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Effects of Operating Parameters on Proton Exchange Membrane Fuel Cell Performance and Application of Incremental Conductance Technique

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ABSTRACT

Fuel cells have a nonlinear behavior and strong disturbances given by the load changes, and their parameters vary with time and temperature. As a consequence, control techniques are necessary to achieve efficient performance, prolong the fuel cell's life, guarantee safety, and achieve low cost operation. The aims of this research are to investigate how variations in operating parameters influence PEMFC performance, and to evaluate the effectiveness of Incremental Conductance techniques in optimizing PEMFC operation. The methodologies employed are development of PEMFC model, simulation of parameter variation, and incremental conductance technique implementation using Matlab/Simulink software. The results presented indicate that operating fuel cell stack of 6000W proton exchange membrane fuel cell at operating conditions of 1.5, 1 atmosphere, and 343 K, produced a voltage of 45V after which the cell output voltage decreased gradually with increase in current density. The sudden drop in voltage as the current density increases from zero can be attributed to activation losses known as over-potentials in the cell. The effect of incremental conductance technique on the performance of a PEM fuel cell stack of 6000W characteristics has a significant influence on the performance of the PEMFC. From the simulated results, it can be seen that incremental conductance technique tracks the 6000W signal waveform indicating an effective tracking algorithm, and an output voltage of 48V obtained can be used for application on a battery as a DC load. . It can thus be easily implemented in real-life for fuel cell power generation systems using a microcontroller.

Keywords: Operating Parameters, Proton Exchange Membrane Fuel cell, Incremental Conductance technique, Performance, Effects.

1. Introduction

Proton Exchange Membrane Fuel Cells (PEMFCs) are electrochemical devices that convert chemical energy directly into electrical energy through the electrochemical reaction of hydrogen and oxygen [1]. They are a type of fuel cell known for their high efficiency, low operating temperature, quick start-up, and environmentally friendly nature as they produce only water and heat as byproducts.

While PEMFCs offer many advantages, several challenges remain for their widespread adoption. These include cost, durability of materials (especially the platinum catalysts), and efficiency under varying operating conditions. Optimizing the operating parameters of Proton Exchange Membrane Fuel Cells (PEMFCs) is crucial for achieving maximum efficiency and performance.

Several key parameters play a significant role in the operation of PEMFCs. Temperature greatly influences the kinetics of the electrochemical reactions within the fuel cell. Higher temperatures generally result in faster reaction rates but can also lead to thermal management challenges. Finding the optimal temperature range is critical for balancing performance and durability. Research by [2], [3] highlights that a temperature too high can accelerate electrode degradation, while a temperature too low can limit reaction rates.

Operating pressure affects the rate of reactant transport and the concentration of gases at the electrodes. Higher pressures can improve performance by increasing reactant availability. Studies by [4], [5] emphasize the importance of pressure optimization for achieving higher power output and efficiency.

Proper humidity levels are essential for maintaining proton conductivity within the electrolyte membrane. Insufficient humidity can lead to decreased performance due to poor proton transport. Research by [6], [7] underscores the need to balance humidity levels to prevent membrane dehydration or flooding, both of which can impair performance.

The flow rates of hydrogen and oxygen at the anode and cathode, respectively, influence reactant distribution and removal of reaction products. A study by [8], [9] highlights that optimizing flow rates can enhance reactant utilization and reduce reactant crossover, thereby improving overall efficiency.

Properly optimizing these parameters can lead to substantial efficiency gains. For instance, research by [10], [11] found that collectively optimizing temperature, pressure, and humidity led to a 15% increase in PEMFC efficiency. Efficiency improvements can also translate into cost reductions, particularly in applications where fuel cell operation directly impacts operational expenses, such as in fuel cell vehicles (FCVs) and distributed power generation.

Optimizing operating parameters such as temperature, pressure, humidity, and flow rates is vital for maximizing the efficiency and performance of PEMFCs. Research studies have demonstrated that a holistic approach to parameter optimization can lead to significant gains in efficiency, thereby improving the viability and competitiveness of PEMFC technology.

Understanding and optimizing the operating parameters of PEMFCs, such as temperature, pressure, humidity, and flow rates, is crucial for maximizing their performance and addressing these challenges. This research aims to delve into the effects of these parameters on PEMFC performance and to explore the application of Incremental Conductance techniques to enhance their efficiency further.

Incremental Conductance (IC) techniques are a class of control algorithms used in Proton Exchange Membrane Fuel Cells (PEMFCs) to optimize their operating conditions. These techniques adjust the load current to maintain the fuel cell at its maximum power point (MPP) by continuously comparing the measured voltage and current with their incremental changes.

Research by[12], [13] demonstrated the effectiveness of IC techniques in achieving higher efficiency and quicker response times compared to traditional fixed operating point methods.

Some studies, such as that by [14] have compared IC with fuzzy logic control. IC is favored for its simplicity and efficiency in tracking the MPP.

Incremental Conductance (IC) techniques offer a promising approach to optimize the operating conditions of Proton Exchange Membrane Fuel Cells (PEMFCs). By continuously tracking the Maximum Power Point (MPP) through incremental adjustments to the load current, IC techniques can improve efficiency and response times, particularly in dynamic operating environments. Experimental studies validate their effectiveness in enhancing PEMFC performance.

2. Methodology

2.1 System Description

The system consists of a fuel cell stack, boost DC/DC converter, and control Unit. A load is connected to the PV module through the boost DC/DC converter. The fuel cell stack generates the DC voltage. The voltage supplied by the fuel cell stack does not have constant values, but fluctuates according to operating parameters such as pressure, temperature, and flow rate. The DC/DC boost converter is used to regulate a chosen level of the fuel cell stack output voltage and to keep the system at the maximum power point. It is mainly useful for fuel cell stack maximum power tracking purposes, where the objective is to draw maximum possible power from fuel cell stack at all times, regardless of the load. It also has a capability to regulate the perturbed voltage by increasing or decreasing the voltage reference of the Pulse Width Modulation (PWM) signal. The controller is used to generate high frequency PWM signal in accordance with the output of fuel cell stack and the load to operate the fuel cell stack at maximum power point. The current and voltage from the fuel cell stack, and voltage from the DC/DC converter are sensed by the sensors and are fed to the controller unit to generate pulse width modulation (PWM) for boost converter regulation. The block diagram of the proposed fuel cell system is shown in Figure 1.

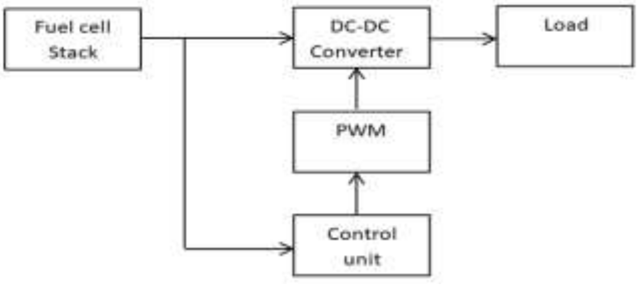

Figure 1: Block diagram of fuel cell System

2.2 Mathematical Model of PEMFC

PEMFC equivalent electrical circuit can be represented by [15] Figure 2

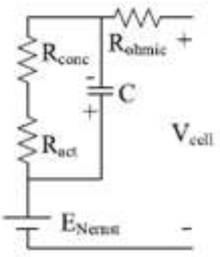

Figure 2: Equivalent circuit diagram addressing different types of voltage drops of a PEMFC

To model the cell performance in terms of voltage-current relation, the overall cell voltage applied from an electric source is broken down to various terms and equal to the sum of individual over potentials [16].

For cells connected in series and forming a stack, the voltage can be calculated by [17]:

$$V_n = n\, V_{FC} \tag{1}$$

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

$$V_n = n(\, E_{Nersnt} - V_{act} - V_{ohmic} - V_{con}) \tag{3}$$

Each individual term is defined by:

$$E_{Nernst} = 1.229 - 0.85x10^{-3}.(T - 298.15) + 4.31x10^{-5}.T.[In(PH_2) + \tfrac{1}{2}In(Po_2)] \tag{4}$$

$$V_{act} = -[\xi 1 + \xi 2xT + \xi 3xTxIn(\mathrm{Co}_2) + \xi 4xTxIn(ifc)] \tag{5}$$

$$V_{ohmic} = ifc(\mathrm{R}_M + R_C) \tag{6}$$

$$V_{con} = -B.\mathrm{In}(1 - \frac{J}{J_{\max}}) \tag{7}$$

$$Co_2 = \frac{Po_2}{5.08x10^6 e^{-(\frac{418}{T})}} \tag{8}$$

where P_{H2} and P_{O2} are the partial pressures (atm) of hydrogen and oxygen, respectively, *T* is the cell absolute temperature(K), *ifc* is the cell operating current(A), and Co_2 is the concentration of oxygen in the catalytic interface of the cathode . The ξ (i=1…4) represent the parametric coefficients for each cell model. R_M is the equivalent membrane resistance to proton conduction.

R_C is the equivalent contact resistance to electron conduction. $J_{\max}$ is the maximum current density. *B* (V) is a constant dependent on the cell type and its operation state. And *J* is the actual cell current density (A/cm2) including the permanent current density J_n.

The equivalent membrane resistance R_M can be calculated by:

$$R_M = \frac{\rho M.\ell}{A} \tag{9}$$

where R_M is the membrane specific resistivity obtained by:

$$\rho M = \frac{181.6x[1 + 0.03x(\frac{ipc}{A}) + 0.062(\frac{T}{303})^2 x(\frac{ipc}{A})^{2.5}]}{[\psi - 0.634 - 3(\frac{ipc}{A})]\,\mathrm{x}\exp[4.18x(\frac{T-313}{T})]} \tag{10}$$

The parametric coefficient $\psi$is considered an adjustable parameter with a possible minimum value of 14 and a maximum value of 23. Most variables are dependent on the cell temperature and pressure operating conditions. Variations in these operating conditions directly affect the FC performance; a higher operating temperature and pressure will increase the FC voltage and efficiency for a certain current.

Equations (1) – (10) represent the FC stack static electrochemical behavior. An electrical circuit can be used to model the FC dynamical behavior as represented in Figure2. The dynamical behavior of a PEMFC stack is modeled as an equivalent electrical circuit as shown in the Figure. The effects of parameter variation on the equivalent resistances can be evaluated, taking into account that the resistance values actually change with the modeling parameters

2.3 Fuel cell parameter specifications

The parameter specifications of fuel cell stack are listed in Table1.

Table1: Electrical characteristics data of Proton Exchange

Membrane Fuel Cell (PEMFC)

Stack power	5998.5W
Fuel cell resistance (ohms)	0.07833
Voltage at 0A, (Voc)	65V
Voltage at 1A	63V
Nominal operating current (I_{nom}(A))	133.3A
Nominal operating voltage (V_{nom}(V))	45V
Maximum operating voltage (V_{max})	37
Maximum operating current (I_{max})	225
Operating temperature	65^{O}C (338K)
Nominal supply Pressure (Pfuel (bar))	1.5
Nominal supply pressure (PAir (bar))	1
Number of cells	65

2.4 Controller Design

In this study, Incremental Conductance is used to control the Fuel Cell output voltage of the system.

2.4.1 Incremental conductance (INC) method

The Incremental Conductance (IC) method operates by utilizing the ratio of delta current to delta voltage, as well as the ratio of current to voltage, in order to determine the MPP [19]. The control strategy employs a decision mechanism to identify the point's position relative to the MPP, along with subsequent step behavior. In the testing phase, it is observed that the standalone IC control proves sufficient to initiate and sustain the desired circuit behavior.

Compared to the P and O method, the INC method offers better tracking efficiency and faster convergence to the MPP. It is less prone to oscillations and has a higher likelihood of reaching the global maximum. However, the INC method requires additional sensors or complex algorithms to measure or estimate the conductance, which may increase system complexity and cost [20].

MPPT techniques are used in various energy systems, including Fuel Cells, to optimize power output and efficiency. The MPPT algorithm ensures that the system operates at its MPP under different operating conditions, such as variations in temperature, load, and Fuel Cell characteristics.

The MATLAB Function block calculates the required values, with the decision table being integrated into the function block. The specifics of this decision table are presented in Table 2.

Table 2: Incremental Conductance Control Decision Table

The equation	Position according to MPP
$\frac{d_i}{d_v} > -\frac{I}{V}$	MPP is on the right
$\frac{d_i}{d_v} < -\frac{I}{V}$	MPP is on the left
$I + V\frac{d_i}{d_v} = 0$	MPP is founded

Based on the acquired results and the decision table, the duty cycle is adjusted to facilitate the search for the MPP of the PV panel and the nominal point of the Fuel Cell.

2.5 DC-DC BOOST CONVERTER

Figure 3 shows the DC-DC boost converter's comparable circuit diagram. This converter is made up of several parts, including a Fuel Cell (FC) as the input supply voltage, a capacitor (C), an inductor (L), a switch (IGBT), a diode (D), and a load resistor (R). On the basis of pulse width modulation (PWM) approach, the boost converter will be operated for the regulation of output voltage. As a result, the PWM modulated signal must alternate between ON and OFF states to modify the output voltage. The following equation might be used to explain the basic relationship in between the input and the output voltage [21]:

$$V_o = \frac{V_{FC}}{1-d} \quad (11)$$

where d indicates the duty cycle, V_o is the output voltage, and V_{FC} is the input voltage

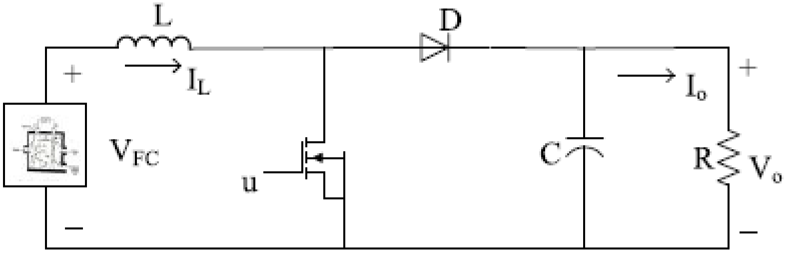

Figure 3: Boost Converter

To regulate the output voltage, controlling of duty cycle is indispensable to control the DC-DC boost converter's switching element via a PWM. A dynamical model is required to manage the duty cycle according to the operational condition of the system of DC-DC boost converter.

2.6 Simulation Model

The fuel cell stack is modeled (figure 4) and simulated using Matlab/simulink software. The simulation is based on the datasheet of PEMFC-6KW-45Vdc stack. The parameters of this fuel cell stack are given in Table 2. The stack is made of 65 fuel cells to give a maximum power output of 6000W.

The simulated voltage-current (V-I) characteristic and power-current (P–I) of the stack is shown in figure 5 and the controlled current, voltage and power output are presented in figure 6.

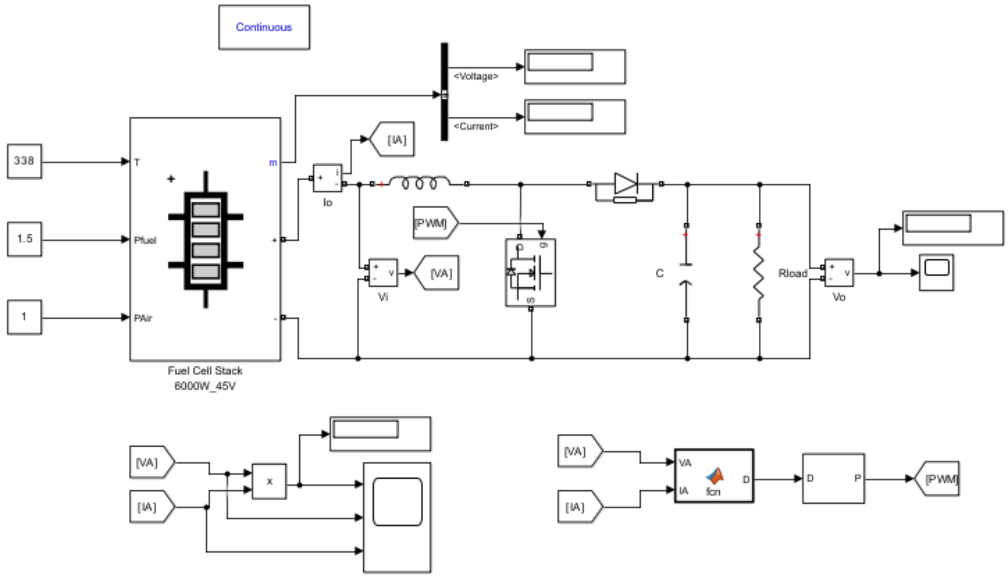

Figure 4: Simulation model of incremental conductance technique

3. Results and Discussion

The simulated results obtained on the influence of various parameters on the voltage output of proton exchange membrane fuel cell are presented in Figures 5 and 6. Figure 5 represents the simulated performance of PEMFC at operating conditions of 1.5, 1 bar and operating temperature of 343 K.

The results presented in Figure 5 indicate that operating fuel cell stack of 6000W proton exchange membrane fuel cell at operating conditions of 1.5, 1 atmosphere, and 343 K, produced a voltage of 45V after which the cell output voltage decreased gradually with increase in current density. The sudden drop in voltage as the current density increases from zero can be attributed to activation losses known as over-potentials in the cell [12]. The literature result is used to validate the results obtained from numerical simulations.

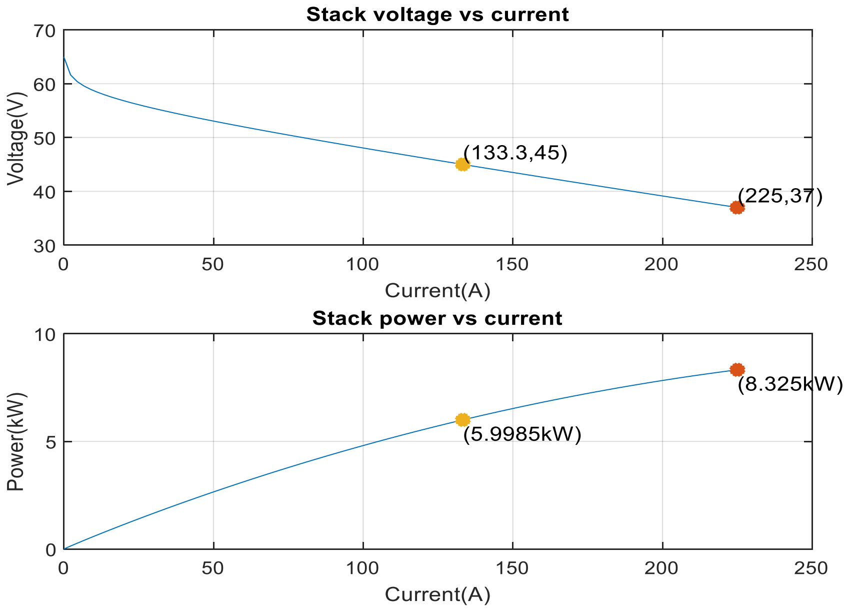

Figure 5: Effects of operating parameters on PEM fuel cell stack of 6000W at operating conditions of 338K, 1.5 and 1bar of temperature, fuel and air pressure respectively.

Figure 6 presents the effect of incremental conductance technique on the performance of a PEM fuel cell stack of 6000W characteristics. The incremental conductance technique has a significant influence on the performance of the PEMFC. From the simulated results, it can be seen that incremental conductance technique tracks the 6000W signal waveform indicating an effective tracking algorithm, and an output voltage of 48V obtained can be used for application on a battery as a DC load.

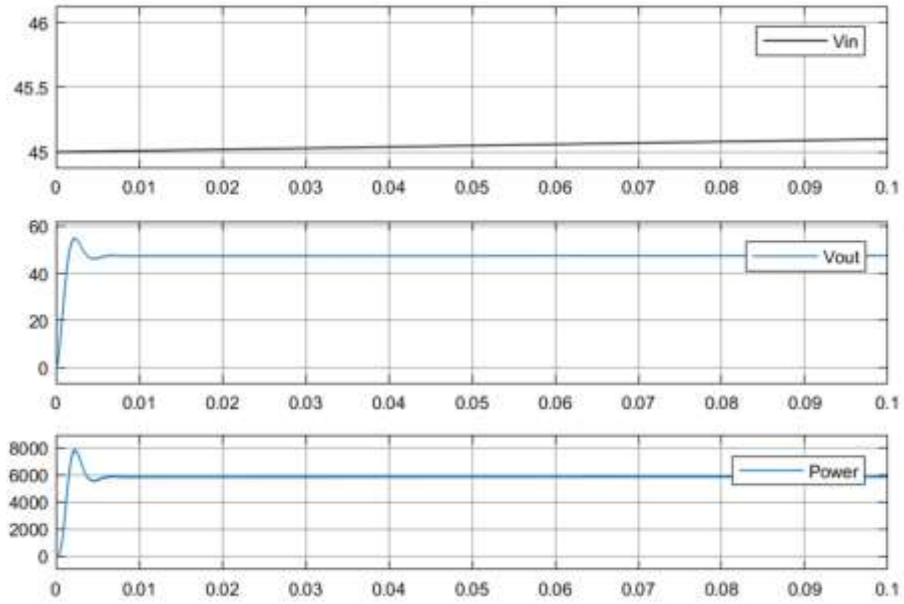

Figure 6: Effect of Incremental Conductance technique on the performance of a fuel cell stack of 6000W

4. Conclusions

In this paper, an incremental conductance algorithm is proposed to track the Maximum Power Point (MPP) for a 6000W PEM fuel cell stack under a varying operating parameter.

The result obtained accurately respond and track MPP. This improves the stability of the system and avoids error when the operating parameter changes. Simulation results validate that the algorithm improves not only the tracking speed but also the tracking accuracy of the system. It can thus be easily implemented in real life for fuel cell power generation systems using a low-cost microcontroller.

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