Stoichiometric Ratio Guided Control Strategies For Efficiency Improvement On Open Cathode PEM Fuel Cell

Katherin Indriawati, Fariz Risqi Maulana, Ruri Agung Wahyuono

Abstract— The increasing demand for hydrogen as a sustainable and environmentally friendly energy source is undeniable. However, the significant cost disparity between power generation and production presents a major challenge. In response to this issue, a control strategy based on reactant stoichiometry is developed to regulate the reactant flow rate effectively. The simulation is carried out using a G-HFCS-1kW36V fuel cell with a nominal capacity of 1 kW. A hydrogen feedback-feedforward control strategy is implemented, with the minimum hydrogen stoichiometry ratio set at 1.3. The simulation results demonstrate that the feedback-feedforward control successfully improves overall efficiency as load currents are gradually increased by 2-3 A, from 5 A to 15 A. The proposed control system achieves a stack efficiency increase of 5.93% and a system efficiency improvement of 5.15%.

Index Terms—Fuel Cell, Stoichiometry, Power, Efficiency

I. INTRODUCTION

The importance of advancing and employing sustainable energy sources stands as a crucial path in the progression of science and technology. Among these, hydrogen emerges as a potential renewable energy source, thanks to its lightweight properties and status as a leading clean energy carrier derived from its lightweight properties, high energy density, and non-harmful production process. [1]. Energy derived from hydrogen can be converted into electricity via fuel cells. These devices generate electrical energy through an electrochemical reaction process. The process within a fuel cell involves integral components: an anode and a cathode. Hydrogen is supplied to the anode, where it is separated into protons and electrons. The protons pass through the electrolyte to the cathode, while the electrons flow through an external circuit, producing an electric current in the process [2].

Research into hydrogen production methods, coupled with fuel cell development, is considered a promising technology for electric vehicles. Fuel cells are projected to serve as sources of zero-emission electricity for future generators. [3]–[7]. However, when considering commercial applications for hydrogen as a clean energy source, two critical factors must be taken into account. Firstly, the cost associated with

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Ruri Agung Wahyuono is a lecturer in Engineering Physics Institut Teknologi Sepuluh Nopember, Indonesia (e-mail: r_agung_w@ep.its.ac.id). hydrogen gas as a reactant tends to be relatively high, posing a significant challenge for widespread implementation. Secondly, ensuring the long-term reliability of fuel cells for sustained operation in commercial applications is essential [8], [9]. Therefore, by implementing effective control strat egies, it is possible to manage and optimize the balance between conserving hydrogen resources and ensuring the long-term reliability of fuel cell operations.

Hydrogen and oxygen are supplied by a control valve and a fan, respectively. During normal operation, hydrogen and oxygen are supplied to the anode and cathode as needed to produce sufficient electrons and protons by utilizing hydrogen oxidation reaction (HOR) and oxygen reduction reaction (ORR). In stationary applications with a constant load, the hydrogen demand can be easily determined using a formula, eliminating the need for advanced hydrogen control. However, this method becomes ineffective under fluctuating loads, as there is a delay between a load increase and the corresponding reactant supply [10]. If there is an increase in the load current demand without a corresponding increase in reactant supply, the system may fail to meet the electron and proton requirements for these chemical reactions, leading to a reactant deficiency scenario [11]. The inadequacy of reactants emerges as a crucial factor contributing to the shortened operational lifespan of a fuel cell. While conservation techniques through control strategies can lead to cost savings, an insufficient supply significantly reduces the reliability and durability of the fuel cell. Therefore, ensuring the optimal balance in reactant flow rates is essential to maintain the reliability of the fuel cell.

Previous researchers have proposed control methods related to fuel rate control to prevent reactant deficiencies. One common strategy to overcome hydrogen deficiencies is to increase the incoming hydrogen stoichiometry ratio [12]. The research proposed by Rosli et al., discusses the use of PID controllers to provide feedback control into the mass flow controller on the hydrogen flow rate so that it can adjust the reactant requirements of the hydrogen flow rate. The research conducted is limited to addressing hydrogen deficiency conditions [13]. Then research conducted by Raceanu et al., proposed PID control to regulate the flow rate of hydrogen and air flow rates and use feedforward control to control fuel stoichiometry ratio by controlling the voltage. The results obtained from this literature explain that by adjusting the reactant stoichiometry ratio values in the literature, it can speed up the response if there is a disturbance in changes in load current, thus reducing the voltage drop if there is a change in load current. There is an optimal value of the reactant stoichiometry ratio value so that reactant deficiency conditions do not occur [14]. Another way of

Katherin Indriawati is a lecturer in Engineering Physics Department Institut Teknologi Sepuluh Nopember, Indonesia (corresponding author, email: katherin@ep.its.ac.id).

Fariz Risqi Maulana is a graduate student in Engineering Physics Institut Teknologi Sepuluh Nopember, Indonesia (e-mail: farizr.official@gmail.com).

hydrogen control is by using advanced control. Research by Li et al., shows the use of MPC controller to adjust the hydrogen flow rates based on the reference voltage require significant computational resources for calculation, making them less suitable for low-power systems [12]. However, These research do not cover the efficiency value due to regulating the amount of reactant and the actuator factors, in this case, the control valves.

Other than from the hydrogen side, savings can also be made by adjusting the supporting components of the fuel cell system. Generally, the supporting component in a fuel cell system that consumes a lot of power is the power used to drive the fan to supply oxygen. In open cathode type fuel cells, the air flow rate is taken from free air sourced from the external environment while the incoming flow rate is controlled by the fan rotation rate. Apart from being a source of oxygen reactant supply, the air flow rate also functions as a membrane temperature controller. Operating temperature in a fuel cell system is a crucial and most important factor in increasing efficiency and reliability in a fuel cell system [15]. Increasing fuel cell temperature can contribute to increasing reaction rates. However, fuel cell membranes have limitation on the maximum temperature that can be accommodated. [16]. Excessive membrane temperatures can cause membrane dehydration, resulting in reduced efficiency of the fuel cell [17]. Therefore, the temperature in the fuel cell needs to be maintained so that it can operate at high temperatures but does not exceed the maximum threshold of the membrane.

The load current directly impacts the temperature regulation of the fuel cell, with higher currents leading to faster temperature increases [18]. Fluctuations in the load current can cause changes in different temperature gradients so that different cooling capabilities are required, which may require different cooling capabilities [19]. Although previous research has highlighted the importance of temperature regulation, such as Ou et al., use of fuzzy control for real-time temperature management and MPC-based control methods explored by Zhang et al., these approaches either focus exclusively on temperature or require significant computational resources, making them less effective for lowpower systems in terms of total energy efficiency [18], [20], [21]. While maintaining a stable temperature is crucial for the overall performance and reliability of the fuel cell, maintaining temperature stability alone does not directly improve system efficiency. Once the temperature is kept within an acceptable range, the primary factor influencing fuel cell efficiency, and directly related to its cost, is the hydrogen flow rate.

This study aims to develop a fuel cell control strategy employing a feedforward-feedback control structure for regulating hydrogen flow rate and air flow rate. The utilization of feedforward-feedback control for hydrogen flow rate is designed to enhance energy efficiency in response to external load current disturbances. Additionally, the integration of feedback-feedforward control for air flow rate is expected to keep the temperature at nominal values and optimize energy efficiency when encountering external load fluctuations. The air flow control, though important for temperature regulation, plays a secondary role in ensuring that the fuel cell operates within the optimal temperature range, which indirectly supports performance stability. Furthermore, this research investigates the effects of control through adjustments in reactant stoichiometry ratios, focusing on the hydrogen stoichiometry adjustment and evaluating its efficiency, an aspect not previously explored in our prior studies [22]. By implementing appropriate control strategies on hydrogen flow rates and air flow rates, this study aim to improve fuel cell energy efficiency and maintain performance despite interruptions in load current by implementing suitable control strategies for hydrogen and air flow rates.

II. SYSTEM DESCRIPTION

A. System Specification

A fuel cell is an electrochemical device that converts chemical energy from fuel directly which in this case is hydrogen into electrical energy. At the anode, hydrogen molecules ionize in the presence of an electrolyte, producing electrons and hydrogen ions (protons) and releasing energy. Meanwhile at the cathode, oxygen reacts with electrons supplied through an external circuit and protons (hydrogen ions), generating water as a byproduct. When electrons from the anode flow through an external load consuming electricity, they power devices with specific current and voltage following the fuel cell's characteristic curve.

TABLE 1 FUEL CELL PARAMETERS USED IN THE SIMULATION

Parameter	Value
Fuel cell type	Open Cathode PEM
Number of cells	60
Rated Power	1 kW
Nominal Operating	50 °C
Temperature	50 C
Nominal Current	52 A
Nominal Voltage	24.23 V

TABLE 2FAN PARAMETERS USED IN THE SIMULATION

Parameter	Value
Fan Motor	DC Brushless
Propeller Type	Axial
Maximum Voltage	12 V
Resistance	2.78 ohm

In this paper, a 1 kW rated power stack PEM Fuel Cell dynamic mathematical model was developed with the specifications as shown in Table 1. The monitored parameters include the voltage, current, and temperature of the fuel cell stack. In the proposed model, cooling of the fuel cell is achieved through forced convection using a fan. Table 2 presents the specifications of the fan utilized for the simulation.

The characteristic curves of the fuel cell, depicting the relationships between current and voltage as well as current and power, were generated through simulations conducted in MATLAB/Simulink and are illustrated in Figure 1. The Curve depicted in Figure 1, providing detailed analysis of the fuel cell's performance from no load condition until nominal

. Validation of simulation model can be conducted by comparing its value into experiment results. The conditions when testing the polarization curve both experiment and simulation was conditioned at the nominal temperature (50°C), partial pressure of hydrogen ($P_{\rm H_2}$) at 0.5 bar and

partial pressure of oxygen (P_{O_2}) at 1 bar in accordance with the nominal operating conditions set by the manufacturer. The validation of the fuel cell simulation model based on the polarization curve is presented in Table 3 and further depicted in Figure 2 for the I-V polarization curve comparison between them.



Fig 1. Polarization curves of PEM Fuel Cell used in the simulation.

TABLE 3 COMPARISON OF SIMULATED FUEL CELL PARAMETERS WITH HARDWARE DATA

Parameter	Hardware	Model
Nominal Power	1000 W	1000 W
Voltage At Nominal Power	40.65 V	40.74 V
Current At Nominal Power	24.6 A	24.55 A
Voltage When the Circuit is Open	57 V	57 V



Fig 2. Results of validation of hardware data and simulation modelling

Validation of the model to the hardware was carried out by matching the fuel cell polarization curve measured from the open circuit voltage and gradually increasing the load until it reached 24.6 A. The results in Figure 2 shows that the validation results of the voltage obtained from hardware and the voltage data obtained based on the model. The result of the MAPE validation calculation shows 0.64% which proves the accuracy of the model in representing the Proton Exchange Membrane Fuel Cell (PEMFC) system in a realistic manner [23].

B. Fuel Cell General System Modelling

Fuel cell stacks generally consist of N identical single cells in series. So the overall stack voltage from the accumulation of each single cell (V_{cell}) can be written in equation:

$$V_{st} = N V_{cell}$$
(1)

where N represents the number of cells in the fuel cell. In the concept of reactant regulation, there is a term stoichiometry ratio refers to theoretical concept of the ratio between the amount of reactants entered and the substances consumed in a chemical reaction [14], [24]. Reactant stoichiometry is one of the crucial factors for regulating flow control within certain value when fuel cell connected with various load. The stoichiometry ratio of fuel cell reactant can be written through equations:

$$\lambda_{\rm H_2} = \frac{Q_{\rm H_2}}{Q_{\rm H_2,reacted}} \tag{2}$$

$$\lambda_{O_2} = \frac{Q_{O_2}}{Q_{H_2}\text{-reacted}}$$
(3)

where λ_{H_2} and λ_{O_2} stand for the value of hydrogen stoichiometry ratio and the value of air stoichiometry ratio, respectively. Q_{H_2} denotes the amount of hydrogen that enters, while $Q_{H_2_reacted}$ denotes the amount of hydrogen that reacts. Similarly, Q_{O_2} denotes the amount of air which oxygen that enters, and $Q_{O_2_reacted}$ represents the amount of air which oxygen that reacts.

The quantity of reactants that undergo reaction can be determined theoretically based on the current and stack temperature, which can be expressed through equations [17], [25]:

$$Q_{H_{2}\text{-reacted}} = 60000 \frac{\text{NRT}_{\text{st}} I_{\text{st}}}{\text{zFP}_{anode} x}$$
(4)

$$Q_{O_2_reacted} = 60000 \frac{NRT_{st}I_{st}}{2zFP_{cathode}y}$$
(5)

where N represents the number of cells in the fuel cell system, R is the ideal gas constant, T_{st} is the stack temperature, I_{st} indicates the stack current, F is the Faraday constant, z is number of moving electrons (z = 2), P_{anode} and $P_{cathode}$ correspond to the partial pressures of the anode and cathode, x refers to the purity of hydrogen gas, and y refers to the purity of oxygen in air.

The reactant stoichiometry ratio, as denoted in equations (4) and (5), plays a significant role in influencing the partial pressures of reactants within the fuel cell membrane. Specifically, the partial pressure of hydrogen at the anode (P_{H_2}) and the partial pressure of oxygen at the cathode (P_{O_2}) can be written as:

$$P_{H_2} = \left(1 - \frac{1}{\lambda_{H_2}}\right) P_{anode} x \tag{6}$$

$$P_{O_2} = \left(1 - \frac{1}{\lambda_{O_2}}\right) P_{\text{cathode }} y \tag{7}$$

The total power available for utilization within the fuel cell system (P_{net}) is determined by subtracting the additional power (P_{aux}) used from the total overall power generated by the fuel cell (P_{gross}) . This calculation can be represented by the following equation [24]:

$$P_{\rm net} = P_{\rm gross} - P_{\rm aux}.$$
 (8)

There are two types of fuel cell efficiency which is stack efficiency and system efficiency. Stack efficiency (ϵ_{stack}) is defined as the ratio of the power produced by the fuel cell (P_{gross}) to the enthalpy of the hydrogen flow rate at the anode. This calculation can be expressed as:

$$\varepsilon_{\text{stack}} = \frac{P_{\text{gross}}}{P_{H_2}} = \frac{V_{\text{st}}I_{\text{st}}}{n_{H_2}\Delta h}$$
(9)

with n_{H_2} denotes the mole of hydrogen, and Δh denotes the value of the higher heating value (HHV) of hydrogen.

Stack efficiency is calculated based on the pure power produced by the fuel cell. However, in the real application, fuel cell power is also used in fuel cell auxilary operations, such as fan rotation which is used to cool the fuel cell system. Efficiency calculations that include reductions in fuel cell operation are referred to as system efficiency. The system efficiency (ϵ_{system}) calculation can be written in the equation [26]:

$$\varepsilon_{\text{system}} = \frac{P_{\text{net}}}{P_{\text{H}_2}} = \frac{V_{\text{st}}I_{\text{st}} - P_{\text{aux}}}{n_{\text{H}_2}\,\Delta h} \tag{10}$$

where P_{aux} denotes the power consumed by the passive components of the fuel cell.

When evaluating the power consumption of auxiliary components, it's crucial to note that the relationship between the fan's power output and the average voltage level follows nonlinear functions, especially when accounting for the impacts of inductance and capacitance in single-phase brushless DC motors. By disregarding the inductive and capacitive effects in the brushless DC motor fan and focusing solely on its resistive aspects, The fan's output power can be calculated to compute stack efficiency in equation (10) can be written as follows:

$$P_{aux} = \frac{(d)^2 V_{fan_supplied}^2}{R}$$
(11)

where *d* denotes duty cycle expressed as a fraction from 0 to 1, $V_{fan_supplied}$ represented the fan supplied voltage and R is the fan internal resistance

C. Electrochemistry Modelling

Electrical modeling of fuel cells is based on the equation of the fuel cell polarization curve. The polarization curve is a measuring curve output fuel cells where voltage measurements are compared to load current and recorded in steady state conditions. The characteristic output of a fuel cell is nonlinear and is influenced by temperature, partial pressure of oxygen and partial pressure of hydrogen [27]. The voltage output depends on the load current applied to the fuel cell and can be seen from characteristic curve from the fuel cell manufacturer. The polarization of the curve provides information about the loss of fuel cell performance under operating conditions [28].

According to the established empirical formula of fuel cell output characteristics, the cell voltage output of fuel cell can be written as:

$$V_{\text{cell}} = V_{\text{Nernst}} - V_{\text{act}} - V_{\text{ohm}} - V_{\text{conc}}$$
(12)

where V_{Nernst} represents the thermodynamic electromotive force, which is calculated based on the redox reaction. V_{act} refers to the voltage loss caused by the energy barrier that occurs during the initiation of the electrochemical reactions at the electrodes. V_{ohm} denotes the voltage drop from the resistance of proton flow in the electrolyte, and V_{conc} is the voltage loss from the reduction of gas concentration [25]. Values of V_{Nernst} can be obtained from the gibbs free energy coefficient and specific entropy which can be expressed as:

$$V_{\text{Nernst}} = \frac{-\Delta G_0}{nF} + \frac{\Delta S}{nF} (T_{\text{st}} - T_{\text{amb}}) + \frac{RT_{\text{st}}}{nF} \ln P_{\text{H}_2} P_{\text{O}_2}^{0.5}$$
(13)

where ΔG_0 indicates the gibbs free energy under ideal conditions, ΔS indicates the specific entropy, T_{st} denotes the stack temperature, T_{amb} denotes the ambient temperature [29].



Fig 3. Electrochemistry modelling block diagram used in simulation

The usable energy derived from fuel cells comes from electrochemical reactions, which are associated with the gibbs free energy change of the reaction. V_{Nernst} can be explained mathematically as the energy results from the combination of the free energy gibbs (ΔG) and the specific entropy, ΔS in ($kJ \mod^{-1}$). Gibbs free energy is influenced by changes in the partial pressure of reactants in a certain volume in the fuel cell. Mathematically, this theory can be expressed as:

$$\Delta G = \Delta G_0 - RT_{st} (\ln P_{H_2} + \frac{1}{2} \ln P_{O_2})$$
(14)

where the value of ΔG_0 equals to $-237,17 \frac{K_j}{mol^{-1}}$ under standard conditions (STP), R is the ideal gas constant (8.31 J (mol K)⁻¹).

Activation voltage (V_{act}) is the minimum voltage required to start the electrochemical reactions that occur at the anode and cathode. The activation voltage in the fuel cell system is related to the activation energy required to react chemical substances in the fuel cell [29]. The magnitude of V_{act} in equation (12) can be obtained using the equation:

$$V_{act} = A \ln \left(\frac{I_{st}}{i_o} \right)$$
(15)

where the value of A denotes the slope of the tafel equation, and I_0 represents the exchange current density.

The value of the slope level itself as written in equation (15) can be approximated by the equation:

$$A = \frac{RT_{st}}{z\alpha F}$$
(16)

where R is the ideal gas constant, T_{st} represents the stack temperature, z is the number of moving electrons, and α represents the charge transfer coefficient.

Exchange current density (i_0) is a value that describes the rate of electrochemical reactions under equilibrium conditions or ideal conditions when there is no load current. Under these conditions, the forward and reverse reaction rates have the same value. When an external load is linked to the fuel cell, the forward reaction rate escalates, leading to a potential drop that is proportionally related to the logarithmic function of the stack current density divided by the exchange current density value. Exchange current density (i_0) in equation (15) can be approached using the equation:

$$i_{o} = \frac{zFk(P_{H_{2}} + P_{O_{2}})}{Rh}e^{\frac{-\Delta G}{RT}}$$
 (17)

where k denotes the Boltzman constant ($1.38 \times 10^{-23} \text{ J/K}$), while h indicates the Planck constant ($6.626 \times 10^{-34} \text{ J/s}$)

Ohmic voltage (V_{ohm}) in fuel cells is a voltage drop caused by the resistance of materials in the cell such as electrodes, electrolyte, and the interconnections between the electrode layers and the electrolyte. The ohmic voltage of a fuel cell can be affected by a number of factors, including the type of fuel cell, operating temperature and pressure, and the state of the materials within the cell. The value of V_{ohm} which stated on equation (12) can be approximated using the ohm's law equation in equation (18) [25]:

$$V_{ohm} = R_{ohm} I_{st}$$
(18)

where R_{ohm} indicates the internal resistance of the fuel cell stack, accounting for both membrane and contact resistances.

The value of V_{conc} which stated on equation (12) represents the voltage loss caused by a reduction in gas concentration. This condition generally occurs at high load currents when the requested load current approaches the current density limit value. The equation that can be used to calculate losses due to reduced gas concentration can be approached using the equation: [17], [30]:

$$V_{\text{conc}} = \frac{RT_{\text{st}}}{2F} \left(1 - \frac{I_{\text{st}}}{I_{\text{max}}}\right)$$
(19)

where I_{max} represents the maximum load current that can be accommodated by the fuel cell.

The Electrochemistry block diagram model which composed by electrochemistry modelling can be shown at Figure 3. The parameters considered for modeling the reaction and electrical processes within the system include Q_{H_2} , Q_{O_2} , T_{st} and I_{st} . These input variables form the basis for determining the values of hydrogen stoichiometry ratio λ_{H_2} and air stoichiometry ratio λ_{O_2} . Subsequently, these parameters are utilized in the computation of hydrogen partial pressure P_{H_2} and oxygen partial pressure P_{O_2} , which can be calculated using the nernst voltage, exchange current density, and Tafel slope. The nernst voltage value is important for calculating the theoretical voltage output prior to accounting for power losses. Losses in voltage within fuel cells are categorized into activation losses, ohmic losses, and concentration losses. Activation losses on fuel cell voltage are determined using the values of exchange current density and Tafel slope. Ohmic losses are influenced by stack current, while concentration losses are contingent upon both stack current and stack temperature.

D. Thermal Modelling



Fig 4. Thermal modelling block diagram used in simulation

According to the law of conservation of energy, the dynamic thermal behavior of the open-cathode fuel cell system can be represented by the following equation.[17]:

$$\frac{dT_{st}}{dt} = \frac{1}{m C_{fc}} \left[P_{gen} - P_{nat} - P_{fan} - P_{l/g} \right]$$
(20)

where P_{gen} denotes heat generated by fuel cell, C_{fc} indicates fuel cell specific heat, P_{nat} refers to natural convection by environment and P_{fan} corresponds to forced convection by using fan, and lastly $P_{1/g}$ represents heat dissipasion and heat dissipasion due to phase changes

Sources of heat generation in fuel cells can be caused by changes in entropy reactions, electrochemical reactions, as well as heat generated from ohmic resistance and air vapor condensation. In general, the heat produced during a reaction (P_{gen}) can be written by equation:

$$P_{gen} = (NV_{Nernst} - V_{st})I_{st}$$
(21)

where N denotes the number of stacks of fuel cells used. V_{Nernst} represents the value of the nernst voltage , V_{st} is the output voltage stack , and I_{st} is the load current applied to the stack. Heat transfer in a fuel cell system can be modeled by the cooling influence from three different sources: Natural heat transfer, forced heat transfer, and heat dissipasion due to phase changes [17].

Natural heat transfer (P_{nat}) is heat that transfered from the surface of the fuel cell to the external environment. The natural cooling equation P_{nat} can be written in equation:

$$P_{nat} = h S_{eq}(T_{st} - T_{amb})$$
(22)

where h denotes the natural convection coefficient, S_{eq} represents the air exchange coefficient. To enhance acceleration, forced convection is facilitated by the fan, denoted as P_{fan} .

Forced cooling power from fan (P_{fan}) can be formulated in equation:

$$P_{fan} = \frac{1}{60} \rho_{air} Q_{0_2} C_{p_air} (T_{st} - T_{amb})$$
(23)

where ρ_{air} denotes the density of the air, and C_{p_air} indicates the specific heat of the air.

Apart from the convection process, heat transfer can also occur due to phase changes in the fuel cell. $P_{1/g}$ shows the heat removal process during the liquid/gas phase from the air produced in the fuel cell. The heat dissipation process in a fuel cell system can be written in equation [17]:

$$P_{l/g} = \rho_{H_20} \frac{NR}{4P_{cathode}F} T_{st} L_{H_20} I_{st} k_w$$
(24)

where ρ_{H_2O} denotes the density of air, L_{H_2O} denotes the latent heat of air evaporation, and k_w is empirical coefficient that represents the evaporation of air on the membrane ρ_{H_2O} .

The thermal modelling block diagram can be shown at Figure 4. If the thermal model equation is modeled using an approach to the 1st order transfer function model, then the thermal transfer function can be written in the equation:

$$\frac{T_{st}(s)}{Q_{0_2}(s)} = \frac{a_1}{s+b_1}$$
(25)

The value of the transfer function parameter a_1 and b_1 can be written in equations 26 and 27. The transfer function is clearly shown that there is non-linearity on the transfer function in terms of current and stack temperature, which can be represented as follows:

$$a_{1} = \left[\left(\frac{1}{m C_{fc}} \right) \left((N V_{Nernst}(I_{st}, T_{st})) - V_{st}(I_{st}, T_{st})) I_{st} - h S_{eq} T_{amb} - \frac{1}{60} \rho_{air} Q_{O_{2}} C_{p_{-air} T_{amb}} - \frac{\rho_{H_{20}} NR}{4 P_{cathode} F} L_{H_{20}} I_{st} k_{w} \right) \right]$$

$$b_{1} = \left(\frac{1}{m C_{fc}} \right) \left(h S_{eq} + \frac{1}{60} \rho_{air} C_{p_{air}} \right)$$
(27)

III. PROPOSED CONTROL STRATEGIES



Fig 5. Block diagram of the hydrogen flow rate and air flow rate control system in an open cathode fuel cell.

After the modeling can be verified, a control system design is carried out for each fuel cell actuator. The block diagram of the control system design that will be designed can be shown in Figure 5. Control design was carried out on the valve and fan controls on the fuel cell. Algorithm for control strategies used is shown in Figure 6. Both hydrogen and air flow rate control will be adjusted regarding on the value of load current which will be explained further in the subsection.

The reactant consumed depends on the load current that electrically connected with the fuel cell. There were two types of load current. The former represents the external load, which is the load from external electrical components connected to the fuel cell. The latter represents the internal load, which comes from the fuel cell's internal components. Adding both together will give the accumulation of the load current.

The test will be carried out by varying the load current from the external load as shown on Figure 7. The initial external load current used for the simulation is equal to 5 A. The external load current will be increased by 2 A at 400 s and 800 s, then followed by 3 A addition at 1200 s and 1600 s. The load current increase should not be too high to prevent hydrogen starvation caused by a sudden surge in load current. [31]. The external load current change along with internal load current change from the fan actuator will act as disturbance of the control system.



Fig 6. Flowchart of control algorithm used for proposed reactant control strategies



Fig 7. External load current used for the simulation

A. Hydrogen Flow Rate Control

Feedback-feedforward control will be used to adjust hydrogen flow rate. The results of theoretical hydrogen flow rate calculations in control can be a reference adjustment for feedback control ($Q_{H_2,sp}$). Hydrogen stoichiometry ratio is crucial to adjust diffusion limited from the fuel cell membrane. The equation for determining the set point to determine the hydrogen flow rate using the formula in the equation is written in equation:

$$Q_{H_2_sp} = 60000 \frac{NRT_{st}I_{st}}{zF P_{anode} x} \lambda_{H_2}$$
(28)

The selection of the hydrogen stoichiometry ratio value is carried out by considering the smallest value approach so that the voltage value in the fuel cell is maintained. The output voltage will be compared with the polarization curve where under these conditions the hydrogen flow rate is at maximum. Apart from that, determining the hydrogen stoichiometry ratio value also needs to meet reactant requirements if there is a change in reactant requirements due to random changes in load current. Increasing the load current will increase the need for reactants and if the hydrogen flow rate is insufficient it can cause hydrogen deficiency.



Fig 8. Control valve opening percentange relation corresponding into the CV value

The adjustment flow rate value will be compared with the actual flow rate read on the flow meter sensor (Q_{H_2}) . Calculation of the error value $e_{H_2}(t)$ in feedback control of the hydrogen flow rate can be written in equation:

$$e_{H_2}(t) = Q_{H_2}(t) - Q_{H_2 sp}(t)$$
⁽²⁹⁾

The error value will serve as the input for the PI control, where the error signal will be used to update the valve control opening value. The PI feedback control equation for opening the control valve used can be written in equation:

$$Cv_{opening_cmd} = K_p e_{H_2}(t) + \int_0^t e_{H_2}(t) K_i dt$$
 (30)

The relationship between CV value and valve opening used in simulation can be modelled as a third-order function (Quick Opening) model referring into the body valve manufacturer data as follows:

$$K_{cv} = 0.6442X^3 - 1.3729X^2 + 1.2606X$$
(31)

where the value X denotes the valve opening in the fuel cell system, used to regulate the hydrogen flow rate and K_{cv} is the valve flow coefficient, representing the capacity of the control valve and indicating the flow rate through the valve at a specified pressure drop

The valve control modeling used can be approached with 1_{st} order system which can be written in the equation:

$$G_{cv} = \frac{K_{cv}}{\tau_{cv}s + 1} \tag{32}$$

where the gain value of the control valve is obtained by the ratio between the Cv value and the control valve opening command signal. τ_{cv} is the time constant of the control valve based on the datasheet of the servo motor actuator connected to the body valve which equal to 0.69s.

In theory, the valve quick opening approach can be approximated by a square root relationship between the CV value and the opening value X. The slope of quick opening plug valve is steeper which produces a higher initial gain than the linear plug Figure 8 depicts of the relation between the valve opening and CV value used in the simulation. Linear flow control characteristic valve was added for comparison purposes.

 TABLE 4

 CRITERIA FOR HYDROGEN STOICHIOMETRY RATIO SELECTION

Order	Parameters to be Considered	Hydrogen Stoichiometry Ratio Selection Criteria
1	Control Valve Opening Operation Zone	Select hydrogen stoichiometry ratio values which aligns with the operating range of the control valve
2	Voltage Drop 4% maximum threshold [35]	Select hydrogen stoichiometry ratio values that result in a voltage drop below 4% in the event of a change of load current.
3	Stack Efficiency and System Efficiency	Select hydrogen stoichiometry ratio that yields the highest efficiency.

To increase efficiency, it is necessary to adjust the adjusting the control system parameters. In previous research, hydrogen stoichiometry ratio was based on greater savings because it would be wasted during purge, as discussed by researchers Liang et al who tried up to 1.89 [32]. However, subsequent researchers generally only tried hydrogen stoichiometry ratio values up to 1.5, as was done by Raceanu et al. who tried stoichiometry ratio values of 1.25 and 1.5 [14]. Further research was carried out by Liu et al. where experiments were carried out with hydrogen stoichiometry ratio values of 1 to 1.5 [33]. The choice of upper limit for the hydrogen flow rate in each fuel cell has different characteristics, depending on the characteristics of the fuel cell used, in this case the gas channel of the reactant channel and considering about diffusion limited from the fuel cell membrane [34]. This limit plays a critical role in defining hydrogen stoichiometry ratio. Consequently, its selection will be guided by a specific selection criterion. To facilitate this evaluation, hydrogen stoichiometry ratios of 1.20, 1.30, 1.40, 1.50, and 1.60 will be analyzed.

Table 4 shows the criteria for selecting hydrogen stoichiometry ratio adjustment values. Based on the order of priority in selecting hydrogen stoichiometry values, the main priority in the criteria for selecting hydrogen stoichiometry values is to ensure that the adjustment for hydrogen stoichiometry ratio aligns with the operating range of the control valve. This step is critical to guarantee that the control valve maintains its capacity to regulate the incoming flow of hydrogen. Ensuring the hydrogen stoichiometry ratio adjustment remains within the control valve's operating range is crucial for maintaining control and stability over the hydrogen input, thus optimizing the fuel cell operation.

Once the hydrogen stoichiometry ratio set-point value is confirmed to be within operational range of control valves. The selection criteria proceed to ensure that the value of the voltage drop ($V_{st_{drop}}$) when selecting the hydrogen stoichiometry ratio value has a maximum value of 5% according into IEC 60364-5-52 standards which stated the maximum of voltage drops for electronics [36]. For calculating sudden voltage drop ($V_{st_{drop}}$), this following equation can be used as follows:

$$V_{st_{drop}} = \frac{V_{st_{drop_{t-1}}} - V_{st_{drop_t}}}{V_{st_{drop_t}}} (\%)$$
(33)

which $V_{st_{drop_{t-1}}}$ denotes voltage when sudden load changes occur and $V_{st_{drop_t}}$ denotes voltage before the load changes. For this research, 4% voltage drop is used for safety boundary purposes. This particular limit is set with the primary objective of preserving the durability and reliability of the fuel cell, especially in the context of hydrogen deficiency issues.

Subsequently, the criteria for selecting the hydrogen stoichiometry ratio adjustment continue by focusing on choosing the value that maximizes both stack efficiency and system efficiency. This phase aims to pinpoint the hydrogen stoichiometry ratio value that leads to the highest levels of efficiency for the fuel cell stack and the entire system. Prioritizing stack and system efficiency helps enhance overall performance while ensuring that the fuel cell operates at its optimal capacity.

B. Air Flow Rate Control

Feedforward control combined with P Controller will be used to regulate the duty cycle of the fan. The feedforward control equation for the fan flow rate is shown in equation (26). The temperature adjustment along with air Stoichiometry value will be varied to regulate the ratio between the amount of oxygen entering compared to the amount of oxygen used to react. To control the air flow rate which also controlled the oxygen flow rate, the average voltage (V_{fan}) of the fan is manipulated by adjusting the duty cycle value. The relationship between the average voltage and the duty cycle can be written in equation [37]:

$$V_{fan} = dV_{fan_supplied}$$
(34)

where the voltage applied to the fan ($V_{fan_supplied}$) during the experiment) equals to 12 Volts, and d denotes the duty cycle.

For fulfilling oxygen needed for reaction, air from external source will be used so that the oxygen flow rate is related to the air flow rate with an oxygen composition of 21%. The controlled variable is the oxygen flow rate, while the manipulated variable is the average voltage of the fan's brushless DC motor Feedforward control will be used to maintain the oxygen flow requirements met during the reaction process. The feedforward control equation for the fan flow rate can be shown as:

$$Q_{O_{2ff}} = 60000 \frac{NRT_{st}I_{st}}{2zFP_{cathode}y} \lambda_{O_2}$$
(35)

For comparison purposes, the temperature of fuel cell was set at 50°C after it reaches steady state value and air stoichiometry ratio was set on 10 λ_{O_2} when initial load and 40 λ_{O_2} when operational load. Further research is required to optimize the air stoichiometry ratio for both the initial and operational load conditions. To better understand the impact of these adjustments on performance, The relationship between the oxygen flow rate and the average fuel cell voltage is approached using a 3rd order equation based on the experimental results approach, which can be shown as:

$$V_{fan_cmd_{ff}} = -0.0087 Q_{0_{2ff}}^{3} + 0.1727 Q_{0_{2ff}}^{2} + 0.0331 Q_{0_{2ff}} + 1.64705$$
(36)

To maintain the operating temperature of the fuel cell membrane, a proportional feedback control system is implemented. This control mechanism ensures stable operation by continuously adjusting to deviations from the desired temperature set point. The error, which represents the difference between the actual and desired temperature, is calculated using the following equation:

$$e_{T_{\rm st}}(t) = T_{\rm st} - T_{\rm st_sp}$$
(37)

Proportional feedback control equation is shown in equation:

$$V_{fan_cmd_{fb}} = K_{p}e_{T_{st}}(t)$$
(38)

The addition of air produced by feedback control will increase the average fan voltage (V_{fan}). As a result, this adjustment affects the total voltage, which can be expressed using the following equations:

$$V_{fan_cmd} = V_{fan_cmd}_{ff} + V_{fan_cmd}_{fb}$$
(39)

$$V_{fan_cmd} = - -0.0087 Q_{0_{2}ff}^{3} + 0.1727 Q_{0_{2}ff}^{2} + 0.0331 Q_{0_{2}ff} + 1.64705 + K_{p} e_{T_{st}}(t)$$
(40)

IV. CONTROL RESULTS BY VARYING HYDROGEN STOICHOMETRY

Figure 9 shows the combined load current from the external load (as shown in Figure 7) and the auxiliary load with variations in the hydrogen stoichiometry ratio. These variations in accumulated load current for each hydrogen stoichiometry ratio slightly differ to compensate for cooling, which in turn enhances the net power produced by the reaction, particularly affecting lower stoichiometric ratios more than higher hydrogen stoichiometry ratio. Furthermore, as the applied load current increases, the differences in the

combined load current for each hydrogen stoichiometry ratio become more significant.

To better understand these effects and identify the most advantageous operational parameters, it is crucial to examine how variations in hydrogen stoichiometry influence system performance. The hydrogen flow rate must be regulated using control valves to minimize waste while adequately fulfilling the membrane's requirements. Voltage drop influences the system's capacity to maintain stable operation when sudden load current occur, Gross and Net power output serves as a critical parameter of total energy that can be used, and lastly, the stack and system efficiency for indicating overall performance of the fuel cell and control systems.



Fig 9. Value of combined load current used in the simulation

A. Control Valve Response And Hydrogen Input Flow Rate Analysis

Control valve response analysis is employed to ensure that the control valve can accommodate the desired hydrogen flow rate set-point. This analysis is necessary to identify the actuator factors that limit the hydrogen flow at the fuel cell dead-end anode (DEA). The hydrogen flow rate at the fuel cell dead-end anode (DEA) is limited by:

- 1) The amount of hydrogen that reacts depends on the hydrogen demand by the membrane
- 2) The amount of hydrogen that can be accommodated in the membrane, due to the membrane output being closed by the purge valve
- 3) Opening of the control valve controlled by the system



Fig 10. Illustration of the hydrogen flow rate system in a fuel cell



Fig 11 Control valve opening response to step changes of load current for each hydrogen stoichiometry ratio variation

The hydrogen flow rate system is illustrated in Figure 10. The first and second limiting parameters are primarily influenced by the fuel cell manufacturer, while the third parameter can be regulated by the fuel cell controller. By adjusting the hydrogen stoichiometry ratio, the control response of the system can be affected, as shown in Figure 11. When the adjustment value exceeds the membrane's manageable flow rate capacity, the control valve tends to fully open, rendering it ineffective under these conditions. This phenomenon, known as the wind-up effect, is clearly observed when the hydrogen stoichiometry ratio is set at 1.60.

Wind-up occurs in PI (Proportional-Integral) controllers when there is a large and persistent error between the set point (desired value) and the process variable (actual value). The integral component of the PI controller is responsible for eliminating steady-state error. However, when the error persists over time, such as when the valve has reached its fullopen position but the process variable has not yet met the set point, the integral component continuously accumulates the error. If the error is large and sustained, this accumulation results in a very large integral value, causing the controller output to become excessively large (overshoot), even as the error begins to decrease. As a result, the actuator will continue to push the valve to open further, even though it has already reached the full-open position. This prevents the valve from controlling the flow, and the process variable becomes difficult to control.



Fig 12. Hydrogen flow rate against adjustment value when hydrogen stoichiometry ratios equal (a) 1.60 and (b) 1.50

The wind-up phenomenon can cause a control valve to become stuck in the full-open position and lose control of the flow. Therefore, it is important to understand this phenomenon and implement appropriate anti-windup strategies in the control system. However, in this paper, controllers with anti-windup features are beyond the scope of discussion. Therefore, what is proposed in this paper to avoid the wind-up phenomenon is to select the appropriate hydrogen stoichiometry value so as to produce a reliable flow rate set point.



Fig 13. Hydrogen flow rates at varying load currents and hydrogen stoichiometry ratios. (a) Overview of hydrogen flow rate trends across all load currents. (b) Zoomed-in view of hydrogen flow rate changes as load current increases from 5–7 A. (c) Zoomed-in view of hydrogen flow rate changes as load current increases from 12–15 A.

The comparison between the actual flow rate and the adjustment (set-point) values when used the hydrogen stoichiometry ratio of 1.6 can be observed in Figure 12a. Within the initial 55 seconds, the control valve opening indicates a controllable condition, characterized by hydrogen flow rate inhibition by control valve. On the contrary, the control valve has remained no control for the rest of the time, indicating wind-up condition. From the results shown on Fig 12b, it becomes apparent that by using hydrogen stoichiometry ratio 1.5 resulted in system controllability. It is obvious for the control valve will remain control for the stoichiometry below 1.5 as long as the control valve design selection such as CV values is already properly set within the process. The results in Fig 12b indicates that there are no significant error steady state between set-point and actual response.

In DEA fuel cells, the anode is sealed, allowing hydrogen to enter the anode compartment but preventing continuous outflow. Excess hydrogen accumulates in the anode, along with liquid water and nitrogen. Over time, an equilibrium is established where the rate of hydrogen supply balances with its consumption and diffusion losses through the membrane. Once this equilibrium is reached, the pressure stabilizes, and no additional hydrogen can enter the anode compartment unless it is consumed or released through purging. In this paper, it is called limited diffusion. As a result, the hydrogen flow cannot exceed a certain threshold [38].

The flow rate of unreacted hydrogen in DEA fuel cells will be released along with nitrogen gas and water after a specific period [39]. The maximum hydrogen flow rate of fuel cell to accommodate hydrogen varies for each type of fuel cell [40], [41], commonly depends on the fuel cell membrane material and its condition. Because this data is not available in the datasheet provided by the manufacturer, the data for maximum hydrogen flow rate was obtained based on experimental results which showed in Fig 13 as open loop data.

TABLE 5 PERCENTAGE OF HYDROGEN SAVINGS COMPARED WITH OPEN LOOP CONDITIONS

λ_{H_2}	Hydrogen Savings by Percentage (%)				
	5 A	7 A	9 A	12 A	15 A
1.05	31.55	30.84	30.4	29.8	29.3
1.1	28.43	27.77	27.25	26.66	26.17
1.2	22.19	21.43	20.85	20.26	19.8
1.3	15.95	15.02	14.4	13.82	13.39
1.4	9.63	8.61	7.95	7.34	6.93
1.5	3.3	2.2	1.49	0.86	0.46
1.6	0.09	0.13	0.11	0.12	0.13

Table 5 shows hydrogen gas savings in comparison to open-loop conditions with different current load conditions. It is become clear that when using hydrogen stoichiometry ratio of 1.6, it shows only marginal difference between no control condition, proving its ineffectiveness of control. On the other hand, the other hydrogen stoichiometry ratio proves that there are some savings compared with open loop conditions. The best percentage of hydrogen savings is obtained when using lower hydrogen stoichiometry ratio. By using smaller hydrogen stoichiometry ratio value, the wasted hydrogen on the purging process can be optimized besides optimizing the purging time which both can be conducted to maximizing fuel cell efficiency [42]. The controller will set closer to the amount actually consumed in the electrochemical reaction, leaving less excess hydrogen that would otherwise need to be purged. However, it should be noted that when using lower stoichiometry ratio, it can lead into hydrogen deficiency, resulting in voltage drop which will be explained in more detailed in subsection B.

B. Voltage Drop Analysis

A voltage drop in fuel cells is the difference between the theoretical voltage and the actual voltage output under load. As discussed before, there are various types of losses (activation, ohmic, and concentration) that contribute to voltage drop and how they impact fuel cell efficiency. When calculating the voltage drop percentage, the initial voltage should be the open-circuit voltage (OCV), representing the maximum potential of the fuel cell under no-load conditions.

Figure 14a shows the voltage drop that occurs when varying the value of the load current changes as shown at the graph between load current and time. Based on Figure 14, an increase in load current can lead to a voltage drop, which varies depending on the adjustment value of the hydrogen stoichiometry ratio used. This voltage drop can be explained by reviewing the equations used in hydrogen stoichiometry ratio calculations. Hydrogen stoichiometry ratio, defined as the ratio of moles of incoming hydrogen to moles of hydrogen that react, plays a crucial role in fuel cell operation. Changes in load current affect the amount of hydrogen that reacts, contributing to electrochemical losses such as activation losses, ohmic losses, and concentration losses. [43].

When a fuel cell operates at higher loads or produces more power, it requires a higher amount of hydrogen to maintain the electrochemical reactions within the cell. This increased demand for hydrogen is due to the higher load current requiring more electrons, which accelerates the reaction rate. Faster reactions necessitate faster flow rates, and if the fuel supply cannot meet this demand, a hydrogen deficiency process can occur, impacting cell performance.

Hydrogen needs to diffuse through the membrane to reach the electrode where the chemical reaction occurs, as shown at illustration on Figure 10. During normal operation, when a sufficient supply of hydrogen is provided, hydrogen diffusion through the membrane will be uniform throughout the fuel cell stack. However, in the case of deficiency, hydrogen diffusion becomes uneven causing a reduction in the amount of incoming hydrogen concentration. This uneven distribution of hydrogen diffusion causes hydrogen deficiency in several parts of the stack [32]. This causes a local hydrogen deficiency which contributed into sudden decline of hydrogen flow partial pressure, resulted in additional activation voltage losses [44].

When the hydrogen stoichiometry ratio set-point is adjusted, the resulting level of local hydrogen deficiency varies. Activation losses can be minimized by maximizing the exchange current density, with higher current loads producing higher exchange current density. However, load current changes can increase activation losses, a phenomenon explained by analyzing the dynamics of the exchange current density, which represents the reaction rate within the fuel cell. A lower reaction rate contributes to a slower response, highlighting the drawbacks of hydrogen control compared to an open control condition (fully opened control valves), as shown with a hydrogen stoichiometry ratio of 1.6. Additional increases in load current at 1200 s and 1600 s result in sudden drops in exchange current density, as reflected in the exchange current density equation.



Fig 14 Voltage drop characteristics under varying hydrogen stoichiometry ratios. (a) Overall voltage drop trends across different hydrogen stoichiometry ratios. (b) Voltage drop during the load current step from 5 A to 7 A. (c) Voltage drop during the load current step from 7 A to 9 A. (d) Voltage drop during the load current step from 9 A to 12 A. (e) Voltage drop during the load current step from 12 A to 15 A.

Figure 14b and 14c illustrate the voltage drop when increasing the current load from 5 A to 7 A and from 7 A to 9 A, while Figure 14d and 14e shows the increment of current

load from 9 A to 12 A and 12 A to 15 A. The magnitude of the voltage drop that occurs can also be explained by the concentration of hydrogen entering the fuel cell. A higher stoichiometry adjustment implies a greater amount of hydrogen available for the electrochemical reactions that generate electrical current. This increased availability of hydrogen allows the fuel cell to sustain hydrogen flow partial pressure which allow more load currents addition without experiencing significant voltage drops or performance degradation [11].

TABLE 6PERCENTAGE OF VOLTAGE DROP THAT OCCURS ON LOWERCURRENT BY ADJUSTING HYDROGEN STOICHIOMETRY RATIO

	5 - 7 A		7 - 9 A	
λ_{H_2}	Voltage Drop (V)	Voltage Drop (%)	Voltage Drop (V)	Voltage Drop (%)
1.05	2,33	5,31	1,93	4,53
1.10	2,35	5,26	2,02	4,64
1.20	1,92	4,20	1,51	3,41
1.30	1,78	3,84	1,4	3,11
1.40	1,7	3,63	1,34	2,95
1.50	1,66	3,52	1,3	2,84
1.60	1,41	2,98	1,07	2,33

TABLE 7 PERCENTAGE OF VOLTAGE DROP THAT OCCURS ON LOWER CURRENT BY ADJUSTING LOAD CURRENT ADDITION AND HYDROGEN STOICHIOMETRY RATIO

	7 +	2 A	7 + 2	2.5 A	7 + 2	2.8 A
λ_{H_2}	Voltage Drop	Voltage Drop	Voltage Drop	Voltage Drop	Voltage Drop	Voltage Drop
	(V)	(%)	(V)	(%)	(V)	(%)
1.05	1,93	4,53	2,25	5,28	2,56	6,01
1.10	2,02	4,64	2,47	5,67	2,74	6,29
1.20	1,51	3,41	1,84	4,15	2,03	4,58
1.30	1,4	3,11	1,71	3,80	1,88	4,18
1.40	1,34	2,95	1,64	3,61	1,8	3,96
1.50	1,3	2,84	1,58	3,45	1,74	3,80
1.60	1,07	2,33	1,31	2,85	1,44	3,14

To increase the durability of fuel cells. it is essential to minimize the reactant deficiency conditions [45]. However, voltage drop conditions in fuel cell systems with purging dead-end anode design cannot be completely avoided [38]. To facilitate analysis of the voltage drop and provide numerical values for comparison, Table 6 presents the percentage of voltage drop relative to the hydrogen stoichiometry ratio at lower current levels.

In general, the value voltage drop become smaller with the same ΔI addition on higher load currents. This phenomenon can be explained by the activation loss equation, where the relationship between current and voltage on the polarization

curve exhibits a steeper gradient compared to the ohmic and concentration loss regions. In the case of a 2 A step-up scenario, as presented in Table 6, the resulting voltage drop with hydrogen stoichiometry ratio (λ_{H_2}) above 1.3 satisfy the requirement. Table 7 conveys the voltage drop values with varying levels of voltage drop increments. These findings also confirm that higher hydrogen stoichiometry adjustments can support greater load currents. It is also clear that hydrogen stoichiometry ratio (λ_{H_2}) of 1.3 didn't satisfy the requirement for stepping up with 2.8 A. Furthermore, results from Table 8 shows higher load currents addition of 3 A. Using 4% criteria, hydrogen stoichiometry ratios above 1.3 is sufficient to mitigate voltage drops when the fuel cell operates under accumulated load currents exceeding 9 A.

TABLE 8 PERCENTAGE OF VOLTAGE DROP THAT OCCURS ON HIGHER CURRENT BY ADJUSTING HYDROGEN STOICHIOMETRY RATIO

	9 - 12 A		12 - 15 A	
λ_{H_2}	Voltage Drop (V)	Voltage Drop (%)	Voltage Drop (V)	Voltage Drop (%)
1.05	2,24	5,39	1,89	4,69
1.10	2,28	5,38	1,89	4,60
1.20	1,82	4,20	1,52	3,61
1.30	1,69	3,85	1,40	3,28
1.40	1,61	3,63	1,33	3,08
1.50	1,56	3,49	1,29	2,96
1.60	1,25	2,79	1,01	2,32



Fig 15. Voltage responses when using quick opening flow characteristic valves compared with linear flow characteristic valve using λ_{H_2} of 1.4 when increasing external current from 5A into 7A

Besides hydrogen stoichiometry ratio, control valve selection with steeper gradient of opening is more preferable to reduce voltage drop. Figure 15 depicts the relation between voltage responses between quick opening valves with linear valve which shows that linear flow characteristic suffers more on voltage drop compared with quick opening flow characteristic. This phenomenon can be explained when considering relation between CV value and opening percentage (%). A higher slope at lower valve openings, as observed in quick-opening valves, enables the valve actuator to reach the set-point more rapidly. This enhanced responsiveness allows the control valve to adapt more efficiently within the activation loss zone under conditions of low current in the fuel cell, thereby reducing the overall voltage drop

Based on the simulations that have been carried out. it can be concluded that the method that can be used to reduce the value of the voltage drop is by:

- 1) Using a control valve with a steeper slope between CV and its opening on the operation zone
- 2) Set a higher stoichiometry adjustment value, but this can impact hydrogen gas savings

Following an analysis of the voltage drop, the results can be used to enhance the efficiency of the fuel cell system. Efficiency improvement can be examined through two parameters: increasing power generation and conserving incoming hydrogen energy which would be covered on the next section.

C. Gross and Net Power Analysis

The hydrogen input flow rate analysis significantly influence the calculation of stack efficiency and system efficiency. However, a comprehensive review of these efficiency values requires an examination of the output power as well. Gross Power refers to the total electrical output generated by a fuel cell, excluding energy losses within the system. It represents the maximum potential electrical power output of the fuel cell. Figure 16a presents a graphical representation of the gross power produced. The data depicted in Figure 16a indicates an increase in power output corresponding to higher hydrogen stoichiometry values.

Increasing the stoichiometry value of hydrogen within a fuel cell enhances electrochemical reactions, resulting in more electron production and increased electrical power output, thus elevating the gross power produced by the fuel cell. The increases in gross power from raising the hydrogen stoichiometry ratio become less significant at higher stoichiometry levels, as lower hydrogen flow rates enter the fuel cells. However, it's essential to note that gross power represents the theoretical maximum power output of a fuel cell without accounting for external factors. In practical terms, the actual power consumed by a load is determined by net power. Net power in a fuel cell refers to the usable electrical power output after considering energy consumption by internal components of the fuel cell system. Therefore, for a more accurate energy analysis in practical applications, net power is commonly utilized.

Figure 16b illustrates a graph depicting the net power output of the fuel cell. Net power is influenced by two primary factors: the power generated by the fuel cell (gross power) and the power consumed by the fan. Analysis of net power data reveals lower overall power compared with the results obtained from the gross power analysis due to the fact that the net power has already been reduced by the power used by the fan. The increases in net power from raising the hydrogen stoichiometry ratio become less significant at higher stoichiometry levels, similar to the trends observed in the net power analysis.

An important factor in net power analysis is comparing the power consumed by the fan with the total gross power. Figure 17 illustrates the percentage of total power consumed by an external load relative to the overall gross power. Higher load currents indicate greater utilization of net power. Additionally, increasing the hydrogen stoichiometry ratio can raise the percentage of net energy usage relative to the total. The analysis of the results presented in Figure 17 is crucial for efficiency analysis, as it directly influences the overall system efficiency.



Fig 16. a) Gross power (b) net power for each hydrogen stoichiometry ratio variation



Fig 17. Net power utilization compared with gross power with variation of hydrogen stoichiometry ratio

D. Stack and System Efficiency Analysis by Varying Hydrogen Stoichiometry Ratio

Increased gross and net power, along with higher hydrogen savings can have a substantial impact on both stack efficiency values and overall system efficiency. Figure 19a provides an insight into stack efficiency within the fuel cell, showcasing variations associated with changes in the hydrogen stoichiometry ratio value.

The graphical representation in Figure 18a both for stack and system efficiency illustrates that lower hydrogen stoichiometry ratio values are associated with increased stack efficiency. Conversely, higher hydrogen stoichiometry ratio values lead to a decrease in stack efficiency. Therefore, reducing the hydrogen stoichiometry ratio value can positively impact stack efficiency. For easier analysis, Table 9 provides average stack efficiency values obtained during a 1800-second simulation period. The control performance can also be reviewed based on system efficiency values. Based on the results in Figure 18b, it shows that decreasing the hydrogen stoichiometry ratio value causes an increase in the system efficiency value. The value of system efficiency is affected by stack efficiency value and internal load that applied into fuel cell.

At low currents, it is observed that if the load current is increased, there is an increase in system efficiency which is the opposite of stack efficiency where a decrease is clearly shown. This can be explained by considering the effects that can influence the system efficiency value. The decrease in system efficiency value can be reviewed from two aspects when considering the system efficiency equation in equation 10, which influenced by the overall power distribution between the power that can be used for auxiliary load and the power consumed internally.



Fig 18. (a) Stack Efficiency (b) System Efficiency with variations of hydrogen stoichiometry ratio

TABLE 9
AVERAGE VALUE OF STACK EFFICIENCY OF VARYING
HYDROGEN STOICHIOMETRY RATIO SET-POINT AFTER 1800
SECONDS OF SIMULATION

Variation of Hydrogen Stoichiometry Values	Average Stack Efficiency Value (%)	Average System Efficiency Value (%)
1.05	52.53	46.30
1.10	51.10	45.15
1.20	47.88	42.45
1.30	44.84	39.84
1.40	42.08	37.44
1.50	39.59	35.28
1.60	38.93	34.70
Open Loop	38.91	34.69

It is clear that the stack efficiency value will decrease if there is an overall change in load current an smaller hydrogen stoichiometry ratio is used. However at low currents, the power consumed by the internal fan still dominates power consumption compared to the power that can be used for external loads with a certain amount of hydrogen energy supply. This results in a decrease in system efficiency due to the reduction in P_{aux} which is still quite significant compared to the value of P_{gross} at lower load currents. This can be clearly seen in Figure 18 in the analysis of net power utilization compared to gross power. If the load current is increased up to 9 A, the effect of P_{aux} becomes less dominant compared to the increase in P_{gross} , resulting in higher P_{net} utilization which impacts the increase in system efficiency. However, at higher load currents, system efficiency will decrease with the addition of load current due to the greater effect of stack efficiency decrease and it is no longer dominated by higher P_{net} utilization.

E. Summary of Hydrogen Stoichiometry Ratio Selection

TABLE 10 HYDROGEN STOICHIOMETRY RATIO SELECTION BASED ON CONSIDERED PARAMETER

		Hydrogen
	Parameters to be Considered	Stoichiometry Ratio
Order		(λ_{H_2}) Meets the
		Criteria
1	Control Valve Opening Operation Zone	1.05, 1.1, 1.2. 1.3. 1.4. and 1.5
2	Voltage Drop 4% maximum threshold [35]	1.3, 1.4 and 1.5
3	Stack Efficiency and System Efficiency	1.3

Based on the selection criteria and discussions regarding the parameters outlined in sub-sections A and D. the hydrogen stoichiometry ratio values that meet the criteria in Table 4 can be provided in Table 10. Upon evaluating the control valve opening response, it is clear that hydrogen adjustment values of 1.60 resulted in ineffective hydrogen control conditions as shown in Figure 11 and 12. Consequently, based on this analysis, the hydrogen stoichiometry ratio that aligns with the standard criteria falls within the range of 1.05 to 1.5.

After establishing the hydrogen stoichiometry ratio that meets the control valve opening criteria, the analysis extends to the voltage drop phenomenon. It was observed that the hydrogen stoichiometry ratio values of 1.05 to 1.2 did not meet the criteria for voltage drop (4%) under the simulated load current conditions as shown in Figure 14, Table 6, and Table 8. Despite this, both of those values resulted in greater efficiency compared to the stoichiometric values of 1.3 and above which met the voltage drop criteria. Based on this phenomenon, in order to obtain high efficiency in all load conditions, the stoichiometric value should be made different for each load condition. Especially on 1.2 which satify some of the load current addition variation. In further research, to improve the overall efficiency of the system, hydrogen savings can be achieved by implementing supervisory control whose a supervisory level determine the stoichiometry ratio at each load current range. Additionally. to achieve better efficiency, a deeper analysis is needed on the relationship between load current and hydrogen stoichiometry through the modeling of phenomena occurring within the fuel cell. A better understanding of this relationship will provide a strong foundation for developing more energy-efficient control strategies.

Furthermore, if the control system implemented does not use an supervisory level to determine the optimum hydrogen stoichiometry as a set-point and only relies on a single fixed stoichiometry value for the entire operation range, it is recommended to choose the hydrogen stoichiometry ratio that capable to overcome the largest variation in load current (ΔI). This is done to avoid hydrogen starvation (a condition where the hydrogen supply is insufficient), and then to sustain the electrochemical reaction. This strategy must consider the maximum load to ensure optimal performance of the fuel cell system.

For optimizing stack and system efficiency, it is determined that hydrogen stoichiometry ratio value 1.3 yields higher stack and system efficiency compared to hydrogen stoichiometry ratio value of 1.4 and 1.5. Based on the data at Table 10, it is known that when using hydrogen stoichiometry ratio value of 1.4, the control system designed has successfully reached additional 5.93 % of stack efficiency and 5.15% of system efficiency compared to conditions without addition of control system.

It can be concluded that the relationship between current load and fuel cell efficiency shows that higher current loads lead to lower efficiency due to increased voltage drop. Essentially, this research revolved around understanding the factors that influence fuel cell performance, particularly control valve operating zone, voltage drop and its impact on efficiency. It highlights the importance of minimizing voltage drop through operational control to maximize the energy conversion efficiency of fuel cells.

V. CONCLUSIONS

Hydrogen integration within fuel cell systems faces challenges due to the high production costs associated with hydrogen gas, leading to a disparity between the power generated and the incurred production expenses. To address this issue, a feedback-feedforward control system was developed to regulate hydrogen flow rate and temperature. The simulation was conducted using a G-HFCS-1kW36V fuel cell with a nominal capacity of 1 kW.

After analysis based on the control valve opening zone and safe voltage drop within the standard, it is revealed that hydrogen stoichiometry ratio values of 1.30, 1.40, and 1.50 meet the requirements. Besides the hydrogen stoichiometry ratio, employing quick opening-type control valves can reduce voltage drop compared to using linear type control valves with the same maximum CV value. Using a hydrogen stoichiometry ratio of 1.30, which is preferred over 1.4 and 1.5 for better efficiency, enables an enhancement of 5.93% in stack efficiency and 5.15% in system efficiency compared to open-loop conditions without hydrogen control. This finding highlights the importance of employing appropriate hydrogen control, which facilitates the optimization of hydrogen utilization, enhances system efficiency, and performance, and potentially results in energy and operational cost savings in fuel cell operations.

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