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Critical evaluation of Genetic Algorithm based fuel cell parameter extraction

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Abstract

Accuracy of fuel cell characteristics mainly depends on its parameters. Generally, estimation is done in a curve fitting procedure. In this paper, the problem of fuel cell parameter extraction is formulated as an objective function and solved using simple Genetic Algorithm. Explanations about the new formulation and its implementation using GA is elaborated. The candidature of the proposed method is explained. The results are compared with existing curve fitting method.

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Keywords: Fuel cell parameter extraction, Proton Exchange membrane fuel cell (PEMFC), Genetic Algorithm (GA)

1. Introduction

Increased power demand, continuous depletion of fossil fuels and emission of greenhouse gases urge researchers and practitioners to focus on new technologies that can efficiently harness the existing renewable energy sources. Fuel cell is an electrochemical device that converts hydrogen fuel into electric power. Due to its robustness and higher efficiency, fuel cells can be extensively utilized in commercial, industrial and residential applications (such as primary and backup power generation). Fuel cells can be categorised based on type of electrolyte used and the start-up time required. Due to low voltage output, stack of fuel cells are arranged in series to meet the required voltage requirements [1]. PEM fuel cell is popular due to the following advantages such as no waste is generated, high efficiency, low operating temperature, and pressure [2]. It is appreciable to build an effective fuel cell model before proceeding into the installation part of system so that it makes the design and testing much easier [3]. Modelling of fuel cell characteristics has drawn considerable attention of researchers over the last decade as it helps in the better understanding of the phenomena occurring within the cell. The major challenge for researchers and

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practitioners is to model fuel characteristics accurately.

The parameter values are essential for fuel cell modelling and are not provided in manufacturer's datasheet. It can be inferred from the past literature that the previous attempts to estimate the fuel cell parameters was based on curve fitting method [4, 5] and they used mean square error (MSE) as the objective function.

The main shortcomings of this method are: it consumes more time, error is large and the complexity involved is very high. In order to overcome these drawbacks, a new approach based on the derivative of power with respect to current at maximum power point (MPP) is proposed. Henceforth it is named as Maximum Power Point method.

The proposed method uses, only 3 points namely V_{oc}, V_{mpp} and I_{sc} rather than considering entire I-V characteristics. This formulation enhances accuracy, fast convergence and easy implementation. Further, computations with the proposed method results in accurate parameter determination. To estimate the goodness of the solution obtained with the proposed MPP method and for fair comparison, constraints such as fitness function value (best, worst, mean and standard deviation), convergence characteristics, matching of computed and expected I-V characteristics are carried out. Further, the performance of both the methods under consideration is critically checked for two different model parameter ranges; one being a wider range whereas the other one is narrow.

2. PEM fuel cell model

Fuel cell is an electrochemical device that converts the stored energy of fuel directly into electricity with the help of an oxidant [6]. It consists of a cathode and an anode with a proton-conducting membrane which serves as the electrolyte. The electrochemical equations occurring in electrodes of a PEM fuel cell can be described as follows [7].

Overall electrochemical reaction:

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

The electrochemical model of fuel cell is proposed by Amphlett et al. [8]. The output voltage equation governing a single fuel cell is

$$V_{FC} = E_{Nernst} - V_{act} - V_{ohmic} - V_{con} \tag{2}$$

$$E_{Nernst} = 1.229 - 0.85\times10^{-3}(T - 298.15) + 4.3085\times10^{-5}\times T[\ln(P_{H_2} + 0.5\ln(P_{O_2})] \tag{3}$$

where P_{H_2} and P_{O_2} are partial pressures (atm) of hydrogen and oxygen, respectively. T is the fuel cell absolute temperature (K).

The Activation over potential can be expressed in a parametric form as follows,

$$V_{act} = \varepsilon_1 + \varepsilon_2 T + \varepsilon_3 T\ln(C_{O_2}) + \varepsilon_4 T\ln(i) \tag{4}$$

where the terms ε_i are semi-empirical coefficients, i is the cell current (A), C_{O_2} is the concentration of oxygen in the catalytic interface of the cathode (mol cm^{-3})

$$C_{O_2} = \frac{P_{O_2}}{5.08\times10^{-6}e^{\left(\frac{-498}{T}\right)}}$$

The ohmic voltage drop is given by the expression [9]

$$V_{ohmic} = i(R_m + R_c) \tag{5}$$

And,

$$R_m = \frac{\rho_m l}{A}$$

$$\rho_m = \frac{181.6\left[1 + 0.03\left(\frac{i}{A}\right) + 0.062\left(\frac{T}{303}\right)^2\left(\frac{i}{A}\right)^{2.5}\right]}{\left[\lambda - 0.634 - 3\left(\frac{i}{A}\right)\right]\exp\left[4.18\left(\frac{T-303}{T}\right)\right]}$$

where R_m and R_c are the equivalent inner membrane resistance and outer contact resistance to the respectively. l is the thickness of the PEM (cm), which serves as the electrolyte of the cell, A is the active cell area (cm^2), ρ_m is the membrane specific resistivity and λ is an adjustable parameter.

$$V_{con} = -b\ln\left(1 - \frac{I}{I_{\max}}\right) \tag{6}$$

where b is the parametric coefficient (V) that depends on the type of cell and its state of operation. I is the actual cell current (A), $I_{\max}$ is the maximum possible value of I .

For the PEM fuel cell, the relationship between P_{H_2}, P_{O_2}, P_{H_2O}, and C_{O_2} can be expressed as [13]:

$$\log(P_{H_2O}) = 2.95\times10^{-2}(T-273.15) - 9.18\times10^{-5}(T-273.15)^2 + 1.44\times10^{-7}(T-273.15)^3 - 2.18 \tag{7}$$

$$P_{N_2} = \frac{0.79}{0.21}P_{O_2} \tag{8}$$

$$P_{O_2} = P_c - RH_c\,P_{H_2O} - P_{N_2}\exp\left(\frac{0.291(i/A)}{T^{0.832}}\right) \tag{9}$$

$$P_{H_2} = 0.5\,RH_a\,P_{H_2O}\left[\left(\exp\left(\frac{1.635(i/A)}{T^{1.334}}\right)\times\frac{RH_a\,P_{H_2O}}{P_a}\right)^{-1} - 1\right] \tag{10}$$

where P_{H_2O} is the saturation pressure of water vapour (atm), P_{N_2} is the partial pressure of N_2 at the cathode gas flow channel (atm). P_a, P_c are the anode and cathode inlet pressures (atm), RH_a and RH_c are the relative humidity's of the vapour in anode and cathode respectively.

3. Problem Formulation

From the equations mentioned above, it is evident that many parameters are involved for describing the fuel cell operation and most of them are unknown. Since, they are not given in the manufacturer's datasheet; the calculation of these parameters are carried out by applying some optimization procedure. The specific set of parameters required for fuel cell modelling are $\varepsilon_1, \varepsilon_2, \varepsilon_3, \varepsilon_4, b, R_c$ and λ .

It is important to mention that derivative of power with respect to current in fuel cell characteristics is equal to zero at Maximum Power Point (MPP).

i.e. $$\frac{dP}{dI} = 0$$

$$P = VI \tag{11}$$

Where P- Power, V- Voltage and I- Current
Applying MPP condition to the above equation we get,

$$\frac{dP}{dI} = V + I\frac{dV}{dI} \tag{12}$$

Applying MPP condition and rearranging equation (8) we get

$$\frac{dV}{dI} + \frac{V}{I} = 0 \tag{13}$$

Thus, the objective function is expressed as

$$\min(J) = \left|\frac{dV}{dI}\right|_{(V_{mpp}, I_{mpp})} + \frac{V_{mpp}}{I_{mpp}} \tag{14}$$

In the above equation $\left|\frac{dV}{dI}\right|_{(V_{mpp}, I_{mpp})}$ can be obtained from the basic voltage equation

$$\left|\frac{dV}{dI}\right|_{(V_{mpp}, I_{mpp})} = -\left[\left(\varepsilon_4 \frac{T}{I_{mpp}}\right) + \left(\frac{b}{I_{\max} - I_{mpp}}\right) + \left(R_c + \left(\frac{l \times 181.6}{A \exp\left(\frac{4.18(T-303)}{T}\right)}\right)\right) \times \Gamma\right] \tag{15}$$

where

$$\Gamma = \frac{\left((\lambda - 0.634) + J_p(0.6\lambda - 0.038) + J_p^{2.5}\Delta T^2(0.217\lambda - 0.1375 - 0.465 J_p) - 0.9 J_p^2\right)}{(\lambda - 0.634 - 3J_p)^2}$$

$$J_p = \frac{I_{mpp}}{A}$$

$$\Delta T = \frac{T}{303}$$

The above framed objective function is solved using the GA procedure which is explained below:

4. Optimisation Technique

Genetic algorithm is one among the evolutionary algorithms which is based on Darwin's theory of "survival of the fittest". The application of this concept for optimization was put forward by Holland in 1975 which was later modified by different authors. The essence of GA constitutes the encoding of optimization function arrays comprising of bits to emulate chromosomes, different operations performed on chromosomes by genetic operators and selection of fitness function which leads to the proper selection of best one [10].

The important processes employed in Genetic algorithm are reproduction, selection, crossover and mutation. A set of probable solutions entitled as population is made to undergo GA operations and their values are frequently modified in order to converge to the best solution. In every step, the parents are chosen from the current population to produce offspring with a new set of chromosomes. The various steps involved in GA can be described as follows [10]:

Step 1: Create initial population of fixed length.
Step 2: Evaluate Fitness of objective function for each candidate present in the population

Step 3: Candidates are ranked according to their fitness value.
Step 4: Select parents via roulette wheel selection procedure and allow crossover selected parents.
Step 5: After mutation, the old population is replaced with new population of chromosomes
Step 6: Check for termination criteria and if it is satisfied stop and print the result; else go to step 2

5. Results and discussion

To accentuate the supremacy of the new formulation, its performance is compared with that of conventional curve fitting method. Further, the performance of proposed MPP approach and conventional curve fitting approach is evaluated in terms of fitness function value (best, worst, mean and standard deviation) and convergence characteristics.

5.1. Importance of range parameter selection

The range of fuel cell model parameters namely $\varepsilon_1, \varepsilon_2, \varepsilon_3, \varepsilon_4, b, R_c$ and λ plays a significant role in the proper modelling of fuel cell system. Hence, to refine the search process in a proper manner and to guarantee sufficient closeness between the computed and exact characteristics, the model parameters should be constrained to a pre-set range. The range should be wide enough to accommodate the accurate parameter values and it must be selected according to the physical meaning of parameter so that it is realizable. If the chosen range is wide, the search space is large and the optimization technique takes longer time to converge to the best possible solution. Moreover, there is a great possibility that the method may converge to any of the local best solution which resembles the best one and further deteriorates the efficiency of search process. The advantage of this range selection is that it is capable of accommodating allowed values of parameters. To avoid the drawbacks of wide range selection, a narrow range can be chosen. The issue of settling to local best value and higher convergence time can be expelled with this preference but; care should be taken that the best value should be contained in the prescribed range. The proper selection of parameter ranges assures the expected class of accuracy.

The ranges for model parameters employed in this work is presented in Table 1 where Range 1 is a narrow range whereas range 2 is a wider range.

Table 1 Different Parameter Ranges for performance evaluation

	ε_1	ε_2	ε_3	ε_4	b	R_c	λ
Range 1, Min.	-0.95	2e-3	6e-5	1.1e-4	0.02	1e-4	16
Range 1, Max.	-0.944	4e-3	8.5e-5	1.88e-4	0.06	8e-4	24
Range 2, Min	-0.9	1.5e-3	5.5e-5	1.05e-4	0.01	0.5e-4	10
Range 2, Max	-0.87	4.5e-3	9e-5	1.93e-4	0.07	8.5e-4	24

GA is made to run 150 times for both the approaches and comparison is made in terms of best, worst, mean and standard deviation of objective function value obtained for all the iterations is described in Table 2.

Table 2 Best, Worst, Mean and the standard deviation values of both the approaches for 150 runs

	APPROACH	BEST	WORST	MEAN	STANDARD DEVIATION
Range 1- GA	Proposed Method	0.003366	0.003749	0.003532	0.0000793
Range 1- GA	Point by Point Method	0.5147	1.44003	0.7511	0.209617
Range 2- GA	Proposed Method	0.001259	0.00199	0.001544	0.00013793
Range 2- GA	Point by Point Method	0.35283	2.46632	1.122	0.384907

From Table 2, it is clearly evident that the proposed MPP method provides better results for all range of initial values. There is a remarkable improvement in the fitness function value obtained through the novel proposition compared to conventional curve fitting procedure which again proves the effectiveness of the formulation by exactly meeting the required standards. The results confirm that the proposed approach is robust and it can be employed for any chosen parameter range.

Fig. 1 and Fig. 2 shows the variation of fitness function value against the number of iterations for a single run for the proposed MPP approach and conventional curve fitting approach respectively. There is a drastic reduction in the objective function value when the new approach is employed which is clearly evident from the graphs. Independent of the model parameter range, the novel formulation guarantees a very low fitness value after settling which is of the order 10^{-2} whereas it lies in the range very close to unity when conventional approach is utilised. The ultimate feature of the proposed MPP approach is that, it always ensures the proper matching of characteristics with reduced complexity. Moreover, the number of iterations required to converge at the best position is lowered. It is preferred to select a narrow parameter range as it results in improved accuracy in both the methods. The reduction in objective function value when a narrow range is used is very significant in case of proposed method whereas it is not much pronouncing when conventional method is used.

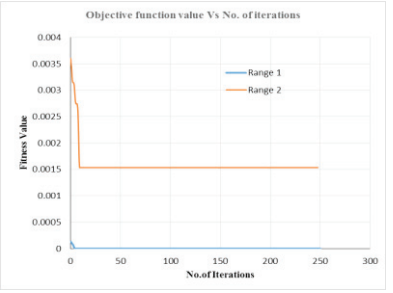

Fig. 1. Variation of objective function for proposed method for range 1 and range 2

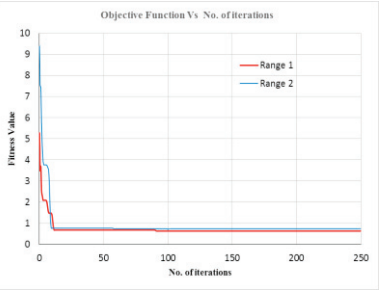

Fig. 2. Variation of objective function by conventional curve fitting method for range 1 and range 2

The extracted model parameters for both the approaches are subsequently substituted in the MATLAB/SIMULINK fuel cell model to plot the I-V characteristics of the fuel cell stack. For comparison, experimental data is taken from manufacturer's datasheet and compared with computed values for the same fuel cell stack. The comparison of actual and extracted I-V characteristics for different conditions of pressure and temperature is done in detail.

The PEM fuel cell model was simulated using model parameter values obtained applying GA for proposed MPP method as well as conventional curve fitting method for various test conditions and the corresponding I-V curves are plotted.

From the close observation of graphs of Fig. 3 and Fig. 4, it is very much clear that the computed and the expected fuel cell characteristics are exactly matching when the proposed approach is employed for different test conditions whereas there is a noticeable drift between both the characteristics when point by point approach is done. The proposed formulation always guarantees the appropriate matching of the computed as well as exact characteristics irrespective of the test conditions whereas the error between both the characteristics varies with changes in pressure and temperature when the conventional point by point approach is used. This again proves the superiority of the novel formulation.

Case 1: 3/5 bar; 353.15K

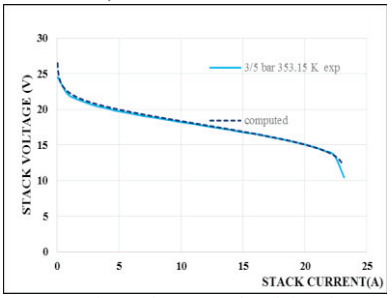

Fig. 3. Comparison of computed and datasheet values under 3/5 bar; 353.15K –proposed MPP method

Case 2:1.5/1.5 bar; 343.15K

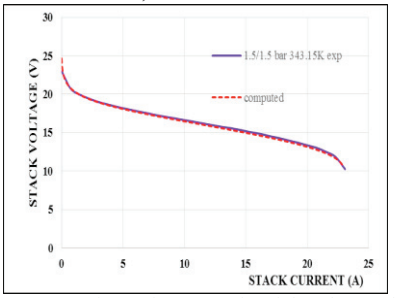

Fig. 4. Comparison of computed and datasheet values under 1.5/1.5 bar; 343.15K-proposed MPP method

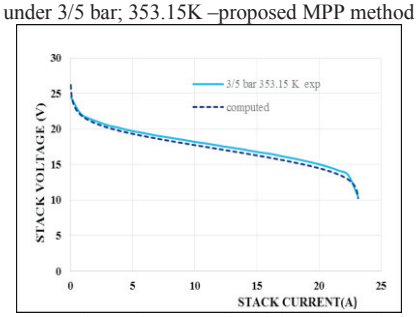

Fig. 5. Comparison of computed and datasheet values under 3/5 bar; 353.15K –conventional curve fitting method

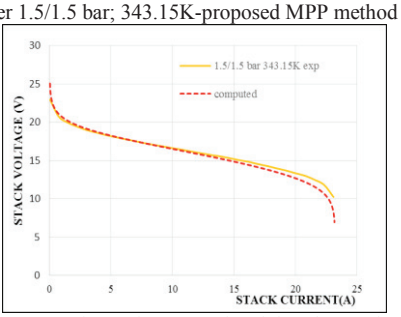

Fig. 6. Comparison of computed and datasheet values under 1.5/1.5 bar; 343.15K –conventional curve fitting method

6. Conclusions

In this paper, a novel problem formulation based on derivative of power with respect to current at maximum power point is proposed. A simple Genetic Algorithm is used to solve the above formulation. The seven model parameters $\varepsilon_1, \varepsilon_2, \varepsilon_3, \varepsilon_4, b, R_c$ and λ are extracted via GA procedure. For demonstration, results obtained with GA are benchmarked with widely used curve fitting approach. The results demonstrate that the new formulation applying GA performs better than curve fitting method in terms of accuracy, convergence characteristic, convergence speed, and objective function value.

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