a matrix of $HMS \times d$ dimension.

Step 3. The objective function value for each harmony is calculated.

Step 4: A new harmony vector x_{new} is improvised as follows:

$$
\begin{array}{l}
\textit{for } j = 1:d \\
\quad \textit{if } r_1 \geq HMCR \\
\quad\quad x_{new}(j) = l(j) + r_2 \times (u(j) - l(j)); \\
\quad \textit{else} \\
\quad\quad n_{HM} = \textit{a random integer number between } 1 \textit{ and } HMS \\
\quad\quad x_{new}(j) = \mathrm{HM}(n_{HM}, j); \\
\quad\quad \textit{if } r_3 < PAR \\
\quad\quad\quad x_{new}(j) = x_{new}(j) + (r_4 - r_5) \times bw \times \left| u(j) - l(j) \right|; \\
\quad\quad \textit{end} \\
\quad \textit{end} \\
\textit{end}
\end{array}
$$

where r_1, r_2, r_3, r_4, and r_5 are random numbers from the interval [0, 1].

Step 5: The new harmony is checked to see if it is in the search space or not. If the new harmony is in search space, its objective function value is computed. If it is better than the worst harmony of the HM, the worst harmony is removed and the new harmony is added to the HM.

Step 6: Step 3 to step 5 are repeated until a predefined number of iterations t_{max}, is reached.

5. Results and discussions

In order to evaluate the optimization power of HS, a fuel cell with the parameters given in Table 1 is considered. Optimization process is used to determine the parameters n_s, n_p, and s. The upper and lower bounds of the parameters are given in Table 2. Note that the physical size of the stack has to be suitable to use in a family house. The parameter setting of HS is as follows: HMS = 20, $HMCR$ = 0.95, PAR_{max} = 0.65, PAR_{min} = 0.35, bw_{max} = 1, bw_{min} = 0.001, and t_{max} = 5000.

Table 1. Values of the model parameters

Parameter	E_0 (V)	A (V)	i_n (mA/cm^2)	i_0 (mA/cm^2)	r ($k\Omega\ cm^2$)	B (V)	i_L (mA/cm^2)
Value	1.04	0.05	1.26	0.21	98e-6	0.08	129

Table 2. Range of the unknown parameters

Parameter	n_s	n_p	s (cm^2)
Max.	100	100	300
Min.	10	1	100

Because of the stochastic nature of the investigated algorithm, the results obtained in one attempt will differ from the results obtained in another one. Therefore, the performance analysis of the method must be statistically based. Consequently, the algorithm is run in the Matlab environment 10 times with random initial harmony memory and in each run the minimal objective function value is recorded. The mean (*Mean*), the best (*Best*), the worst (*Worst*), and the standard deviation (*Std*) of the objective function values obtained by HS are summarized in Table 3.

Table 3. Performance of HS algorithm during 10 runs

Index	*Mean*	*Std.*	*Best*	*Worst*
Value	3.9694e-3	0.0103	4.1088e-4	3.4958e-2

The optimum parameters related to the best performance of the HS have been reported in Table 4. In order to verify the performance of the designed stack, these parameters are returned to the mathematical model and the related characteristics are plotted. Figs. 2 and 3, respectively, represent the power vs. voltage (P-V) and voltage vs. current (V-I) characteristics of the optimized stack system. As figures verify, the maximum power output is delivered at the load's operation voltage.

Table 4. Comparison of the best stack configuration obtained by HS algorithm

Parameter	n_s	n_p	s
Optimum value	22	1	150.52

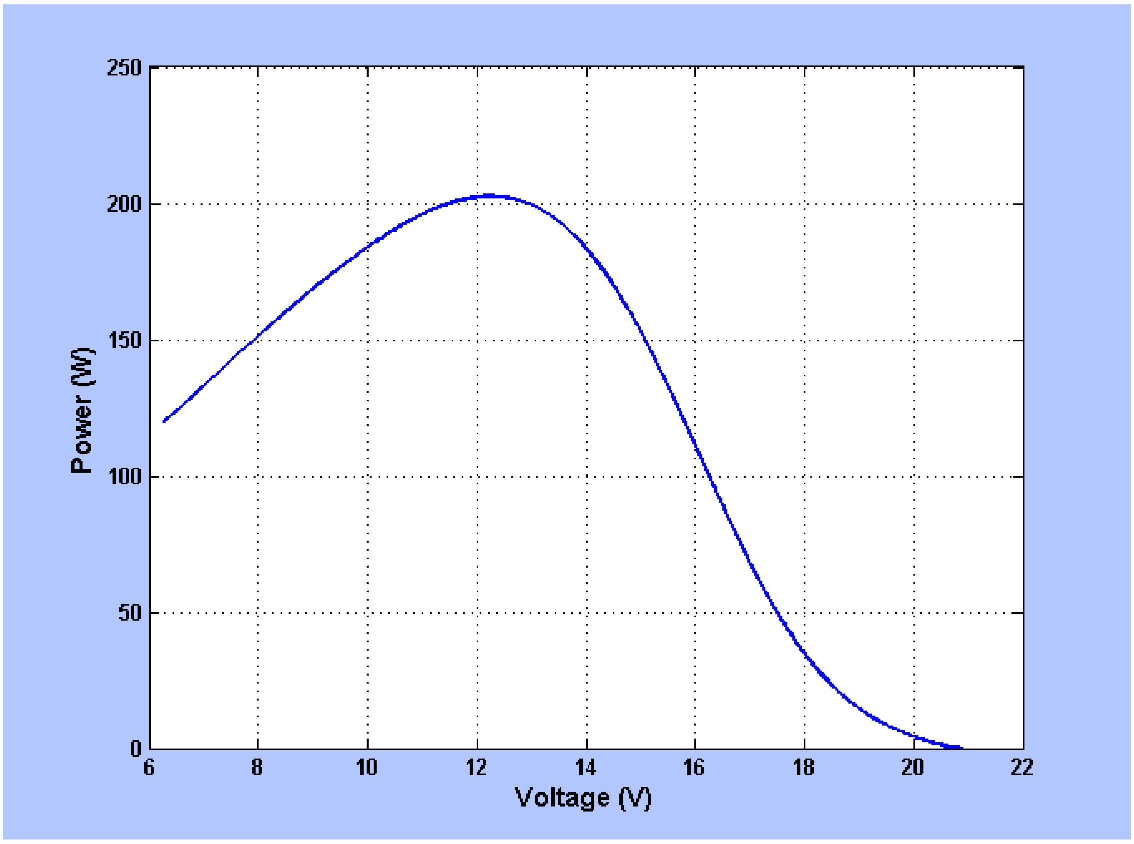

Fig. 2. Power versus voltage characteristic of the optimum stack configuration

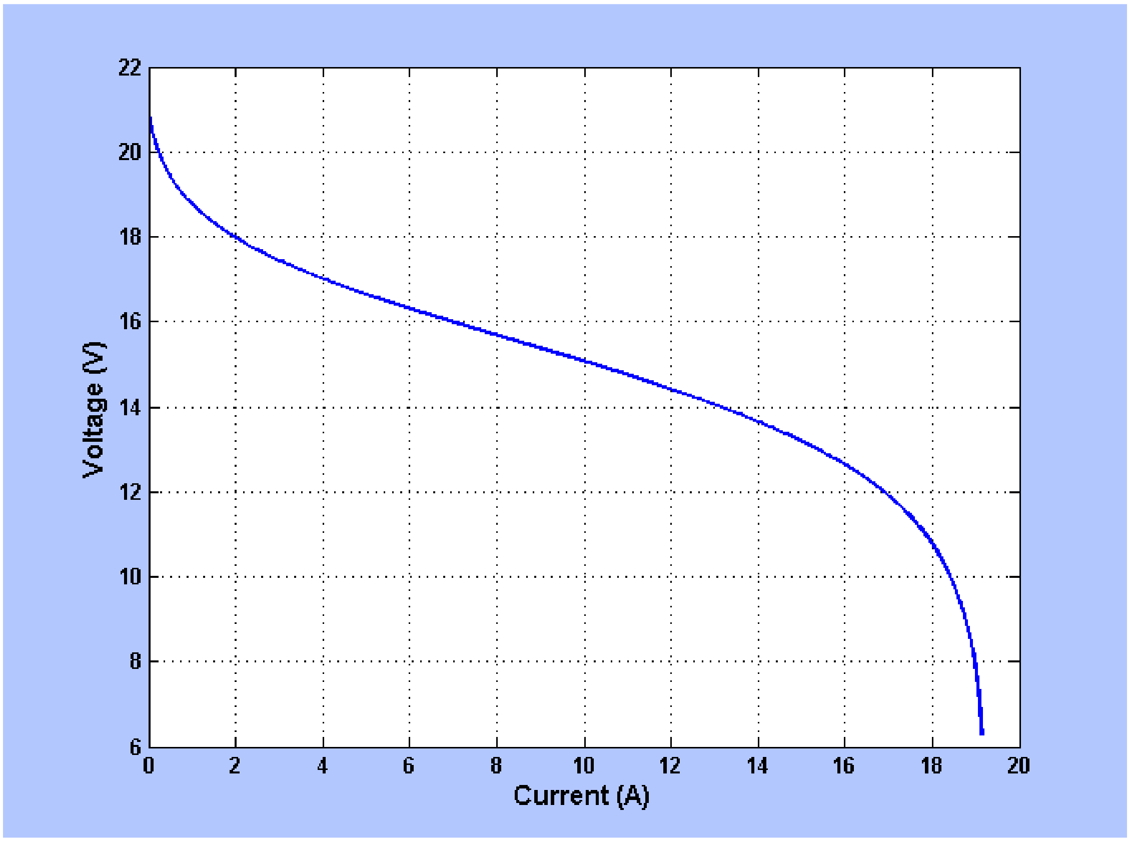

Fig. 3. Voltage versus current characteristic of the optimum stack configuration

To study the convergence rate of HS algorithm, the value of the objective function during iterations is illustrated. Fig. 4 indicates the convergence process of HS algorithm during iterations. This figure is related to the best performance of the HS algorithm. As can be seen, convergence rate of the HS is very fast.

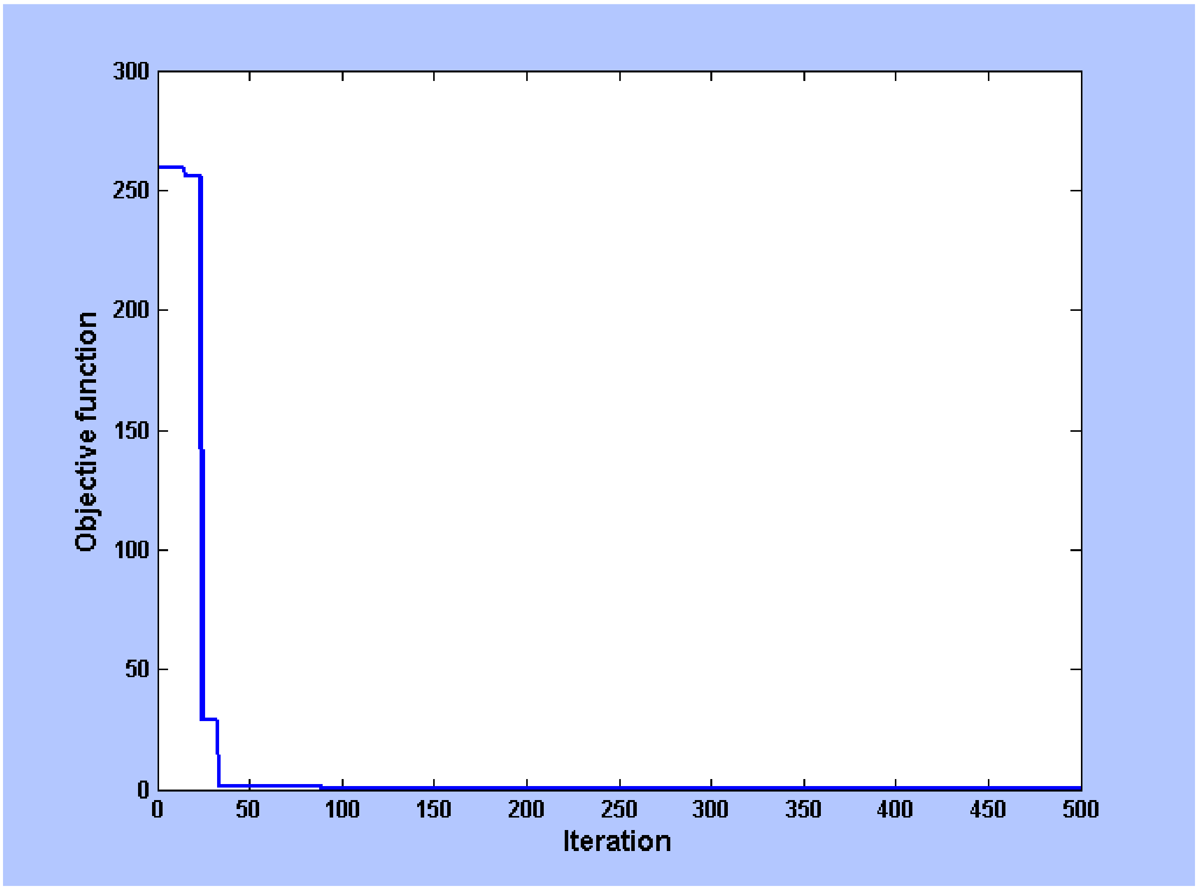

Fig. 4. Convergence process of the investigated algorithm

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6. Conclusion

Because of its fast convergence speed, high capability, simple concept, and easy implementation, harmony search algorithm has been proposed in this paper to find the optimum configuration of a fuel cell-based stand alone power supply system. The optimum configuration makes the system able to deliver its maximum output power at the load's operating voltage. The quality of the optimum solution is confirmed by feeding it to the stack model and plotting P-V characteristic. Simulation results manifest that HS can achieve promising results. Hence, it can be effectively used to solve optimization problems related to fuel cell systems.

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