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Research article

A novel approach for predicting PEMFC in varying ambient conditions by using a transient search optimization algorithm based on a semi-empirical model

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Abstract: Proton exchange membrane fuel cell (PEMFC) is an alternate energy source that produces electricity without any adverse effects on the environment. The drawbacks of PEMFC are its short life and its non-linear voltage with loading current. Also, PEMFC is prone to ambient conditions, and its performance varies with different ambient conditions. In this work, the semi-empirical modeling approach has been used to predict the PEMFC voltage accurately. However, when the ambient condition varies, the voltage of PEMFC varies accordingly and consequently the previous parameters of the EMI-empirical model don't produce good results. Previously the voltage variation due to changes in ambient has been predicted with the help of ambient conditions and load resistance, but this model isn't sui for all PEMFCs. In this work, a new method has been proposed where fast and accurate optimization technique such as Transient search optimization (TSO) has been used to optimize parameters when ambient condition varies and predicts the PEMFC voltage accurately and doesn't consume a lot of time. The proposed method will be very helpful in future research for predicting the PEMFC voltage for various PEMFC systems at different ambient conditions. The proposed method has been validated experimentally by performing experiments on n single-cell PEMFC system at normal and high ambient temperature.

Keywords: ambient conditions; modelling; optimization; prediction; PEMFC; transient search optimization

1. Introduction

Proton exchange membrane fuel cell (PEMFC) is an alternate energy source that takes hydrogen and oxygen as fuel, the PEMFC converts the chemical energy of fuel gases to electrical energy. PEMFC doesn't produce any harmful gases for the environment, water is the final product after the reaction with some heat energy loss. The non-linear voltage-current characteristics of PEMFC make it difficult to predict the voltage of PEMFC. PEMFC voltage depends on loading current, the temperature of PEMFC, and the internal characteristics of PEMFC. The pure theoretical model of PEMFC contains extremely complex electrochemical equations. These models cannot be used for online purposes; a simple approach has been used which is called the semi-empirical modeling approach. The semi-empirical approach represents half theoretical model equations and half empirical equations. The first semi-empirical approach was presented in [1], this approach was more simplified in [2] and is used in various updated papers where the parameters are optimized by using the various approaches such as mentioned in [3–8].

The ambient conditions affect PEMFC performance directly and the voltage of PEMFC varies by a great deal with the change in ambient temperature and ambient pressure. In [9,10] the effect of ambient conditions on PEMFC performance has been studied experimentally. In [11] the ambient conditionhaveas have been discussed in detail and also used directly in the voltage/temperature modeling of PEMFC. In [12] the effect of ambient conditions on PEMFC has been reviewed and discussed in detail, in this review it is suggested that the model in [13] is very essential for predicting the change in PEMFC voltage due to ambient conditions. The model in [13] predicts the changes in PEMFC voltage, the formula given predict the voltage variation of PEMFC from normal ambient conditions (at 298 K ambient temperature and 1 atm air pressure) to other different ambient conditions. The formula for variation of voltage entirely depends upon ambient temperature and pressure, however, the equations vary with loading conditions (high load and low load).

In this research work, it is revealed that the variation in PEMFC voltage due to changes in ambient conditions cannot be predicted easily as it is too complicated. Parameters of the semi-the empirical model vary by a great deal when the ambient condition (especially ambient temperature) varies. These parameters must be optimized by using fast and accurate optimizatiotechniquesue when the ambient condition varies. Thus a new method is proposed for predicting the PEMFC voltage which includes the use an of optimization technique where parameters are optimized when the ambient condition varies. In the literature, several optimization techniques have been used to extract the values of the unknown parameters of PEMFC models; for example, the Particle Swarm Optimization (PSO) method was proposed in [14] and a Modified Artificial Ecosystem Optimization (MAEO) was presented in [15]. The eagle strategy based on JAYA and JAYA-NM algorithms and the Nelder-Mead (NM) simplex method was developed in [16]. Moreover, Electromagnetic Field Optimization (EFO) [17], Thermal Exchange Optimization (TEO) [18], Ions Motion algorithm (IMO) [19], Water Evaporation Optimization (WEO) [20], and Water Cycle algorithm (WCA) [21] are created as competitive algorithms. Furthermore, many metaheuristic optimization algorithms appeared recently such as Bonobo Optimizer (BO) [22], Equilibrium Optimizer (EO) [23]. Recently a combination of method is used, an artificial neural network (ANN) with the genetic algorithm (GA) in [24]. Each model has a specific issue, for fault diagnosis [25], analysis of the reaction rates in the cathode [26], or maximum power [24,27]. The performance of the different models is analyzed in [28].

The optimization technique used in this research is the most modern optimization technique which is not been used before for PEMFC applications, this metaheuristic optimization technique is named Transient search optimization (TSO) which is fast and accurate as compared to other famous techniques that had already been used in PEMFC applications [29]. The experiments are performed on a clean sed-cathode 300 mW single-cell PEMFC system and the ambient temperature has been varied from 298:13 K to 318:13 K. Almost all models of these the equations of the paper [1] optimize the parameters with various metaheuristic/heuristic optimization techniques and these techniques within the range of the parameter give different results. In previous models, the optimization technique will not be part of the model and the model parameters were considered final which was an extremely wrong technique. The paper is organized as follows, in Section 2 the semi-empirical model of PEMFC along with the upper and lower bounds are explained and Section 3 explains the impact of ambient conditions on the voltage variation. Section 4 explains briefly the Transient Search Optimization (TSO) while Sections 5–6 give the experimental setup of Fischertechnik PEMFC and the obtained results. In the end, Section 7 contains the conclusion and prospects of the research.

2. Semi-empirical model of PEMFC

The semi-empirical model of PEMFC is a very detailed model that predicts the voltage with good precision as discussed in [30]; this model, first introduced in [1], was updated as an extension in [2,4,31]. Most new models of PEMFC have used the same equation as given in [1], the notable papers are mentioned in the references [3–8,29,32,33] and [34] and this model is still in use in many new research papers from 2021 [35,36]. Recall that the voltage of PEMFC is predicted by using the expression:

$$V_{cell} = E_{Nernst} + V_{act} + V_{con} + V_{ohm} \tag{1}$$

where E_{Nernst} is the Nernst equation which depends upon the fuel gases partial pressures P_{O2} (atm) and P_{H2} (atm) mainly, V_{act} and V_{conc} are the activation and concentration voltage drops simultaneously, and V_{ohm} is the voltage drop due to internal resistance of PEMFC. E_{Nernst} is given by the following formula:

$$E_{Nernst} = 1.229 - 8.5 \times 10^{-4}T - 298.15 + 4.308 \times 10^{-5}\, T\, ln(p_{H2}) + \frac{1}{2} \ln{(p_{O2})} \tag{2}$$

while, V_{act} is given by:

$$V_{act} = -\{E_1 + E_2T + E_3T[\ln(c_{O2})] + E_4T[\ln(I)]\} \tag{3}$$

where I is the PEMFC load current and T(k) is the PEMFC temperature and the parameters E_1, E_3 and E_4 are constants which mainly depend upon the chemical properties of PEMFC, however, E_2 is given by:

$$E_2 = (4.3 \times 10^{-5})T \ln C_{H2} + 2.1 \times 10^{-4} \ln(A) + 2.9 \times 10^{-3} \tag{4}$$

where C_{H2}(mol cm^{-3}) and C_{O2}(mol cm^{-3}) are, respectively, the concentrations of hydrogen and oxygen defined by:

$$C_{H2} = \frac{P_{H2}}{1.09 \times 10^{6} \exp(\frac{77}{T})} \tag{5}$$

$$C_{O2} = \frac{P_{O2}}{5.09 \times 10^{6} \exp(\frac{-498}{T})} \tag{6}$$

$$V_{ohm} = I \times (R_e + R_p) \tag{7}$$

$$R_p = \frac{r_m l_m}{A} \tag{8}$$

Note that I_m (cm) is the membrane thickness, A (cm^2) is the area of cross-section of PEMFC, r_m is the membrane specific resistivity for protons, R_p is the protonic resistance and R_e is the electronic resistance of PEMFC. The empirical expression for the membrane specific resistivity protons r_m is given by:

$$r_m = \frac{181.6\left[1+0.03\left(\frac{I}{A}\right)+0.062\left(\frac{T}{303}\right)^2\left(\frac{I}{A}\right)^2\right]}{\left[\lambda-0.634-3\left(\frac{I}{A}\right)\right]\exp\left[4.18\left(\frac{T-303}{T}\right)\right]} \tag{9}$$

where the expression $\frac{181.6}{(\lambda - 0.634)}$ stands for specific resistivity at no-load and at a temperature of 30 ℃, the rest of the expression is the correction factor for variable temperature, the numerator term is also an empirical term derived after fitting the protonic resistance data and the parameter λ is an empirical term which is a correction factor to specific resistivity (this factor depends upon membrane average water content and temperature of PEMFC and under ideal condition this factor is as high as 14 but the maximum values given in [2] is 23); however, the factor λ is influenced by membrane preparation procedure and stoichiometric ratio of the anode feed gas (this factor is also called the average membrane water content).

The concentration voltage drop V_{conc} depends upon the temperature T, the current I, the maximum current $I_{max,}$ and the area A of PEMFC, the detailed formula for V_{conc} is given by:

$$V_{con} = -\beta \times \ln\left(1 - \frac{I_{den}}{I_{max}}\right) \tag{10}$$

where N is the factor which has an inverse relationship with PEMFC temperature, see [19], and Imax is the maximum limiting current; many parameters need to be optimized for each PEMFC system, Table 1, see [30], gives lower and upper bound of these parameters (an optimization algorithm is needed to optimize the parameters for the PEMFC on which the experiments are performed).

Table 1. The upper and lower bounds for the considered PEMFC model.

Sr. No.	Parameter	Lower limit	Upper limit
1	E_1	−1.2	−0.853
2	E_2	36×10^{-6}	98×10^{-6}
3	E_3	-26×10^{-5}	-95.4×10^{-6}
4	E_4	10	24
5	E_5	1×10^{-4}	8×10^{-4}
6	E_6	0.013	0.5

3. Voltage variation model with ambient conditions

The voltage of PEMFC surely varies with ambient temperature and pressure as described in various experimental studies [9,10,12,37,38]. The model mentioned in [13] models the variation of the voltage V_{amb} of PEMFC. These variations are from normal ambient conditions i.e., 298 K and 1 atm pressure. The model extracts the equations based on the detailed model given in [32]. The final equations use ambient temperature T_{amb}, ambient pressure of air Pressure, and output resistance Rc(Ω). There are two different equations, one is for low loading conditions, the other is for high loading conditions. For low loading conditions i.e less than 50 percent of the rated current, the equation is based on T_{amb} and Pair. The equation for V_{amb} is given as which depends upon V_{nor} (the voltage of PEMFC at 298 K, 1 atm) and V_{var} (the voltage of PEMFC at different ambient conditions):

$$V_{\text{amb}} = V_{\text{nor}} - V_{\text{var}} \tag{11}$$

where

$$V_{\text{amb}} = 0.01804 + 1.41839\frac{(T_{\text{amb}}-298}{25}) - 0.0189\frac{(P_{\text{air}}-0.8}{0.2}) - 0.00739\frac{(T_{\text{amb}}-298}{25})\frac{(P_{\text{air}}-0.8}{0.2}), + 0.01158\frac{(T_{\text{amb}}-298}{25})^2\ for\ less\ than\ 50\%\ load \tag{12}$$

$$V_{\text{amb}} = 0.0476 + 1.8753\frac{(T_{\text{amb}}-298}{25}) - 0.0508\frac{(P_{\text{air}}-0.8}{0.2}) - 0.043\frac{(R_{\text{c}}-0.75}{0.25}), + 0.1301\frac{(T_{\text{amb}}-298}{25})^2\ for\ more\ than\ 50\%\ load \tag{13}$$

The equations predict the variations in PEMFC voltage for the NEXA 1200 W PEMFC system with ambient conditions and may not work for all PEMFC systems, these equations are to be checked in this paper for single-cell PEMFC (the experimental setup for this research is explained in Section 5).

4. Transient Search Optimization (TSO)

The Transient Search Optimization (TSO) algorithm, mentioned in [29], is a newly developed metaheuristic algorithm, this algorithm is based on the transient behavior of electrical circuits using storage elements such as capacitors and inductors, and it is verified and compared with some recent optimization algorithms, see [29] for more details. In addition, the process of the TSO algorithm begins with the initialization of search agents then evaluates them using the cost function, and finally updates the research agent according to the function evaluation; it is modeled as:

1. Initialization of the search agents between lower and upper bounds of the search area: the initialization of the search agents is randomly generated as:

$$Y = lb + rand\ \times (ub - lb) \tag{14}$$

where Y is the position of the search age and is then a uniformly distributed random number, U_b is the upper bound and L_b is the lower bound.

2. Searching for the best solution (Exploration): the exploration behavior of TSO is inspired by the oscillations of the second-order RLC circuit around zero.

3. Reaching the steady-state or best solution (Exploitation): the exploitation of TSO is inspired by the decaying of first-ordered electricircuitscuit during discharge.

The random number r_1 is used which decides the balance between the exploration and exploitation phases: if r_1 is greater or equal to 0.5 it is the exploration phase and if r_1 is less than 0.5 it is the exploitation phase. The new position Y_l of the search agents can be found from the best position $(Y_l)^*$ of previous search agents, the complete process is explained as follows:

$$Y_{l+1} = \left\{ \begin{array}{c} (Y_l) * +(Y_l - C_1 \times (Y_l) *)e^{-T}\ for\ r_1 < 0.5 \\ (Y_l) * + e^{-T}[\cos(2\pi T) + \sin\,(2\pi T)]|Y_l - C_1 \times (Yl) * |\ for\ r_1 \geq 0.5 \end{array} \right\} \tag{15}$$

$$T = 2 \times z \times r_2 - z \tag{16}$$

$$C_1 = k \times z \times r_3 + 1 \tag{17}$$

$$z = 2 - 2 \times \left(\frac{l}{L_{max}}\right) \tag{18}$$

where z is the variable that changes from 2 to 0, C_1 and T are random coefficients, $(r_i)_{i=1}^{3}$ are random numbers distributed uniformly from 0 to 1, l is the iteration number, k is a constant number (0, 1, 2, …) and L_{max} is the maximum number of iterations. The coefficient T senses the balance between the exploration and exploitation phases and it varies between 2 and −2 (the exploration phase has been achieved when T is less than zero while the exploitation phase is achieved when T is greater than 0). To extract the optimal values of the PEMFC parameters which allow the proposed model to match well with the measured data, the proposed objective function is a measure of the quality of the extracted parameters, the root mean square error (RMSE) between the measured generated voltage of PEMFC and the simulated one is defined as the Objective Function (OF), which depicts the error between the modeled values and the experimental values as described in the following equation:

$$he\ \mathrm{OF} = \mathrm{RMSE} = \sqrt{\frac{\Sigma(\mathrm{V_{mod}} - V_{\mathrm{exp}})^2}{\text{Total number of samples}}} \tag{19}$$

where V_{mod} and V_{exp} describe the model and the PEMFC experimental output voltage according to the Table 1 which illustrates the lower and upper bounds for the considered PEMFC mode [30]. The pseudo-code of TSO is given in Table 2 (see also the research in [29] for more details on TSO).

Table 2. The pseudo-code of TSO.

```
Initialize the population and the best positions Yl and Yl*
Evaluate the objective function (RMSE)
While l < $L_{max}$
    Update the values of C1 and T using Eqs (13) & (14)
    do all populations Yl
        Update the population place by Eq (12)
    End do
    Calculate the objective function for all population
    Update the best value if the recent objective function is less than the previous best l = l + 1
End While
Output the best value Y1*
```

5. Experimental setup and experiments performed

The modeling of the pile requires several experimental data, within the framework of our study, a test bench was used. This test bench has made it possible to obtain a great deal of knowledge on the operation of fuel cells in general and in particular on the influence of the various ambient conditions on the operation of the cell. This is important given the building of the voltage and temperature model of the fuel cell.

In this regard, we proceeded to the realization of an experimental test bench to validate the simulation results of the predictive model.

In the first part, the physical and experimental side is described by specifying the material selected for the realization of the different parts.

- The control part controls ambient conditions (temperature, humidity)
- The control part of the operation of the battery (variable charge, charge, discharge of the battery)
- The measurement and data acquisition part.

The experimental setup is the single-cell PEMFC from Fischertechnik with the rated power of 300 mW. The electrolyzer is supplied with a voltage limited to 3 V to produce H_2 and O_2. Once the storage cylinders are full, the supply stops and waits for the instruction from the control interface to supply the load (the specifications of PEMFC are given in Table 3.)

Table 3. Fischer Technik Single-cell PEMFC specifications.

PEMFC make (company name)	Fischer Technik
Rated power (W)	300×10^{-3}
The pressure of Hydrogen (atm)	0.9
Membrane thickness (cm)	50×10^{-4}
Area of PEMFC (cm^2)	4
Maximum limiting current (A)	0.9

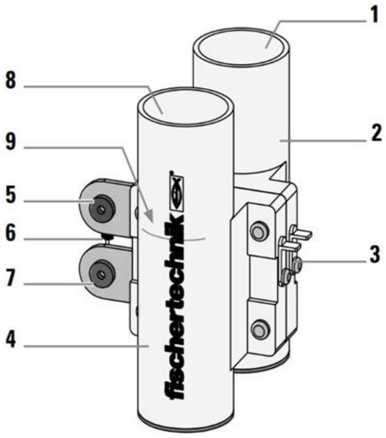

Figure 1. Description of the fuel cell: 1. Overflow chamber, hydrogen side; 2. Hydrogen storage cylinder; 3. Plugs for the vent ducts; 4. Oxygen storage cylinder; 5. Negative connector; 6. Protective diode; 7. Positive connector; 8. Overflow chamber, oxygen side; 9. Fill level marking.

The Experimental setup of Fischer Technik PEMFC is shown in Figure 1 with its schematic diagram in Figure 2.

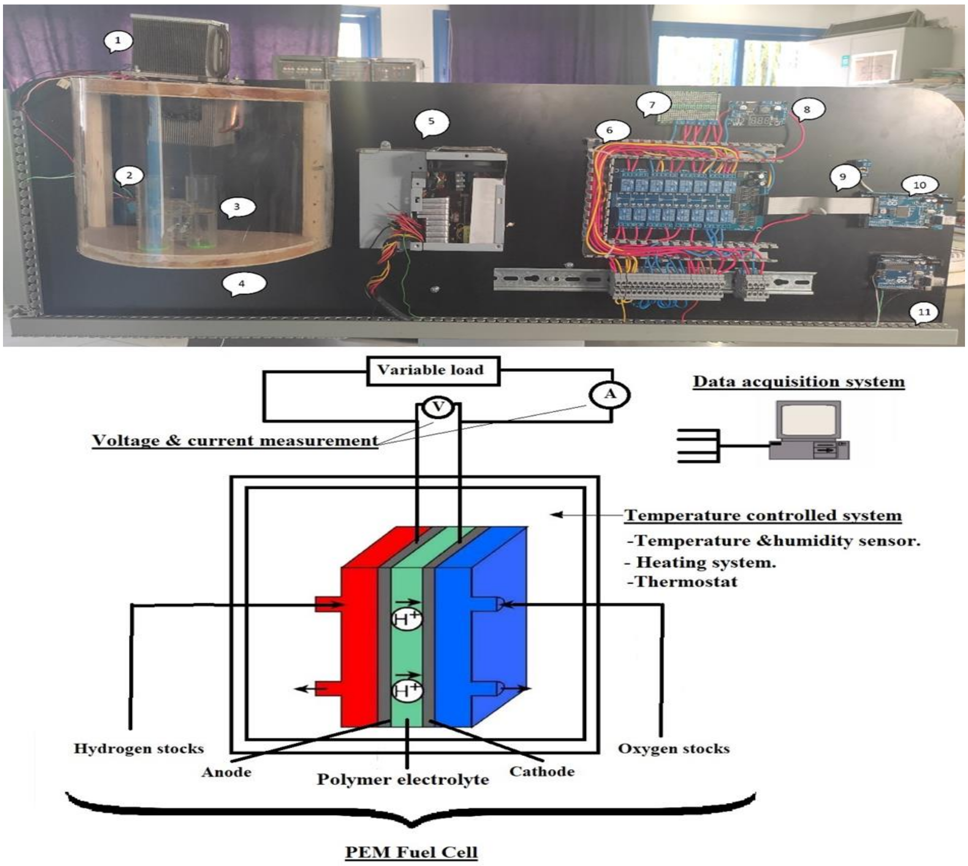

Figure 2. Experimental setup of Fischer Technik PEMFC & Schematic diagram of the experimental setup.

The experiments were carried out on a test bench developed within the Renewable Energies and Power Electronics team, within the ENSMR, Figure 2 shows a photograph of the experimental bench implemented. The details of the test bench are shown by numbers in the Figure 1 which can be listed as follows.

1. The heating and cooling system are based on Peltier technology which makes it possible to implement a heating or refrigeration process within our incubator, indeed as soon as the Peltier element is energized, one side cools, while the opposite side heats up at the same time. The hot and cold sides of the Peltier element are inverted thanks to a simple inversion of the poles of the supply voltage, the conversion is done by the relays controlled by the ARDUINO MEGA card also controlled by the control/command platform, measurement, and supervision developed in the LABVIEW environment. Humidity is manually regulated within the incubator.
2. The DHT22.
3. The electrolyzer is supplied with a voltage limited to 3 V to produce H_2 and O_2.
4. The incubator is a chamber that isolates the fuel cell from the outside and limits heat transfer.

5. Voltage source which represents renewable energy source, and which supplies the electrolyzer.
6. Relay module to control circuits from Arduino.
7. Series and parallel resistor module controlled by relay for desired resistances.
8. LM2596 DC/DC step-down module with digital display. 4/40 V to 1.3/37 V.
9. 5A current sensor /voltage sensor based on voltage division principle.
10. The ATMega2560.

The bench control system is made with the Labview software. It allows the acquisition of the various measurements. The Figure 3 shows the control block through LIFA under LABVIEW, and Figure 4 shows the interface and application window created in LBAVIEW.

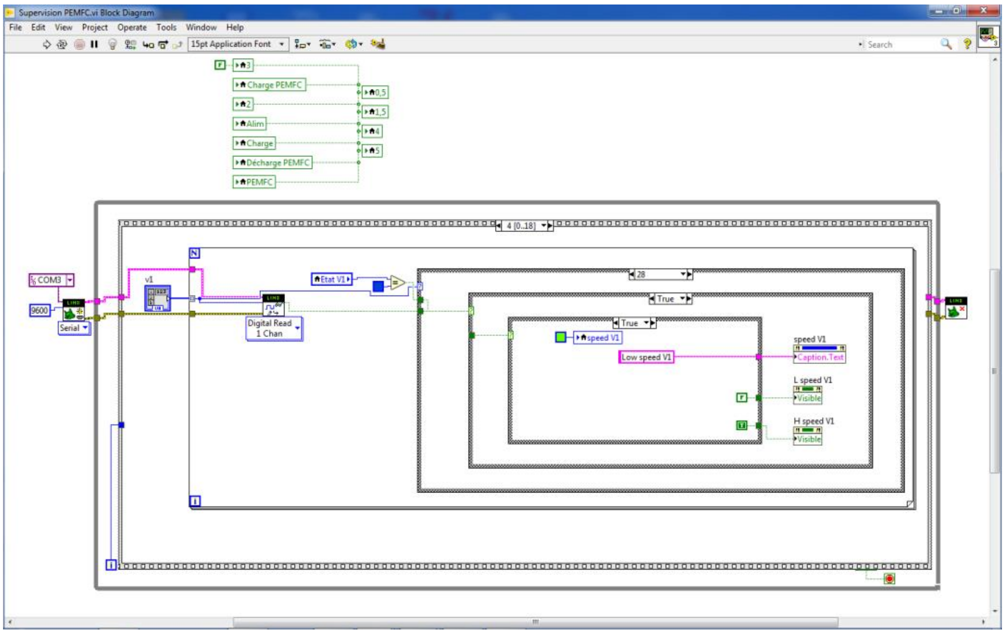

Figure 3. LABVIEW block diagram.

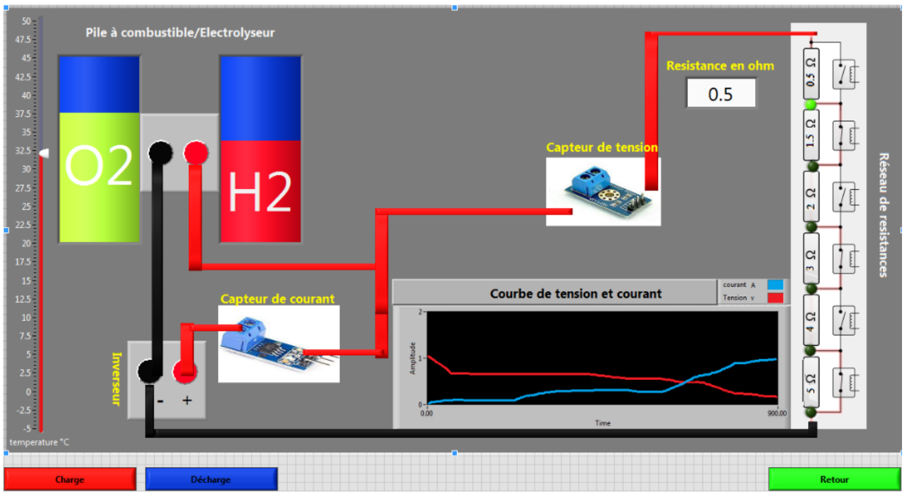

Figure 4. LABVIEW front panel.

The experiments are performed at normal ambient conditions where the first one is performed at 298.13 K and the second one is performed at 318.13 K (both experiments are performed at an air pressure of 1atm but the subject PEMFC is a closed cathode so the pressure of air doesn't matter and the pressure of oxygen remains at 1 atm). The fuel cell bias curve is the voltage versus current characteristic. It is measured statically, positioning the current point and letting the voltage stabilize before noting the values. The load current of the PEMFC remains the same for both experiments, see Figure 5, and the voltage is shown in Figure 6 while the temperature of the PEMFC is given in Figure 7.

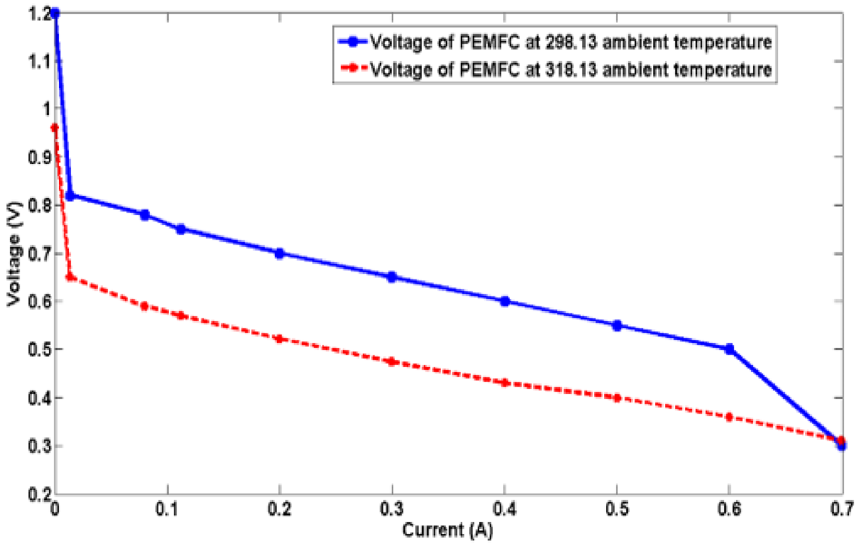

Figure 5. Voltage of PEMFC for experiment 1 & experiment 2.

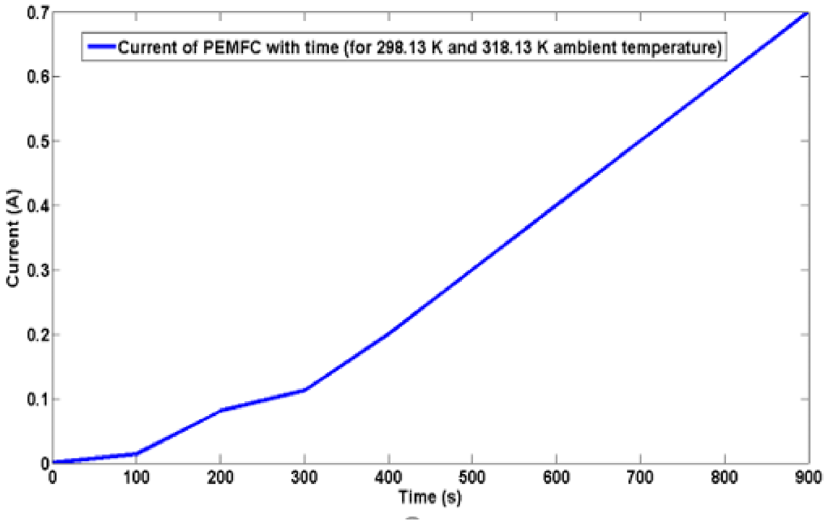

Figure 6. Current of PEMFC for experiment 1 & experiment 2.

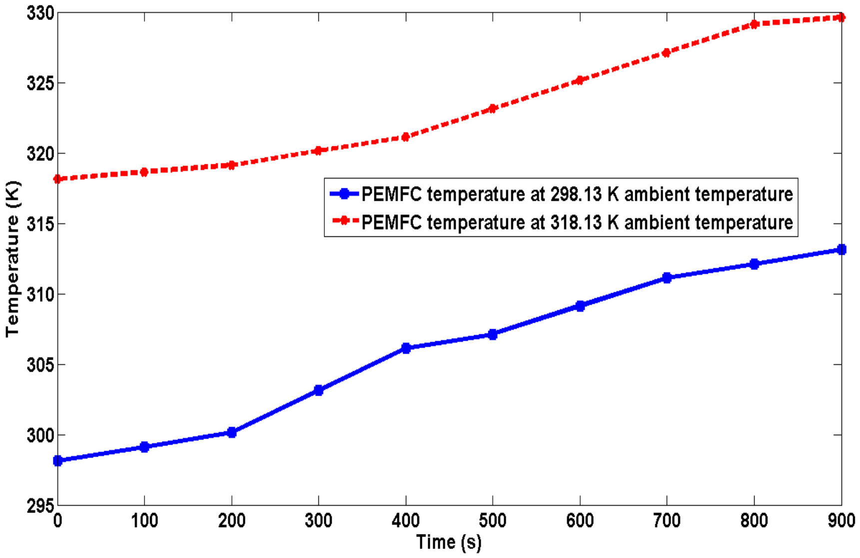

Figure 7. Temperature of PEMFC for experiment 1 & experiment 2.

6. Results and discussion

The semi-empirical model mentioned above can also be fit for the experiments performed on PEMFC. The parameters are to be optimized by using the TSO algorithm by using the limits mentioned in Table 1. The initial population is set as 50 and the maximum number of iterations is set at 200. The optimized parameters are given in Table 4 with RMSE being 0.02 and the runtime being almost 2 seconds.

Table 4. Optimized parameters for Fischer Technik PEMFC at normal ambient condition.

Sr. No.	Parameter	Final values
1	E_1	−1.152
2	E_3	3.6×10^{-5}
3	E_4	−0.0001
4	λ	23
5	R_e	0.0001
6	β	0.2551

The comparison of the modeled and the experimental voltage waveform is given in Figure 8 and it shows the good fit with new parameters.

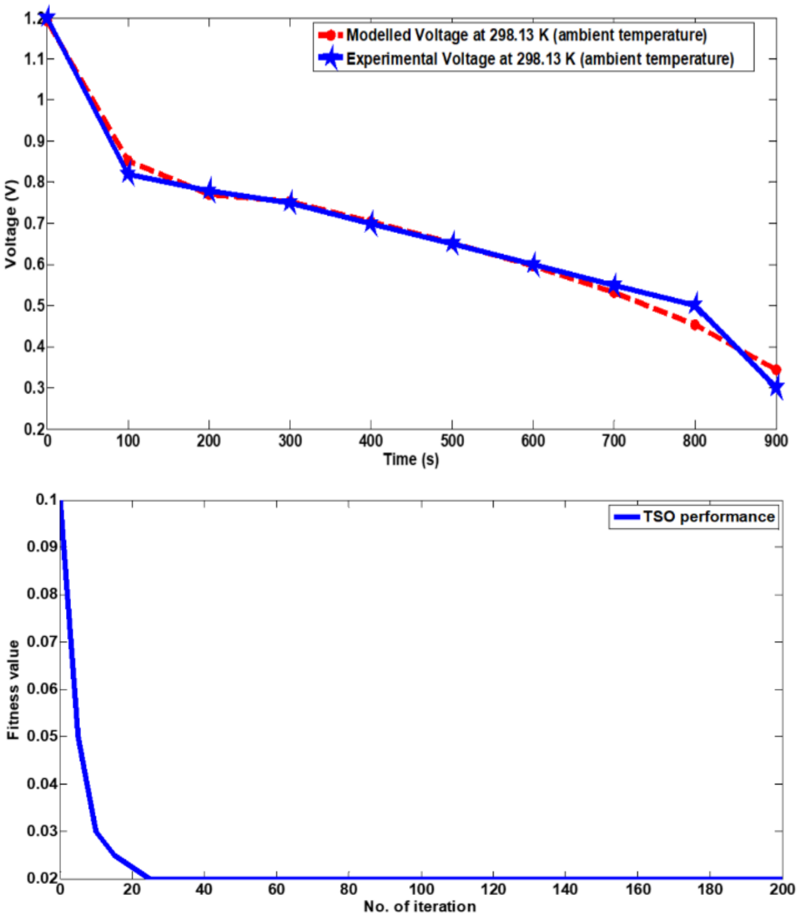

Figure 8. Comparison of model and experimental voltage for experiment 1 & TSO performance.

Now the Experiment-2 voltage (at 318.13 K ambient temperature) has been modeled by using the parameters mentioned in Table 4. Here RMSE is very high and its value is almost 2. The comparison of the model and experimental voltage is shown in Figure 9.

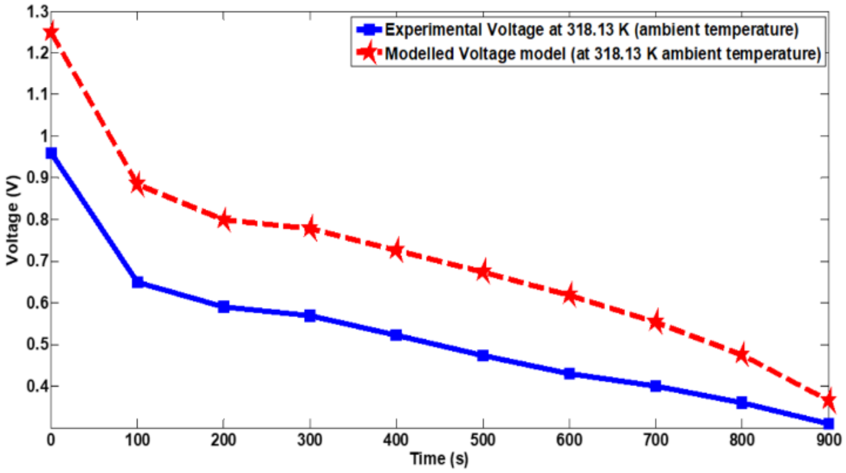

Figure 9. Performance comparison of model and experimental voltage for experiment 2.

This change in voltage due to the change in ambient temperature is modeled in Section 3. The voltage variation has been predicted by using ambient temperature, ambient air pressure (which is constant in this case), and output resistance connected to PEMFC. Figure 10 shows the comparison of improved model voltage by using Eqs 12 and 13 with experimental voltage. The RMSE is huge in this case and the comparison waveform revealed that the model in Section 3 may only be valid for the NEXA 1200 W PEMFC system, and it cannot be applied to any other PEMFC system.

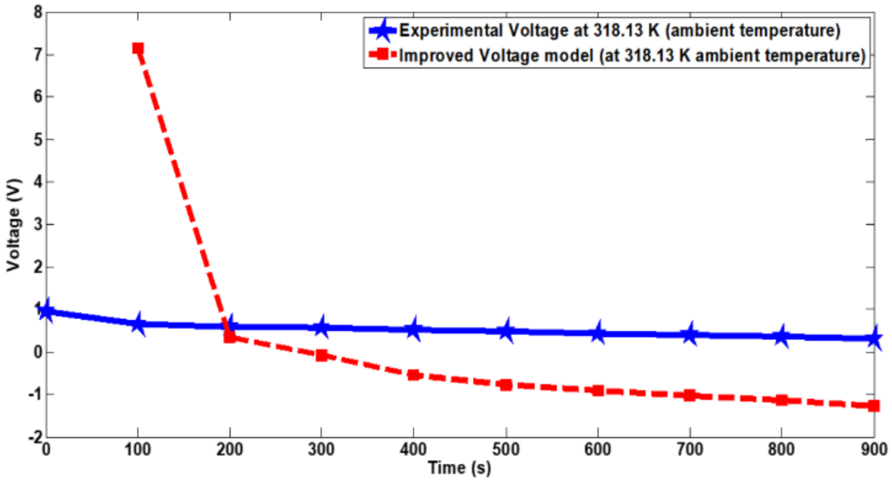

Figure 10. Comparison of improved model and experimental voltage for experiment 2.

Now the parameters are again optimized for Experiment-2 by using TSO and the new parameters are given in Table 5. Here RMSE is almost 0:01 and the comparison of modeled and experimental voltage waveforms reveals a good fit.

Table 5. Newly optimized parameters for experiment 2.

Sr. No.	Parameter	Final values
1	E_1	-1.0966
2	E_3	$9.799*10^{-5}$
3	E_4	-0.0001
4	λ	10
5	R_e	0.000799
6	β	0.14088

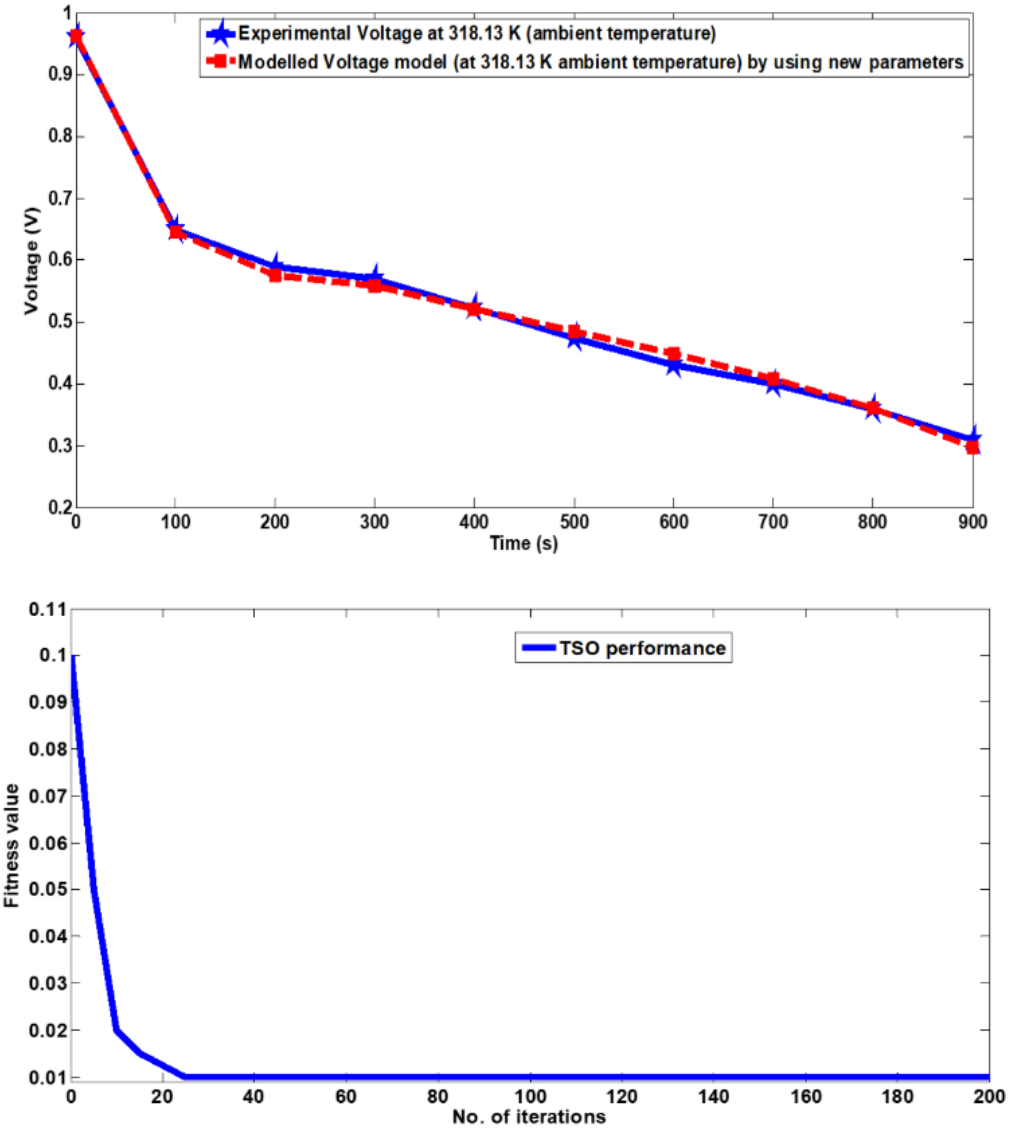

Figure 11. Comparison of model and experimental voltage by using newly optimized parameters & TSO performance.

The new parameters show big variations in the parameters such as E_1, E_3, λ, R_e and β. However, E_4 shows no variation at all. These parameters are explicitly explained in [2] and every parameter has a very complex nature that cannot be generalized, these parameters depend on the nature and behavior of PEMFC under various operating conditions. This work reveals that change in ambient temperature affects the parameters by a great amount, this means that these parameters have different values under different ambient conditions. The prediction of PEMFC voltage at varying ambient conditions is very complex. The difference between the experimental and modeled voltage in Figure 9 (for Experiment-2 with old parameters mentioned in Table 4) is revealed graphically in Figure 12 and it is revealed that the difference is not constant for low loading conditions as well, which means that the Eqs 12 and 13 are not accurate at all and these equations cannot predict the actual change in the PEMFC voltage with ambient conditions.

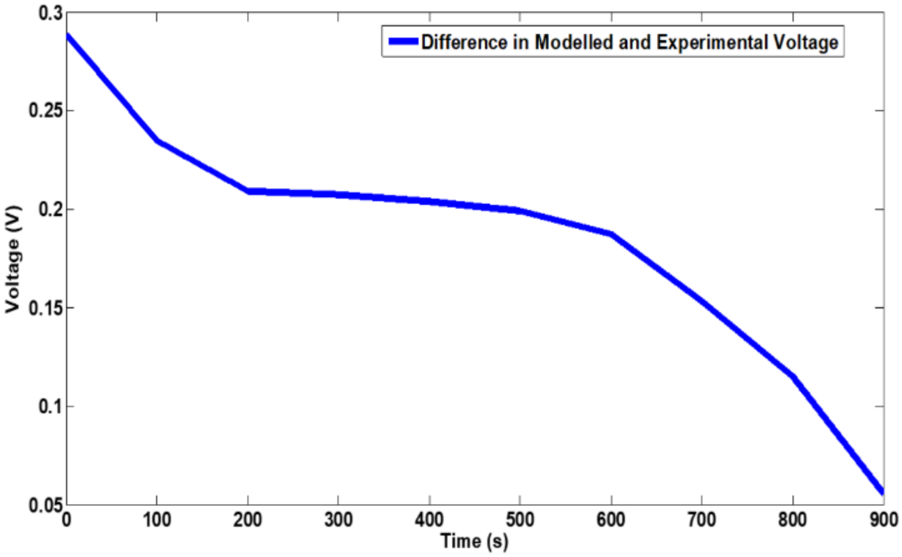

Figure 12. Comparison Difference in model voltage and experimental voltage by using old parameters.

The only feasible solution is to add TSO to the model and the parameters are to be optimized again when the PEMFC is used in different ambient conditions. The TSO runtime is fast and this optimization technique works better than all optimization techniques used before for PEMFC such as Grey Wolf Optimizer (GWO), Particle Swarm Optimization (PSO), and Whale Optimization Algorithm (WOA) with details mentioned in [29,32–34]. The newly proposed method for predicting PEMFC voltage accurately at different ambient conditions is given in Figure 13, this method involves the use of TSO as the part of modeling technique, and the parameters are optimized again by using the voltage, current, and temperature of PEMFC data which is recorded by varying load current from zero to rated current.

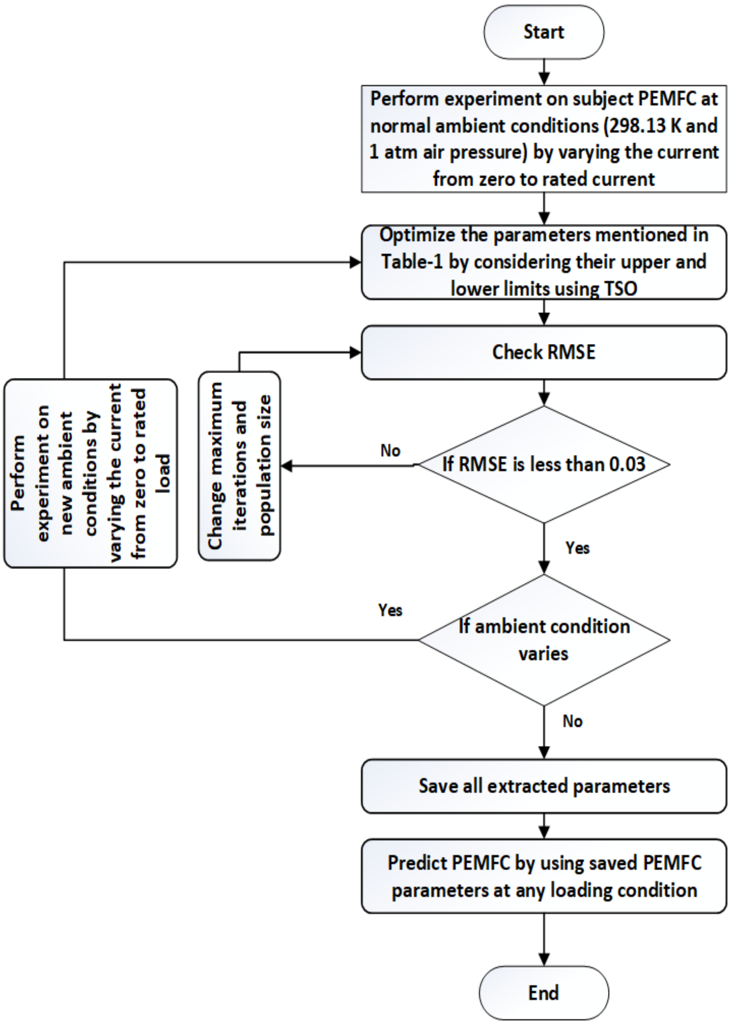

Figure 13. Proposed method for prediction of PEMFC voltage at varying ambient conditions by using TSO.

7. Conclusions

In this research work, the previous semi-empirical model, and the model of PEMFC for varying ambient have been checked. It has been revealed that the varying ambient model is not feasible for predicting the voltage variation of PEMFC. The PEMFC behavior highly depends on loading for high and low loading conditions. The parameters of the semi-empirical model don’t fit all ambient conditions. Hence, an optimization technique such as Transient Search Optimization (TSO) will be used again to optimize the parameters for varying ambient conditions. The Transient Search Optimization (TSO) is fast and takes very less time i.e., 2 seconds to optimize the parameters for 200 iterations. The complete procedure has been proposed in this work where the voltage of PEMFC can be predicted accurately at different ambient conditions with the help of the Transient Search Optimization (TSO) algorithm. In the future various modern optimization techniques have been used to implement the proposed modeling technique. The best optimization, high-performance, cost-effective technique must be adapted based on the accuracy and computation time. This hybridization provides better solutions satisfying the situation. The emulator can be developed by using this technique and can be very helpful in future research for the prediction of PEMFC voltage. It must be used in the prediction applications where PEMFC may undergo ambient temperature change and the power electronics such as DC-DC converters/inverters must be designed to accommodate these voltage variations. Hence this predictive model can be very useful in this regard. This novel method has better performance as compared to the traditional methods.

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Conflict of interest

The corresponding author states that there is no conflict of interest.

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