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Realisation of Optimal Parameters of PEM Fuel Cell Using Simple Genetic Algorithm (SGA) and Simulink Modeling

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Abstract: A methodology to solve parameter extraction of PEM Fuel cell by an optimisation process using simple genetic algorithm and Simulink is proposed. The results are validated using the traditional curve fitting method where in the initial values are compared with the existing curve for its convergence and exactitude. In this work the modelling and extensive simulation of the PEM Fuel cell has been undertaken using MATLAB-SIMULINK. The steps have been elaborated further in order to explain the incorporation and efficacy of Genetic algorithm codes in FC model. Simple Genetic Algorithm (SGA) is a reliable methodology towards optimisation of fuel cell parameters. It is inferred from the simulated results that the process is precise and absolute error is generated to showcase the subtleness of the algorithm. The proposed model can be utilised to study and develop steady state performances of PEMFC stacks.

Index Terms: Simple Genetic Algorithm (SGA), PEM fuel cell, Optimisation, Simulink modeling

I. INTRODUCTION

A synergy of a hybrid propulsion system encompassing traditional powering system coupled with an alternative powering source fuel cell is the most sought-after technology in the field of marine propulsion [1]. These systems offer immense advantage in terms of stealth, efficiency and prevents noxious emissions. Directives towards emission control were proposed by International Maritime Organization (IMO) which includes adaptation of a hybrid electric propulsion onboard [2]. In order to realise true potential of hybrid systems it is essential that the parameters governing them is to be optimized. The Optimised parameters enables to achieve higher efficiency rate in an actual propulsion plant. Amongst underwater platforms, various types of Air Independent Propulsion (AIP) system are being considered for installation and further exploitation all around the world [3-4]. The factors abiding the selection of a suitable fuel cell for integration onboard marine platform is beyond the scope of this paper. However due to the maturity in technology and the need for higher efficiency at lower operating temperatures and high-power density targets PEMFC are considered a strong contender for marine vessels [5-8]. In addition, Molten carbonate Fuel Cell (MCFC) and Solid Oxide Fuel Cell (SOFC) systems are installed on various commercial and military ocean-going surface vessels [9]. Modeling of PEMFC has made great progress over the years with prediction of parameters pertaining to, steady state mathematical and dynamic behavior of fuel cell are being undertaken all over the world [10-14]. Variation of computational evolutionary techniques are utilized in Genetic algorithms and its offsets. These algorithms are used for parameter predictions of various fuel cell models [15-18]. The health of the FC stack is ascertained on the basis of excess oxygen ratio in the fuel cell. Accurate adjustment of excess oxygen ratio enables high efficiency rates from the PEM fuel cell [19-20].

V-I characteristics of fuel cells has been reported in number of publications. The electrochemical model formulated by general steady state characteristics of PEM fuel cell was reported by Mann et.al [21]. An accurate model of fuel cell was presented by Correra et.al by means of physical and empirical formulas [22]. A similar model comprising of physical and empirical values was utilized by Pukrushpan et.al for V-I characteristics [23].

II. MATHEMATICAL MODELING OF PEM FUEL CELL

Proton Exchange Membrane fuel cells emerges as top contenders for implementation onboard subsurface and submerged vehicle operations owing to their relatively low startup time and ease of operations [24]. The greatest advantage of the PEM fuel cell is that byproduct water can be stored onboard or pumped outboard depending on overall necessity of platform without making any major alterations to the draining systems onboard. [25]. The overall endurance of the propulsion system surmounts to the effective storage capacities of oxygen and hydrogen fuel tanks. Underwater vehicles prefer to operate without the presence of atmospheric air such type of powering solutions is known as Air Independent Propulsion (AIP). Though these systems possess low specific energy density and mandate recharging they provide the most invaluable power of stealth to an underwater platform [26]. PEM fuel cell is often the preferred option for submerged vehicles owing to its high gravimetric and volumetric power density with operating temperatures between 80- 100^{0}C [27].

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The hydrogen and oxygen fuel are supplied to the anodic and cathodic nodal points of the fuel cell, the resultant electrochemical reaction inside the cell produces electricity. Based on the distribution network the produced electricity is utilized either for propulsion or stored as reserved power in batteries for utilization at a later stage. The output voltage of Cell is given by

$$V_s = n * (E_{nerst} - V_{act} - V_{ohmic} - V_{con}) \qquad (1)$$

'n' is the number of series connected cells to achieve the desired operating voltage range of the platform. The Nernst voltage of a single cell is given by eqn (2).

$$E_{nerst} = 1.229 - 0.85 * 10^{-3} * (T - 298.15) + 4.3085 * 10^{-5} * T[\ln(PH_2 + 0.5\ln(PO_2)]] \qquad (2)$$

The voltage drop (V_{act}) at the surfaces of anode and cathode is depicted as a parametric expression in Eqn 3

$$V_{act} = \varepsilon_1 + \varepsilon_2 T + \varepsilon_3 * T * ln(Co_2) + \varepsilon_4 * T * \ln(i) \qquad (3)$$

As per Henry's Law, the concentration of oxygen (mol cm^{-3}) at cathode end of fuel cell (Eqn 4) is given by

$$Co_2 = \frac{Po_2}{\left[5.08 * 10^6 exp^{-\frac{498}{T}}\right]} \qquad (4)$$

The overall resistance drop (Eqn 5) contributing to the ohmic voltage drop is obtained from the summation of membrane resistance (R_M) and contact resistance multiplied with current.

$$V_{ohmic} = i.(R_M + R_C) \qquad (5)$$

The values of specific resistivity (ρ_M), thickness of the membrane and area is utilized to calculate the membrane resistance of the fuel cell (Eqn 6)

$$R_M = \rho_M \cdot \frac{l}{A} \qquad (6)$$

Nafion membranes is most commonly used in PEM fuel cell. The specific resistivity of Nafion membrane (Eqn 7) is given by:-

$$\rho_M = \frac{181.6\left[1+0.03\left(\frac{i}{A}\right)+0.062*\left(\frac{T}{303}\right)\left(\frac{i}{A}\right)^{2.5}\right]}{\left[\left[\lambda-0.634-3\left(\frac{i}{A}\right)\right]*exp\left[\frac{4.18(T-303)}{T}\right]\right]} \qquad (7)$$

Concentrations of oxygen and hydrogen are affected by means of mass transportation (Eqn 8) and is calculated using the current density (I/I_{max}) and parametric Co-efficient b.

$$V_{con} = -bln\left[1 - \left(\frac{I}{I_{max}}\right)\right] \qquad (8)$$

Modeling of PEM fuel cell were based on the governing equations (1-8) is formulated by Amphlett et. al [12]. Optimisation of parameters were undertaken by utilization of Genetic Algorithm (GA) codes incorporated in MATLAB-SIMULINK MODEL (Fig.1.)

III. PARAMETER EXTRACTION AND MODELING OF PEM FUEL CELL USING SIMPLE GENETIC ALGORITHM (SGA)

The voltage versus current (V-I) characteristic curve is often utilized to determine the FC performance. The current and voltage parameters form the basis for subsequent design and selection of other components including stack size and other underlying operating parameters. The V-I Curve can be generated from experimental data. These parameters (Table 1) are used as initial inputs to generate the experimental curve. A MATLAB-Simulink model (Fig.1) was developed to generate a Voltage-Current characteristic reference curve from the experimental data. The V-I curve generated is compared with the linear characteristic curve and linear normalization of the data is depicted as a histo-bar subplot in the graph (Fig 2).

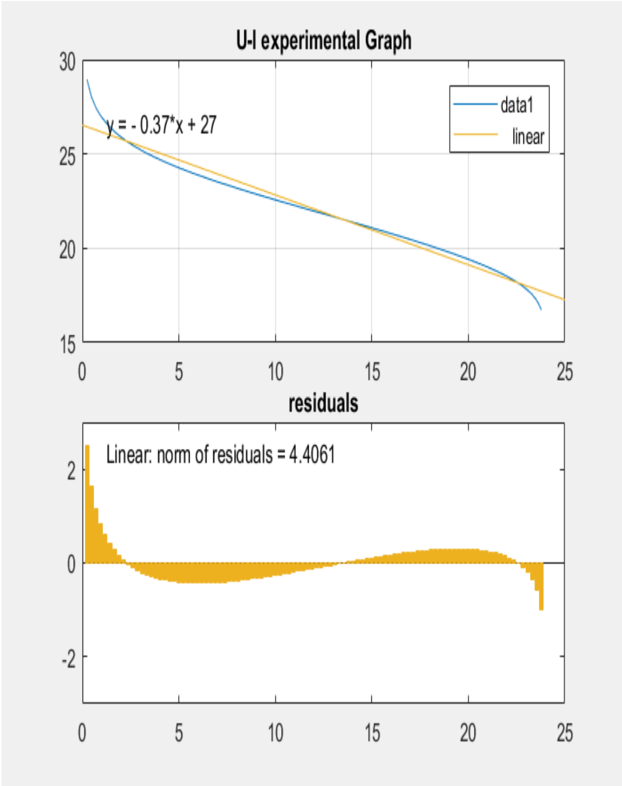

Fig 2: V-I characteristic Curve derived from the experimental data obtained from the first Simulink Model

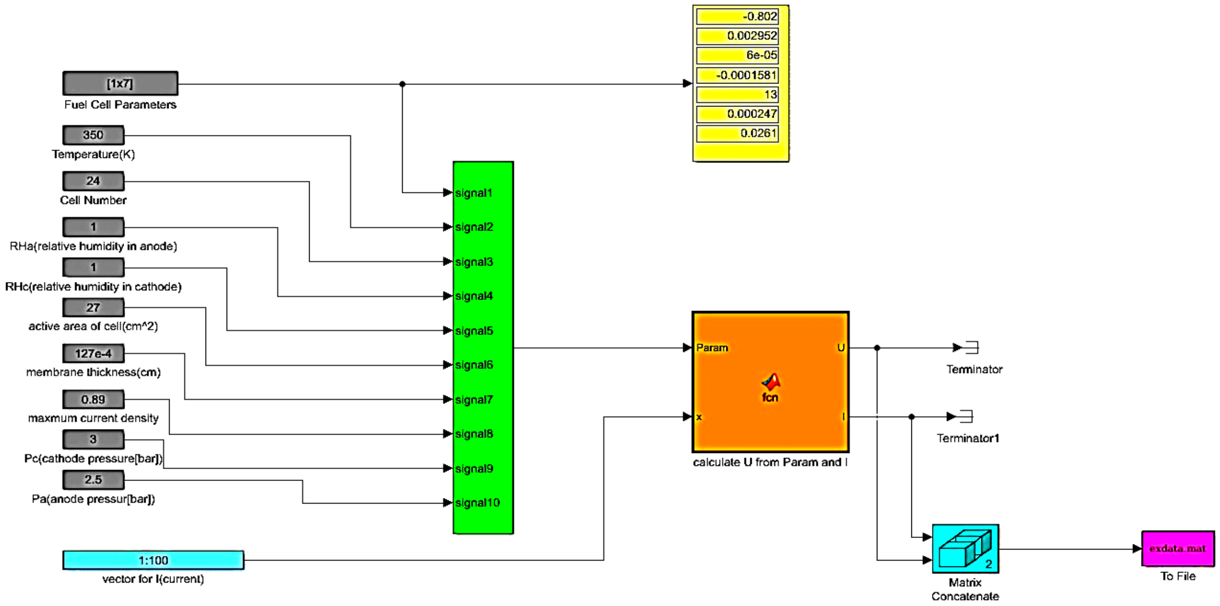

Fig 1: Simulink model of PEM Fuel Cell – creation of Experimental graph.

IV. UTILISATION OF SIMPLE GENETIC ALGORITHM (SGA)

Use Genetic algorithm is a complex metaheuristic process which forms part of the larger evolutionary algorithm group [28]. These algorithms are most commonly used to process and quantify optimization problems heavily relying on the biological concepts of cross-over rates and mutation. The most common prerequisites to resolve a problem is twofold. First is genetic representation of the problem and the second lies in evaluation of fitness function. Post definition of initial steps the process is looped into an iterative process of cross-over and mutation. The pictorial representation of the genetic algorithm process is depicted in the flow chart Fig. 3).

Table 1: Stack Parameters

An example of a column heading	Column A (*t*)
Number of cells	24
Stack Temperature T(K)	350
Effective area of the Cell A(Cm^2)	27
Cathode Pressure (bar)	03
Anode Pressure (bar)	2.5
Relative humidity at anode	1
Relative humidity at Cathode	1
Membrane Thickness	127 e-4

Table 2: Upper and Lower bounds of the parameters

A. Objective Function

Because The objective function can be derived from the voltages obtained from the experimental data and voltage obtained from the model. The parameters can be determined by utilizing the objective function for optimization to derive the squared error between the output voltage of the PEM stack and the experimental data obtained from actual fuel cell.

$$\min(\varepsilon 1, \varepsilon 2, \varepsilon 3, \varepsilon 4, b, Rc, \lambda)\left(y = \sum_{j=1}^{j}(Vexp - Vs)^2\right) \quad (9)$$

Implementation of Genetic Algorithm for Optimisation of Parameters

A comprehensive MATLAB-SIMULINK model of a PEM fuel cell as shown in Fig.4 was modeled in order to optimize the FC parameters. The genetic algorithm was incorporated into the functional blocks of the Simulink Model. The upper and lower bounds of the parameters are given in Table 2.

B. Optimisation Technique

The steps involved during Optimisation of fuel cell parameters using Genetic Algorithm (GA) is appended in the following steps: -

(i) Step 1: - Initialisation and generation of population

Chromosomes are pooled together to generate a population. These chromosomes consist of binary strings which represents the model parameters of the PEM fuel cell. Initialisation of GA operators viz., Population size, Number Cross-over rate and Mutation rate are undertaken in this process. Further the number of iterations and number of variables are defined in this step.

Parameters	ε_1	ε2	ε3	ε4	λ	R_c	b
Upper bound	-0.944	0.005	$7.8 * 10^{-5}$	$-1.88*10^{-4}$	23	$8*10^{-4}$	0.5
Lower bound	-0.952	0.001	$7.4 * 10^{-5}$	$-1.98*10^{-4}$	14	$1*10^{-4}$	0.016

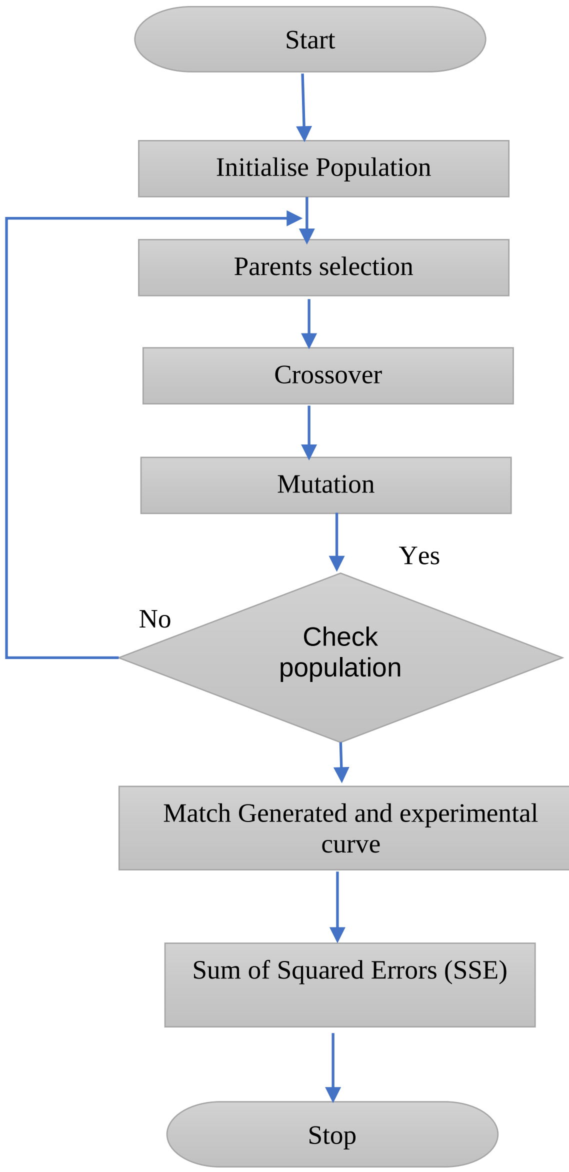

Fig. 3: Flowchart of genetic Algorithm process

(ii) Step 2: - Selection of parents.

Post Initialisation of parameters, the program undertakes selection of parents. Roulette wheel selection method is used for selection of parameters. In this method the chromosomes are assigned virtual sectors in a virtual wheel and the sector value is proportional to the fitness function.so depending upon the number of genes in the chromosome the selection of largest or smallest sector is been undertaken. The selected parents are moved forward in the process to undergo crossover and mutation functions. The above process of parent selection is coded into a Simulink model as shown in Fig.5.

(iii) Step 3: - Crossover and Mutation rate operation

The process involves selection of genes from the parent chromosomes for combination to create a new offspring. Depending upon the combination and the gene pool originating from parents the new chromosome stands to possess better characteristic obtained from the parents. For enhancing efficiency of crossover, a multi-point crossover rate is chosen. The generated offspring undergoes mutation process in which one or more characteristics of the gene are altered. The mutation operator toggles the value of the gene from 1 or 0 based on the preset value of mutation probability. The entire procedure of crossover and mutation rates were coded in MATLAB and incorporated as a functional block in the Simulink model as shown in Fig 5. and Fig 6.

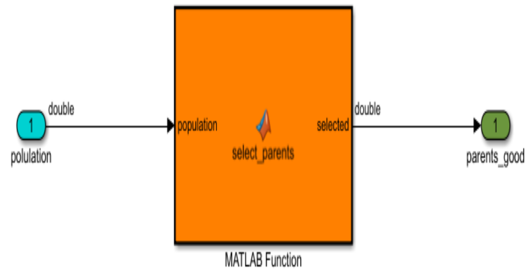

Fig. 4: Selection of Parents

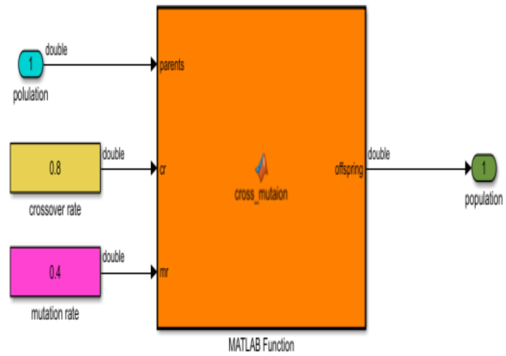

Fig. 5: Crossover and Mutation functions

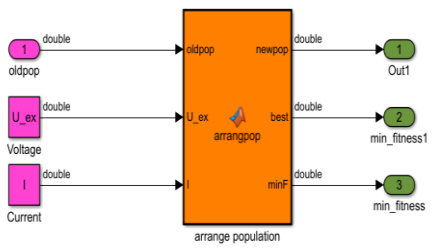

Fig. 6: Arrangement of Population

(iv) Step 4: - Generation of new population

The old population is replaced with the current generated population with newer characteristic traits. The whole procedure is repeated till the termination criteria is achieved. The process of formulation of new population as shown in Fig.6. and Fig. 7 is undertaken using MATLAB codes infused into a functional block of Simulink.

(v) Step 5: - The iterative process is terminated upon achievement of desired criteria; else the process is reverted to step 2 and is continues till the termination criterion is met.

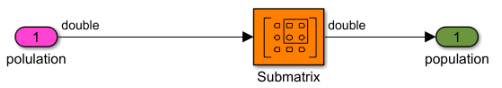

Fig. 7: Iterative matrix for refining of results

V. RESULTS AND DISCUSSION

The outcome of the paper is to generate a set of optimal parameters which would replicate the actual behavior of Fuel cell. In order to implement the influence of Genetic algorithm calculations modeling of PEM fuel cell was undertaken based on the generic equations governing the FC. A Simulink model was shown to generate a reference experimental graph. The purpose of this work was aimed at finding an optimal parameter setting for designing and operation of fuel cell. This work provides a visual appreciation of the Optimisation process through the Simulink block models. Optimisation provides flexibility towards computation of parameters in shorter time, cost effectiveness and provides baseline data for advanced techniques suitable towards fine tuning of the system.

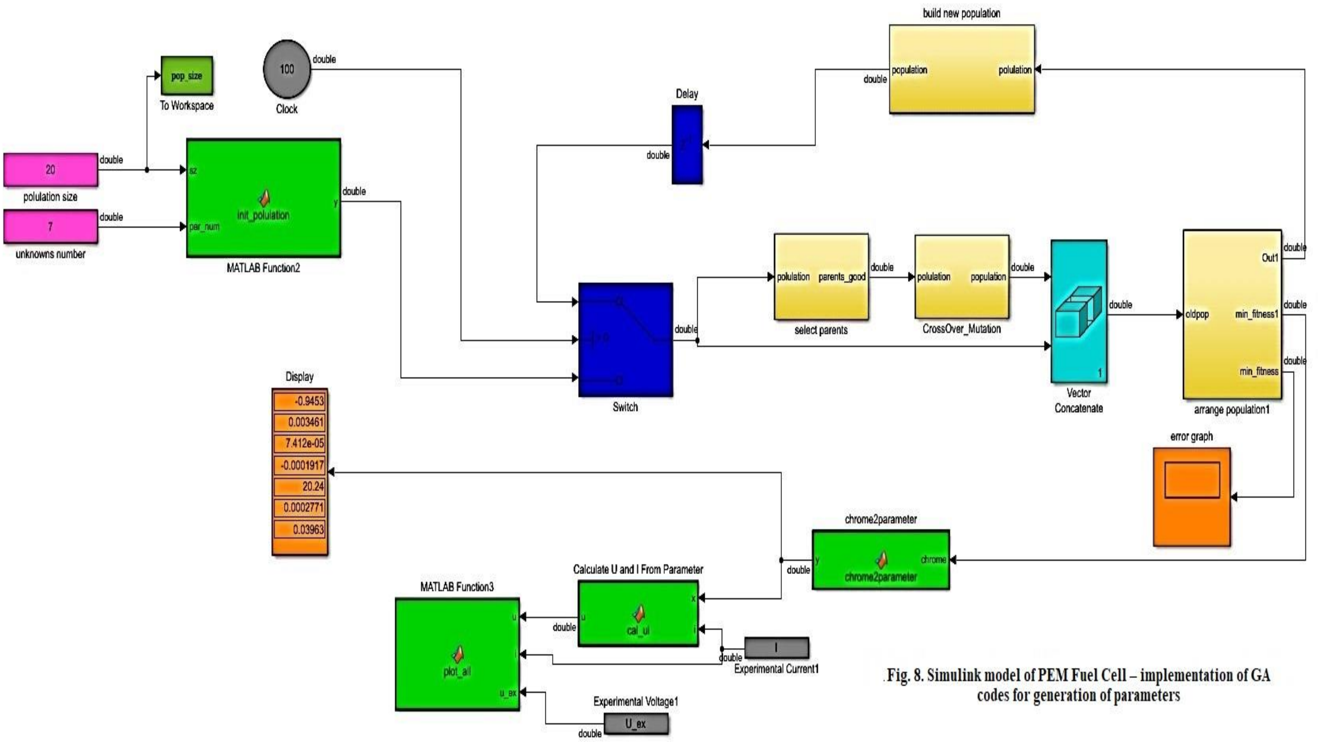

Fig. 8. Simulink model of PEM Fuel Cell – implementation of GA codes for generation of parameters

Table 3: Optimised Parameters

Parameters	ε_1	$\varepsilon 2$	$\varepsilon 3$	$\varepsilon 4$	λ	R_c	b
Optimised	-0.9476	0.003	7.4 $*10^{-5}$	$-1.91*10^{-4}$	20	$3.32*10^{-4}$	0.037

C. Simulink Model of PEM Fuel Cell

Number A Simulink model of PEM fuel cell is modeled incorporating the entire Genetic Algorithm (GA) procedures in a sequential manner in the form of functional Simulink blocks as depicted in Fig.8.Table 3 shows the optimized parameters obtained post running of MATLAB-Simulink model.

The model parameters viz., $\varepsilon 1, \varepsilon 2, \varepsilon 3, \varepsilon 4, b, Rc, \lambda$ are extracted by the GA codes which forms part of the MATLAB-SIMULINK model. Minimisation of the values defined by the objective function defined in eqn (9) is executed. The upper and lower bounds of the parameters are defined in table 2.

The data utilized for the proposed technique has been borrowed from the PEM fuel cell model [21] and are depicted in table 2. A dedicated MATLAB-Simulink program was developed for incorporation of Simple Genetic Algorithm (GA) technique. The simulations were performed using an INTEL(R) CORE (TM) i7-7700 HQ CPU @ 2.80 GHz,64-bit OS, X64-based processor.

In order to highlight the simplicity an efficiency of simple genetic algorithm a comparison of result obtained through optimisation using other evolutionary algorithms [29-30] were undertaken and tabulated in table 4.

Table 4. Comparison of Optimised parameters

Parameters	ε_1	ε2	ε3
SGA	-0.9476	0.003	$7.4 * 10^{-5}$
AIS	-0.951	0.003	$7.43 * 10^{-5}$
PSO	-0.951	.003	7.6910^{-5}

A comparison of the graphical simulations shown in Fig.9. shows that the V-I characteristic curves obtained from experimental and from simulations are exactly a match thus validating the proposed formulation. This method will serve as a bench mark for further simulation models.

An error graph has been obtained by calculating the difference between the experimental and the actual values shown in Fig.10. The Error values are calculated using the equation (9). MATLAB codes were written for infusing the error generation graph into the Simulink model Fig.9.The graph is plotted between the normalized value vis-à-vis the iteration number. The proposed method shows that that the error value shows considerable reduction and under similar conditions for actual and experimental data. The error graph proves the robustness of the method.

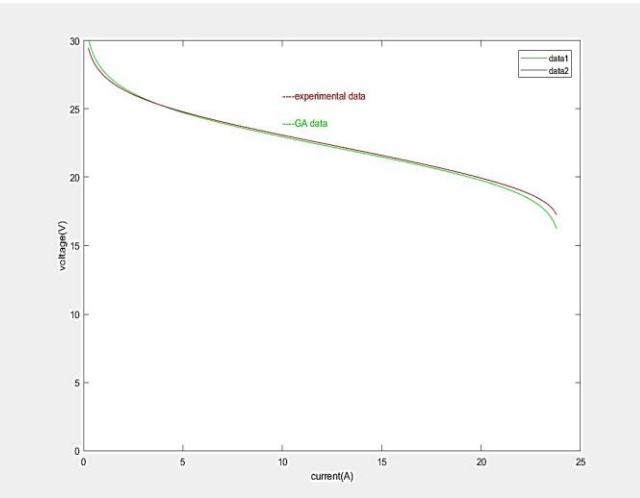

Fig. 9. V-I characteristic curve from Experimental and actual simulated data models

VI. CONCLUSION

In this paper a MATLAB-Simulink model of a PEM fuel cell models was developed in order to extract experimental as well as Optimised parameters. A simple Genetic Algorithm procedure is utilized for parameter Optimisation of a PEM fuel cell. The following $\varepsilon 1, \varepsilon 2, \varepsilon 3, \varepsilon 4, b, Rc, \lambda$ 07 parameters were derived from the simulation models. The results obtained from the procedure are displayed utilizing the traditional curve-fitting approach and the V-I characteristics obtained post optimisation agrees well with the experimental data. This new methodology of infusing the Genetic Algorithm codes into a MATLAB- Simulink functional block model will help in better appreciation of the algorithm and the processes involved in modeling of fuel cell. The Simulink model provides a cost-effective simulation strategy for design of propulsion system with desired power output for commercial and Defence applications. Future studies can be undertaken keeping the optimal parameters as baseline values.

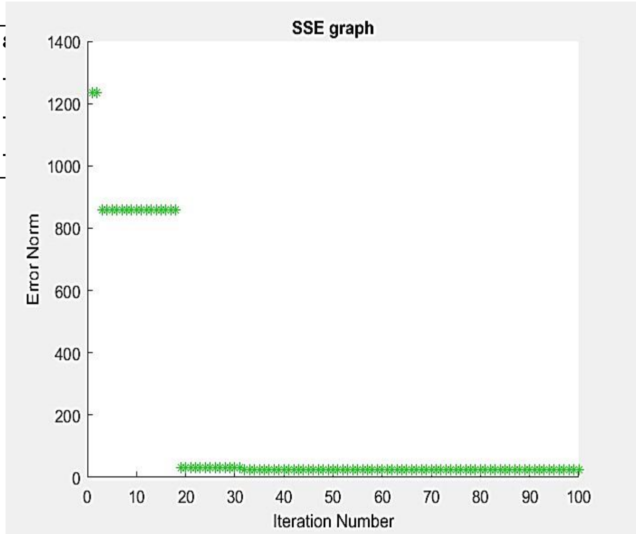

Fig. 10. Error Graph

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