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Optimal control of hydrogen fuel-cell based system with voltage regulation

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Abstract : In recent times, carbon emissions have been increasing rapidly, leading to significant climate changes due to the use of non-eco-friendly energy sources. To reduce emissions and pollution, clean renewable energy sources (RES) are now being employed worldwide. Harnessing the potential of renewable energy sources can provide alternatives for energy generation that mitigate carbon emissions, reduce pollution, and offer clean energy with better performance and maximum efficiency. Hydrogen fuel-cell technology, being a clean and eco-friendly energy source, can meet energy requirements effectively. This paper focuses on the voltage regulation of hydrogen fuel cells. The objective is to control the output voltage using the Integral Time Absolute Error (ITAE) method. Additionally, an intelligent optimization technique, the Genetic Algorithm (GA), is implemented to minimize the objective function and achieve an improved gain value for the controller used in the model.

***IndexTerms* – Hydrogen Fuel-cell, Genetic Algorithm, Voltage regulation, Integral time absolute error (ITAE)**

I. Introduction

The usage of greener energy also known as renewables, which are abundantly available in nature is getting utilized increasingly adopted to reduce harmful emissions and pollution from fossil fuels, while also conserving limited resources used in energy production [1]-[4]. Despite the development of energy production techniques from unconventional sources such as wind, solar, and geothermal, these sources currently fulfill only a small portion of global energy needs and are not sufficient for static, movable, or industrial large scale applications [5]-[6].

Inspired from Proton Exchange Membrane Cell (PEMFC) technology, the current work presents an eco-friendly method for energy generation [7]. This method offers minimal emissions, without producing any pollutant which in turn produces clean energy, and improved efficiency. In this approach, for the fuel cell, hydrogen(H) is used, hence it is named as a hydrogen fuel cell. Additionally, the energy for the mentioned fuel cell may be stored in the form of hydrogen for a prolonged duration, ensuring a reliable energy supply. Hydrogen can be stored depending on requirement on any form and can be transported as solid liquid or gas, this will help in stability and full fulling the energy requirement [8]-[9].

Fuel in the form of hydrogen can be directly converted into usable energy in a fuel-cell through some chemical reactions that drive an electro-chemical process. Where, hydrogen is inserted to the -ve electrode (anode) of the fuel-cell, while oxygen is inserted to the +ve electrode (cathode) [10]-[11].

-ve ions are collected from the hydrogen at the anode of the cell and the oxygen at the cathode combines with the electrons, protons, or water molecules to form ions or hydroxide water. The electrons that are extracted at the anode will not pass directly to the cathode through the electrolyte; instead, they flow through an external electric circuit. This flow of electrons generates an electric current [12]-[15]. In this system, the necessary energy is produced as DC which is converted through a boost converter, where a proportional integral(PI) controller can be implemented to achieve an adjustable and controlled voltage for improved fuel cell capabilities. The proportional integral controller is tuned using an analytical optimization technique, specifically a Genetic Algorithm (GA), which minimizes the Integral Time Absolute Error (ITAE) equation to find the optimal values for the proportional integral controller [16]-[19].

The detail modelling along with the GA based optimization is done in MATLAB to validate the claims in the subsequent sections.

II. FUEL CELL.

A fuel cell is an electrochemical cell that generates electrical energy through an electrochemical reaction using fuel. To produce electrical energy, the fuel cell requires a continuous supply of fuel and an oxidizing agent, typically oxygen, to sustain the electrochemical reaction. The production of electrical energy continues uninterrupted as long as the fuel and oxidizing agent are supplied.

A fuel cell consists of a solution which is electrolytic and positioned between a negative and positive electrode. The electrolyte facilitates the transfer of protons. The functional block diagram of a fuel cell is illustrated in Fig. 1 below.

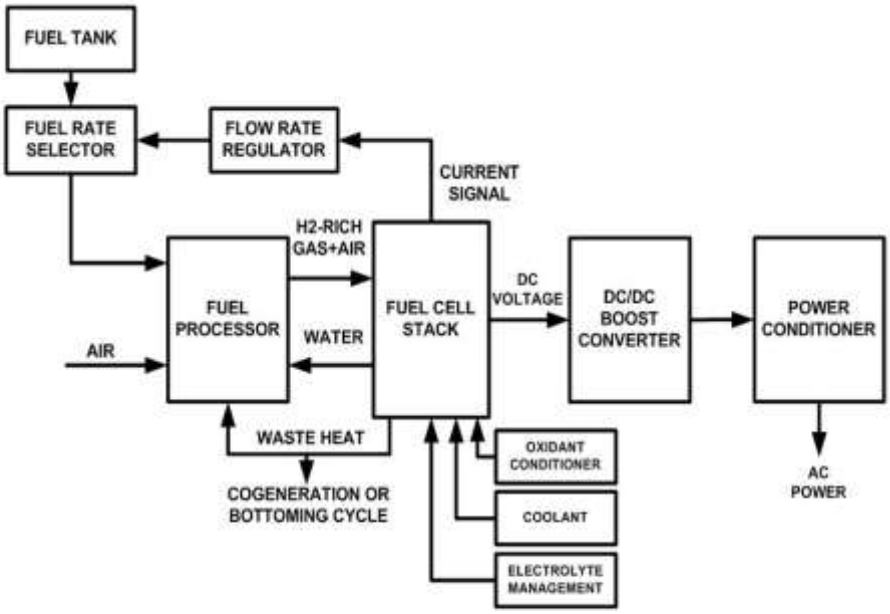

Fig-1: Flow sheet representation of a fuel cell

Principle of Fuel-Cell

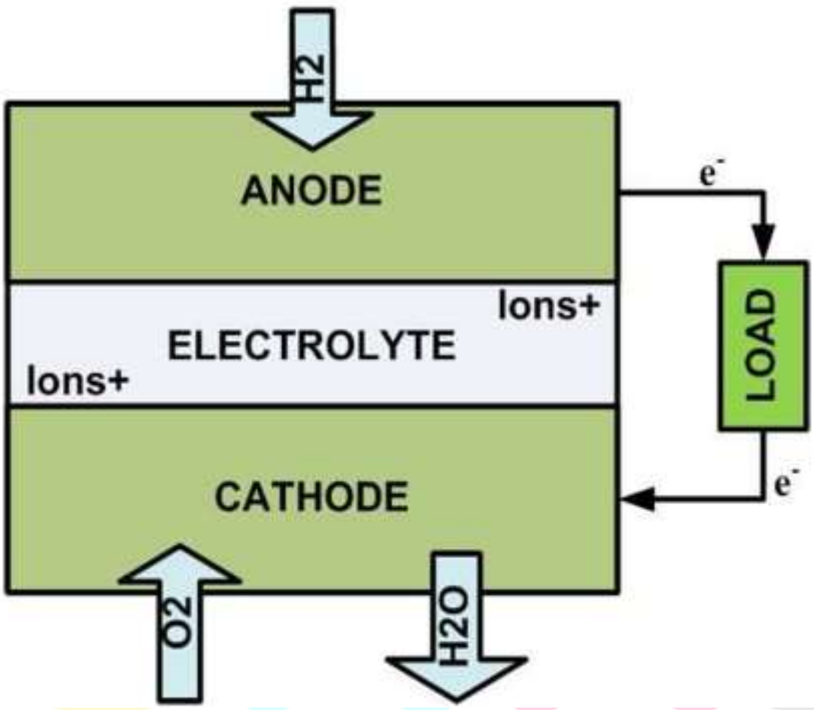

Fig-2: Working principle of a fuel cell

Fig-2 illustrates the operation of a fuel cell. The energy is produced directly by the help of a chemical reaction within the fuel-cell. As an electrochemical cell, the fuel-cell facilitates this reaction through an electrolyte medium. The ionization of fuel substances from the anode to the cathode generates an electric current. Oxygen is typically used alongside the fuel in the input to support the oxidation process during the chemical reaction.

Reaction in the cathode is given by the following equation,

$O2 \rightarrow 2H_2 + 4e^- \rightarrow 4OH^-$ (1)

Anode reaction is as follows,

$2H_2 + 4OH^- \rightarrow 4H_2O + 4e^-$ (2)

The overall reaction in the cell is given in equation 3.

$2H_2 + O_2 \rightarrow 2H_2O$ (3)

As electrons cannot be passed directly from the cathode to the anode through an electrolytic medium, an outside conduction mechanism may be provided to facilitate their transfer. This movement of electrons generates an flow of electric current. The efficiency of the fuel-cell is approximately 65%, significantly higher than that of conventional energy sources.

III. Hydrogen Based Fuel-Cell

As demand of electrical energy continue to rise and nonrenewable resources deplete rapidly, we are increasingly turning to RES that are eco-friendly and produce no emissions. While these renewable technologies are still developing and require significant infrastructure for energy production, hydrogen fuel cells offer a practical alternative. Hydrogen fuel cells operate in a manner similar to conventional fuel cells, providing a more straightforward solution for generating electrical energy.

A. Principle of Hydrogen Based Fuel-Cell

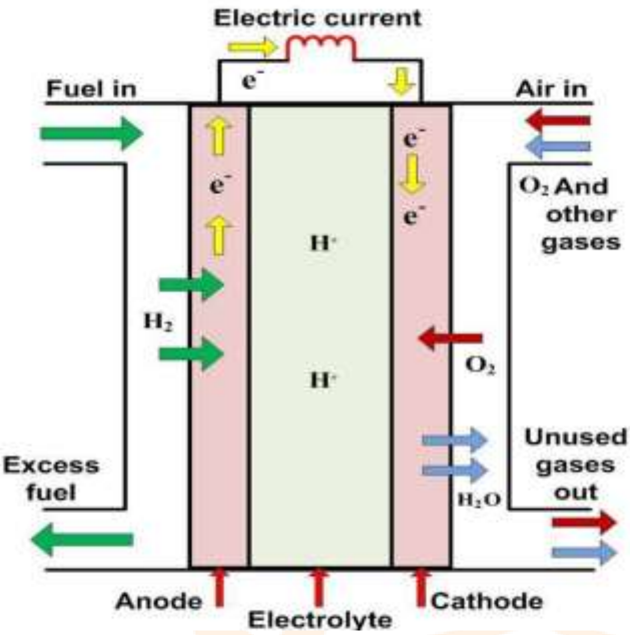

Fig-3: Working of Hydrogen fuel cell

Fig. 3 illustrates the operational basis of a PEMFC type hydrogen fuel-cell. Its operation involves an undiluted electrolytic solution provided with a fuel anode and an oxidant electrode (cathode) within a container, isolated by separators.

At positive electrode, hydrogen is ionized to release free electrons and H^+ ions. Each hydrogen molecule interacts with the electrode surface, splitting into hydrogen atoms because of the catalytic properties of the electrode. The hydrogen atoms enter the solution, while the electrons travel to the positive electrode (cathode).

$H_2 \rightarrow 2H^+ + 2e$ (4)

The above equation(4) shows the reaction of the fuel cell that occurs in the negative electrode. The oxygen that is provided by the positive electrode reacts with the electrolyte and the hydroxyl ion comes with electron.

$(1/2)O_2 + 2OH^- \rightarrow 2H_2O + Energy$ (5)

The above equation (5) shows that the OH^- ions build at the negative electrode participating in the reaction with the anode. This flow of electrons from anode to the cathode through an external path, driven by this electro-chemical reaction, produces an electric current.

$H_2 + (1/2)O_2 \rightarrow H_2O$ (6)

The above equation (6) illustrates the overall result of the electro-chemical reaction, where water and heat are produced as byproducts of the hydrogen fuel cell.

B. Properties possessed by Hydrogen

Hydrogen is odorless, colorless, tasteless, and highly combustible, typically occurring as a gas. Due to its extremely low boiling point, hydrogen is rarely found in its liquid form under natural conditions.

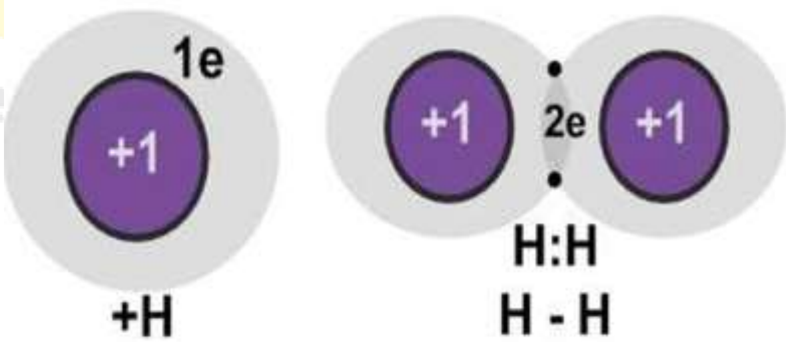

Fig-4: Molecular structure of hydrogen atom

Hydrogen atom consists of one unit of positive electric charge in its nucleus and a proton. Hydrogen gas is composed of diatomic hydrogen molecules, each molecule containing a pair of hydrogen atoms, as illustrated in Fig. 4. It is the most abundantly available on Earth, making up about 0.14% of the planet's surface weight. Hydrogen is found in most compounds and interacts with many other elements, with the exception of some noble gases.

C. Selection of Hydrogen

Hydrogen contains significantly more energy compared to conventional fossil fuels. The energy required to break a hydrogen bond is relatively low, meaning less energy is needed to extract hydrogen from its compounds. This makes hydrogen a promising alternative fuel. However, efficient and safe storage methods still need to be fully developed.
Currently, hydrogen can be stored in small quantities at different pressure level as gas as well as in solid state. Therefore, hydrogen is expected to play a crucial role in meeting future energy demands. On Earth, hydrogen is found in compounds such as water, hydrocarbons in fossil fuels, and biomass. Renewable sources like biomass, geothermal, wind and solar can be used for production of hydrogen. Hydrogen can also be extracted from other sources like glycerol, biomass, water . Now a days it can also be extracted as by product of nuclear stations.

IV. Optimization Technique

Tuning the Proportional Integral controller using ITAE error technique is crucial for minimizing the overall system error and achieving the desired system response. Given the complexity of this task, an intelligent optimization technique, specifically the GA(Genetic Algorithm), is employed to determine the optimal gain values of the proportional and integral controller and to reduce error effectively.
This process involves adapting to environmental changes and ensuring best suited individual will reproduce and survive to next generation. Each generation consists of a large set of individuals, each represented as a point in the search space. Each individual is encoded as a list of characters, analogous to a chromosome.

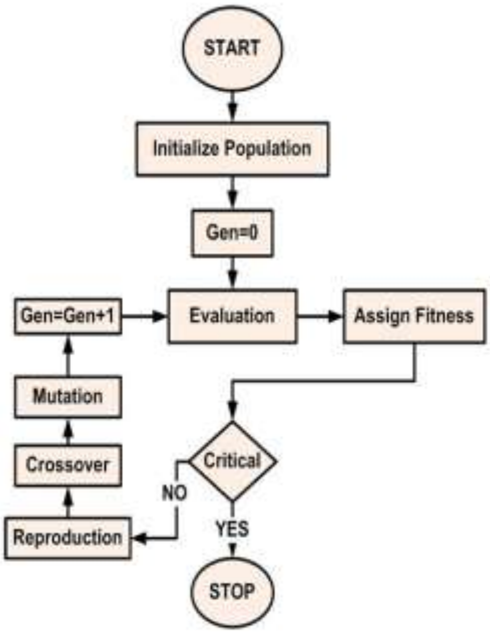

Fig-5: Block diagram representation of GA

The Genetic Algorithm (GA) maintains a population of n number of individuals, each with its fitness level, where each individual consists of parameters K_p and K_i within specified bounds. Reproduction is based on fitness levels, with individuals selected to produce better offspring through crossover with parental chromosomes. When the new offspring closely resemble the previous ones, the most effective solution for the problem is achieved at the end. Figure 5 above illustrates the flowchart for Genetic Algorithm.

V. Simulation

Figure 6 above shows the block diagram representation of the simulation model of proton exchange membrane (PEM) based hydrogen fuel cell for its effective control. In this present model, the input hydrogen is supplied to the fuel stack accompanied by a regulator and selector, which can control the rate of flow of the fuel to achieve the desired outcome.

$$\boldsymbol{FuelFr} = \frac{60000.R.(273+\theta).N_C.I_{ref(fuel)}}{2F.\left(101.1325.P_{f(H_2)}\right).\left(\frac{U_{f(H_2)}}{100}\right)\left(\frac{X_{H_2}}{100}\right)}$$

The above equation provides the rate of flow of fuel to the fuel stack for a given fuel cell where,
Standard atmospheric pressure is 101.1325 and
R= Molar gas constant i.e., 8.3144598 $m^2Kgs^{-2}K^{-1}mol^{-1}$
F= 96485 As/mol
$U_f(H_2)$ = Utilization factor of hydrogen
$P_f(H_2)$ = Fuel supply pressure is 1.5 bar
X_{H2} = Fuel consumption i.e., 99.95%
N_c= Nominal consumption of fuel is 60.38 slpm
$I_{ref(fuel)}$ = Reference for the controller
θ = temperature i.e., 650

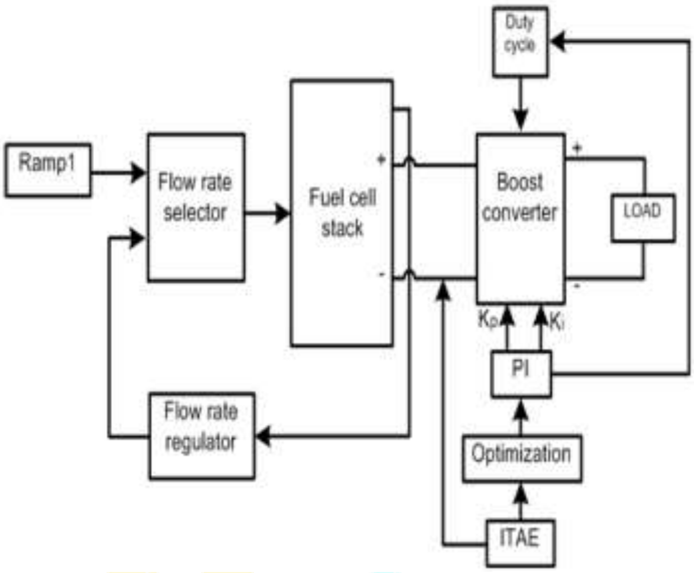

Fig-6: Simulation model of hydrogen fuel cell for the study

The DC power produced is connected directly to the boost converter to raise the potential difference to get the required specifications. The generated voltage is controlled by a proportional integral(PI) controller, which is tuned by using the ITAE error equation as a minimization problem to determine the optimal gain values (Kp and Ki) for the given controller.

$$ITAE = \int_0^T te(t)dt$$

The integral time absolute error is described by the above equation.

VI. RESUTS AND DISCUSSION

A. MATLAB SIMULATION OUTPUT (INITIAL)

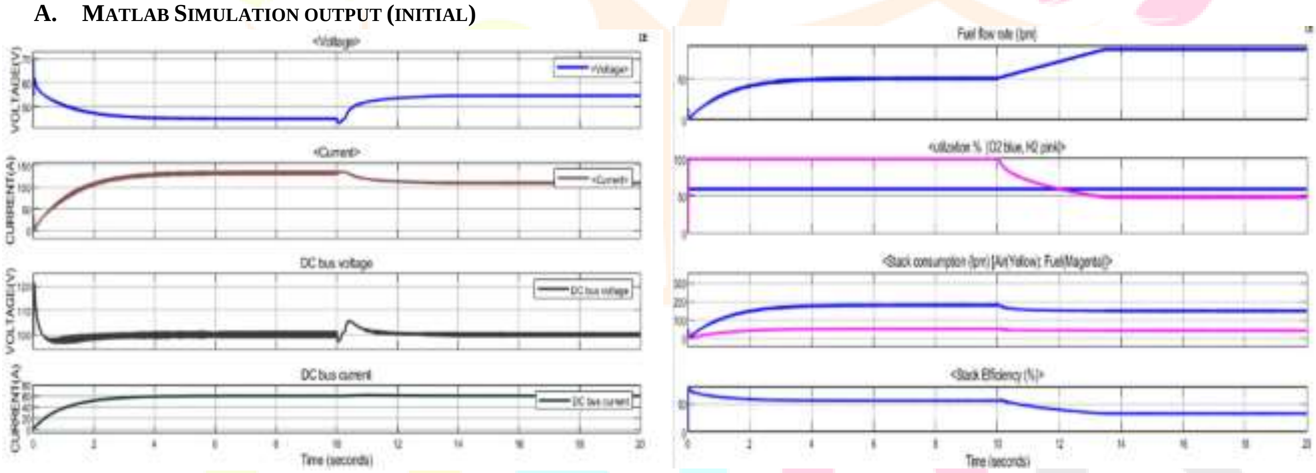

Fig-7: Output characteristics of fuel cell without optimization

Figure 7.a. above displays the DC voltage, current, load voltage, and current with PI control tuned through a trial-and-error approach. Figure 7.b. illustrates the fuel flow rate, utilization, stack consumption, and stack efficiency, also determined using a trial-and-error method.

B. OPTIMIZED OUTPUT AFTER GA

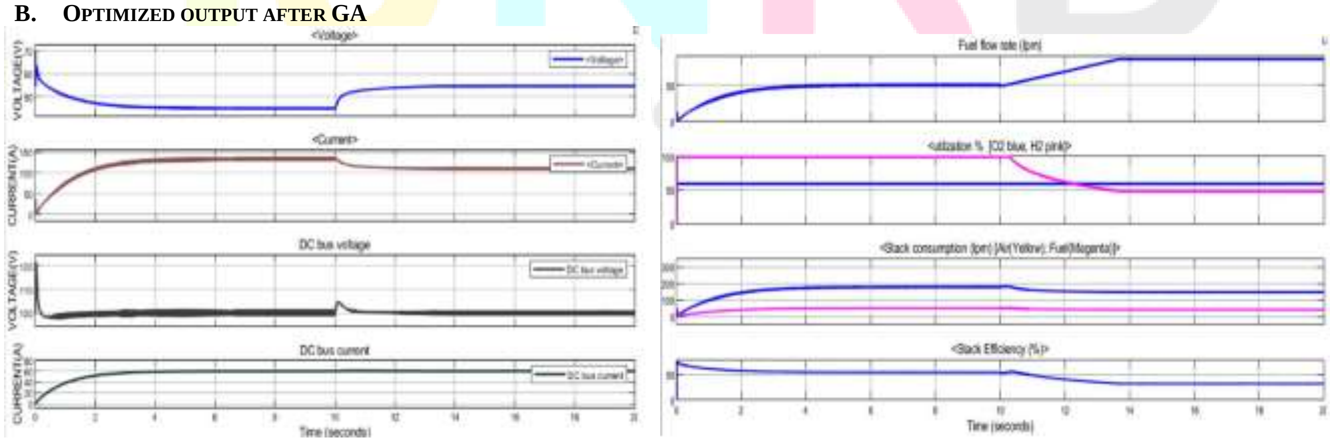

Fig-8: Output characteristics of fuel cell after optimization

Figure 8.a. shows the voltage output, current, load voltage, and current with PI control optimized through tuning. Figure 8.b presents the fuel flow rate, utilization, stack consumption, and stack efficiency, also with optimized PI control. The gain parameter values with ITAE errors obtained for the given controller are mentioned in Table 1.

Techniques	Parameters		
	K_P	K_I	ITAE
Initial	0.00001	0.7243	0.173
GA	0.00015	0.05	0.00632

Table-1: Parameters for Controller

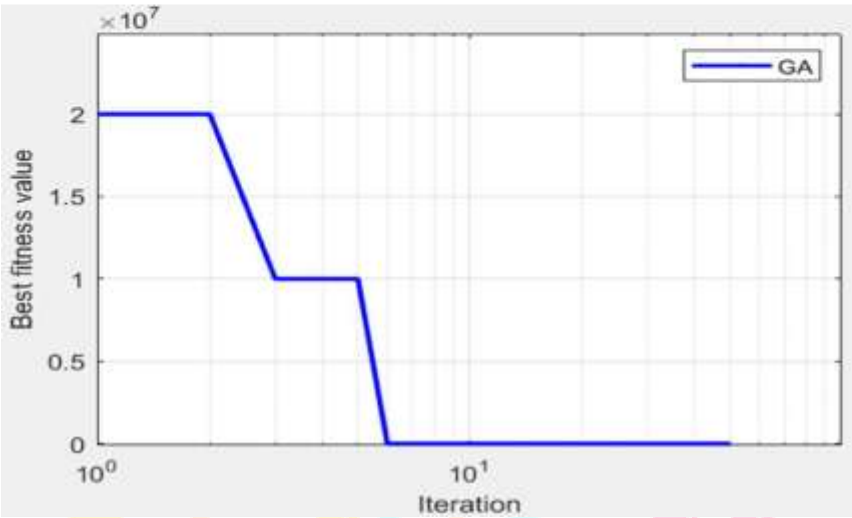

Fig-9: Convergence Plot

The above figure provides the convergence plot for GA based optimization with respect to the fitness values.

VII. Conclusion

The modelling of a Proton Exchange Membrane based hydrogen fuel-cell model was conducted using MATLAB software. The system is controlled using a PI controller, with tuning achieved through an intelligent optimization technique known as the Genetic Algorithm (GA). The GA optimizes the controller by minimizing the ITAE equation to obtain the best fitness and gain values.

The simulation results, as depicted in the figures above, show that the GA technique provides superior performance and control compared to traditional trial-and-error methods. The results include voltage, current, fuel consumption in the stack, fuel flow rate, and bus voltage and current. This approach is promising for future applications in hybrid vehicles and industrial settings. Further improvements could be made by implementing more precise controllers to enhance overall system performance.

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