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Hybrid Modeling of Fuel Cell in Power System

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Abstract:- This paper presents the Steady-state and Dynamic behavior of PEMFC Fuel Cell Stack. As the world's energy use continues to grow, the development of clean distributed generation becomes increasingly important. Fuel cells are ideal for distributed power applications as well as vehicular applications. This paper explains the role of Fuel Cell in Power system in which stress has been given on the most promising applications such as distributed power generation as well as automotives. In this paper a Hybrid stack model has been introduced which is a combination of empirical & an electrical model of fuel cell. For stationary, portable power generation & transportation Fuel cell can overcome the existing fuel sources with low cost, high efficiency & less pollution. Without complicated mathematics, the proposed model is simple, yet obtains more than 93% accuracy in evaluating the fuel cell stack steady-state and dynamic performance. The empirical cell model has been used to represent the steady-state behavior, whereas, the circuit equivalent of the cell is used for dynamic behavior & Hybrid model which gives a very good combination of both the steady-state and dynamic Characteristics of PEMFC Fuel Cell Stack, is simulated by Using MATLAB/SIMULINK.

Key Words:- Fuel cell system, reformer, fuel cell vehicles, distributed power generation.

I. INTRODUCTION

To understand and analyze fuel cell stack performance at the design stage, computer models of fuel cells stacks are needed. To understand and analyze fuel cell stack performance at the design stage, computer models of fuel cells stacks are needed. To ensure a system level simulation, fuel cell stack models should be able to reflect fuel cell characteristics accurately. To ensure a system level simulation, fuel cell stack models should be able to reflect fuel cell characteristics accurately. Moreover they should allow for easy connection with other components such as power electronic circuits or energy storage devices. Two common approaches of fuel cell modeling are: steady-state model and dynamic model. Steady-state model reflects the V - I relationship of the fuel cell and can be divided into two categories: analytical model and empirical model. An empirical fuel cell model proposed by Junbom Kim was shown to fit the experimental V -i data for PEMFC. Since the model parameters are obtained from data fitting technique, the empirical model is accurate only in a small operating range. These have time constants varying over a wide range of order of magnitude [1]. Elmar A. explained this undershoot phenomenon as the effect of internal resistance variation immediately after the load jump ($t = +0$), the cell temperature is still low and related to the initial current value [2]. In the FCPP, there is no speed control but a similar relationship between the output voltage phase angle and the flow of hydrogen can be adopted as follows. Given that the load voltage ($V_s \angle 0$) is constant and the AC source voltage out of the inverter, V_{ac}, the angle δ controls the power flow from the fuel cell to the load, as in [3]. In order to increase the rates of reactions, the electrode material should be catalytic as well as conductive, porous rather than solid. The catalytic function of electrodes is more important in lower temperature fuel cells and less so in high temperature fuel cells because ionization reaction rates increase with temperature [4]. it was not until the mid 1900's when fuel cells began to make a name for themselves in the space industry Shortly after that, several private companies became interested in fuel cell technology, but the economic and technological barriers were difficult to overcome[5]. The high side placement may also allow for a de-rated front-end, depending on the battery size. However, large number of cells in series can be expensive and often lead to unbalance issues [6.]. At high current densities, slow transportation of reactants (products) to (from) the reaction sites is the main reason for the concentration voltage drop Any water film covering the catalyst surfaces at the anode and cathode can be another contributor to this voltage drop[7]. A simple model of the inverter is given in, where output voltage and output power are controlled using the inverter modulation index and the phase angle of the AC voltage V_{ac} [9]. The introduced a simple model of a reformer that generates hydrogen through reforming methane [10]. To control hydrogen flow according to output power from the fuel cell, a feedback from the stack current is considered. A proportional integral (PI) controller is used to control the flow rate of methane in the reformer [11]. Alternative, renewable energy sources have been around for quite some time; however, for numerous reasons, they have not yet emerged as primary power sources. The recent revitalization of the fuel cell hopes to help discontinue this trend.

[12]. The low-temperature fuel cells with aqueous electrolytes are, in most practical applications, restricted to hydrogen as a fuel. In high temperature fuel cells, CO and even CH4 can be used because of the inherently rapid electrode kinetics and the lesser need for high catalytic activity at high temperature [13]. The output power of these systems can range from a few watts to several hundred kilowatts. The area of interest here is distributed power generation & transportation [14]. A plot of electrode potential versus the logarithm of current density is called the “Tafel plot” and the resulting straight line is the “Tafel line” [15]. The time constants for the reformer and stack are of the order of seconds. Hence, model proposed by M. Y. El-Sharkh in including the inverter time constant will have negligible effect on the time response accuracy[16]. J.C. Amphlett proposed an equivalent electrical circuit in [2] which shares the same topology with the one proposed earlier by Larminie and Dicks [17]. The analytical models simulate the performance of fuel cell over a large range of operating conditions. But they require extensive computation and a good knowledge of electrochemistry making them inaccessible to many electrical engineers. Empirical model is derived from experiment results [18]. In addition to these disastrous effects to the environment, gasoline is a finite energy source. Therefore, another efficient and cheap energy source needs to be found quickly. Ideally, this energy source should be unlimited in its supply and friendly to the environment [20].Fuel cell vehicles (FCVs) are achieving energy efficiencies of 40 to 50 percent in current testing and demonstrations; through extensive research and development, these numbers are improving every day. Increased energy efficiency, which holds the promise of reducing dependence on foreign oil and increasing energy security, makes FCVs a very attractive replacement for internal combustion engines (ICEs), which are between 10 to 16 percent efficient [21].

II. THE ROLE OF GIBBS FREE ENERGY AND NERNST POTENTIAL

Understanding the impacts of variables such as temperature, pressure, and gas constituents on performance allows fuel cell developers to optimize their design of the modular units and it allows process engineers to maximize the performance of systems applications. A logical first step in understanding the operation of a fuel cell is to define its ideal performance. Once the ideal performance is determined, losses arising from non-ideal behavior can be calculated and then deducted from the ideal performance to describe the actual operation.

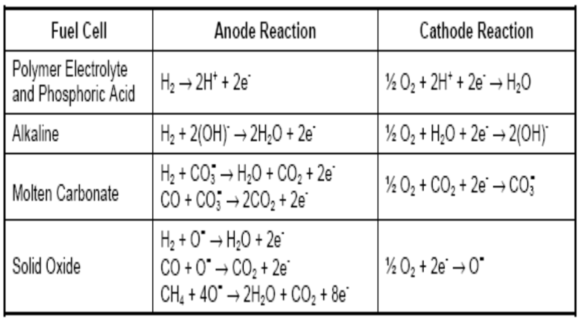
Gibbs free energy: The maximum electrical work (W_{el}) obtainable in a fuel cell operating at constant temperature and pressure is given by the change in Gibbs free energy (ΔG) of the electrochemical reaction:

$$W_{el} = \Delta G = nEW \qquad \text{-------------------(2.1)}$$

Where n is the number of electrons participating in the reaction, *F* is Faraday's constant (96,487 coulombs/g-mole electron), and E is the ideal potential of the cell. The Gibbs free energy change is also given by the following state function

$$\Delta G = \Delta H - T\Delta S \qquad \text{-------------------(2.2)}$$

Where ΔH is the enthalpy change and ΔS is the entropy change. The total thermal energy available is ΔH. The available free energy is equal to the enthalpy change less the quantity T ΔS which represents the unavailable energy resulting from the entropy change within the system. The amount of heat that is produced by a fuel cell operating reversibly is T ΔS. Reactions in fuel cells that have negative entropy change generate heat (such as hydrogen oxidation), while those with positive entropy change (such as direct solid carbon oxidation) may extract heat from their surroundings if the irreversible generation of heat is smaller than the reversible absorption of heat.



Fuel Cell	Anode Reaction	Cathode Reaction
Polymer Electrolyte and Phosphoric Acid	$H_2 \rightarrow 2H^+ + 2e^-$	$½ O_2 + 2H^+ + 2e^- \rightarrow H_2O$
Alkaline	$H_2 + 2(OH)^- \rightarrow 2H_2O + 2e^-$	$½ O_2 + H_2O + 2e^- \rightarrow 2(OH)^-$
Molten Carbonate	$H_2 + CO_3^{=} \rightarrow H_2O + CO_2 + 2e^-$ $CO + CO_3^{=} \rightarrow 2CO_2 + 2e^-$	$½ O_2 + CO_2 + 2e^- \rightarrow CO_3^{=}$
Solid Oxide	$H_2 + O^{=} \rightarrow H_2O + 2e^-$ $CO + O^{=} \rightarrow CO_2 + 2e^-$ $CH_4 + 4O^{=} \rightarrow 2H_2O + CO_2 + 8e^-$	$½ O_2 + 2e^- \rightarrow O^{=}$

Table 2.1 Electrochemical Reactions in Fuel Cells

The ideal standard potential (E_o) at 298K for a fuel cell in which H_2 and O_2 react is 1.229 volts with liquid water product, or 1.18 volts with gaseous water product. The potential is the change in Gibbs free energy resulting from the reaction between hydrogen and oxygen. The difference between 1.229 volts and 1.18 volts represents the Gibbs free energy change of vaporization of water at standard conditions. Figure 2.1 shows the relation of E to cell temperature. Because the figure shows the potential of higher temperature cells, the ideal potential corresponds to a reaction where the water product is in a gaseous state (i.e., E_o is 1.18 volts).

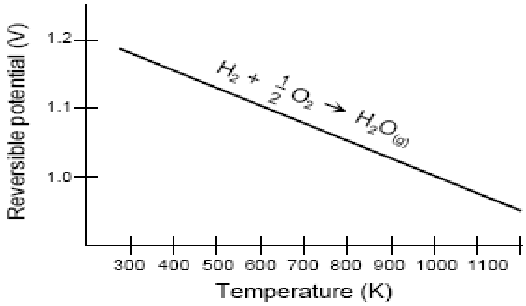


Fig. 2.1 H_2/O_2 Fuel Cell Ideal Potential as a Function of Temperature

III. FUEL CELL SYSTEM MODEL

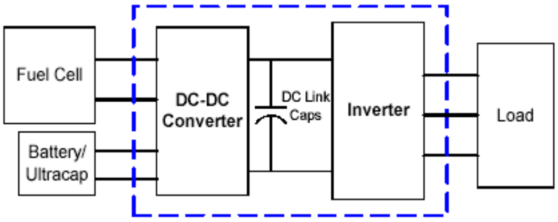


Fig. 3.1 Block Diagram of Fuel Cell System

The basic structure of the system is shown with the block diagram in Fig.3.1.Fuel cell systems often consist of three main stages: the fuel processing, the chemical to electrical conversion, and the power processing. Fuel cell requires hydrogen as fuel which can be extracted from any hydrocarbon such as methane, natural gas etc which is called as fuel processing. Since fuel cell produces an unregulated DC voltage so it is then boosted with DC-Dc converter. If load is of AC type then the regulated Dc voltage is converted into AC by using suitable inverter may be single phase or three phase. Also required is some type of energy storage to supplement the fuel cell during start-up and load transients.

IV. FUEL CELL MODEL

The model has been modified to simulate a PEM fuel cell. This model is based on simulating the relationship between output voltage and partial pressure of hydrogen, oxygen, and water.

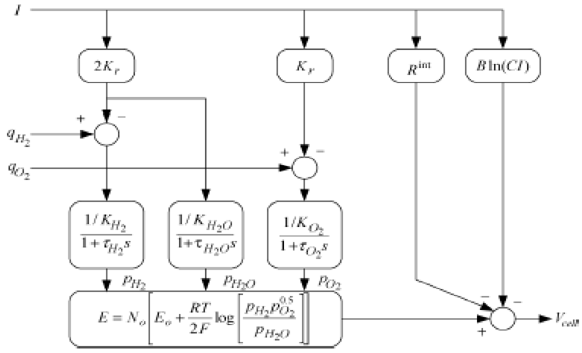


Fig. 4.1: PEM FCPP model.

When using a fuel other than pure hydrogen, a *reformer* or *fuel processor* is required. A *reformer* is a device that produces hydrogen from fuels such as gasoline, methanol, ethanol or naphtha. Three basic reformer designs are being evaluated for fuel cells for use in vehicles: steam reforming, partial oxidation and auto-thermal reforming. Steam reformers combine fuel with steam and heat to produce hydrogen. This paper introduced a simple model of a reformer that generates hydrogen through reforming methane. The model is a second-order transfer function.

$$\frac{qH_2}{q_{methene}} = \frac{CV}{\tau_1\tau_2 s^2 + (\tau_1 + \tau_2)s + 1}$$

……..[4.1]

FCPP system block diagram:

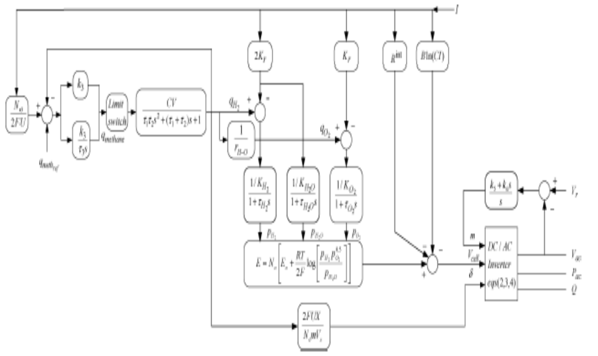


Fig. 4.2: FCPP system block diagram.

This section introduces an integrated dynamic for a fuel cell power plant. The proposed dynamic model includes a fuel cell model, a gas reformer model, and a power conditioning unit block. The model introduces a scenario to control active and reactive power output from the fuel cell power plant. The analysis is based on traditional methods used for the control of active and reactive power output of a synchronous generator. The results obtained from this study, proves the compatibility of FC to supply variable load. Thus this model proves the FC power plant to be better option for distributed power generation. V. Simulation A Hybrid Model With Combined Steady-state and Dynamic Characteristics of PEMFC Fuel Cell Stack

In this section a fuel cell model has been developed which is capable of characterizing fuel cell steady-state performance as well as transient behavior. With the combination of an empirical model and an electrical circuit model, the proposed model exhibits good agreement with experimental results in steady-state and dynamic performance which is simulated by using MATLAB/SIMULINK. The circuit is shown in Figure 4.1 the open circuit voltage of the fuel cell, R_h models the immediate ohmic voltage drops. R_{cl} and C_{cl} represent the "charge double layer" phenomenon.

Electrical circuit stack model:

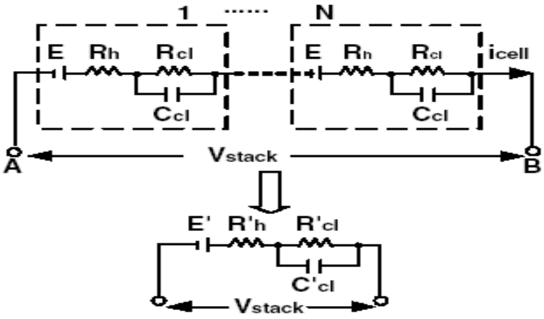


Fig. 5.1: Stack model derivation with single cells connecting in series

Thus the impedance between A & B can be given as $Z_{AB} = N \times R_h + N \times \frac{R_{cl}}{(1 + j R_{cl} \omega_{cl})}$

--------- [5.1]

Model with Combined Steady-State and Dynamic Characteristics**:** The empirical model can be rewritten in steady-state as:

$$v_{cell}(t)\big|t \to \infty = v_0(t)\big|t \to \infty - Ri(t)\big|t \to \infty - f(i,t)\big|t \to \infty$$

……………….[5.2]

where $f(i,t)\big|t \to \infty = b * \log i(t)\big|t \to \infty + m\exp(n * i(t))\big|t \to \infty$

……………[5.3] On the other hand, the electrical circuit shown in Figure 5.1 can be described as:

$$v_{cell}(t) = E - R_h i(t) - v_{cl}(t)$$

------------------ [5.4]

Comparing above equations we have

$$v_{cl}(t)\big|t \to \infty = f(i,t)\big|t \to \infty$$

------------------ [5.5]

Where $V_{cl}(t)$ is the instantaneous voltage across R_{cl}. So R_{cl} can be obtained as

$$R_{cl} = \frac{v_{cl}(t)}{i(t)}|t \to \infty = \frac{f(i,t)}{i(t)}|t \to \infty$$

------------------ [5.6]

And the resulting first order cell model is given by,

$$\frac{v_{cl}}{i_{cell}} = \frac{R_{cl}}{R_{cl}C_{cl}s+1}$$

---------------- [5.7]

Simulation of Hybrid FC Stack model by Using MATLAB/SIMULINK:

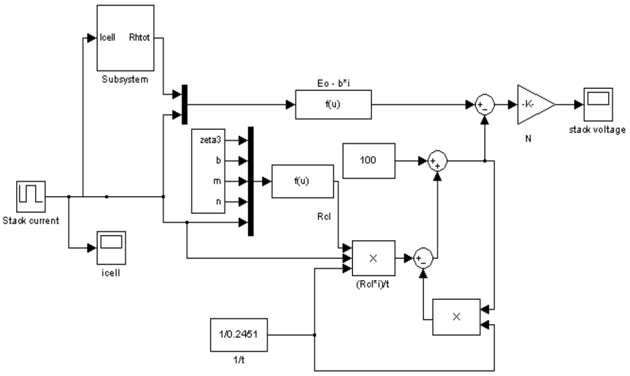


Fig. 5.2: Simulink model of Hybrid FC Stack

V. VERIFICATIONS OF HYBRID MODEL

A 1.2*kW* fuel cell stack is used to verify the steady state & dynamic performance of proposed stack model and in this paper this model is verified by using MATLAB/SIMULINK.

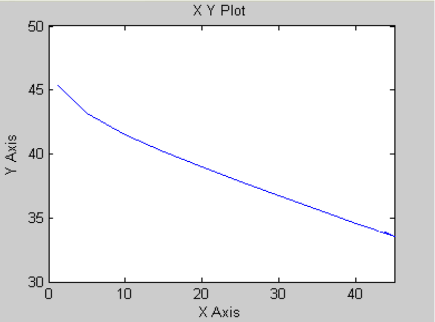


Fig. 6.1 Steady-state Response of simulink model

Dynamic Performance of The Proposed Fuel Cell Stack Model: The rest waveforms with different step changes are used to verify the model dynamic characteristics. Good correlation between the experimental results obtained in reference paper [18] and results of SIMULINK model of Hybrid stack model can be seen from the figure 6.2 to figure 6.7.

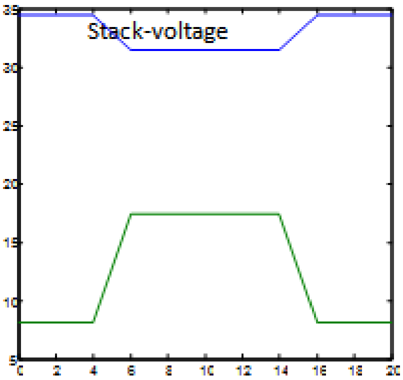


Fig. 6.2: 8.1A-17.4A-8.1A

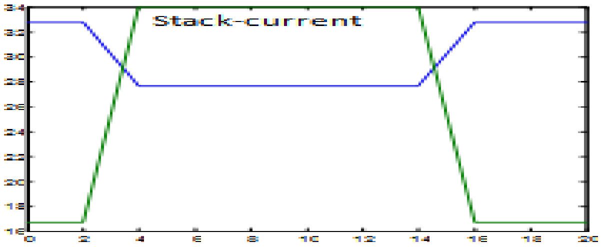


Fig. 6.3: 16.7A-34A-16.7A

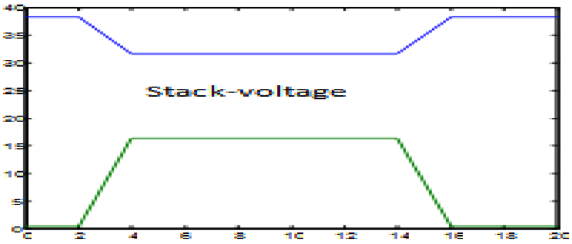


Fig. 6.4: 0.4A-16.3A-0.4A

Fig. 6.5: 18.8A-38A-19.2A

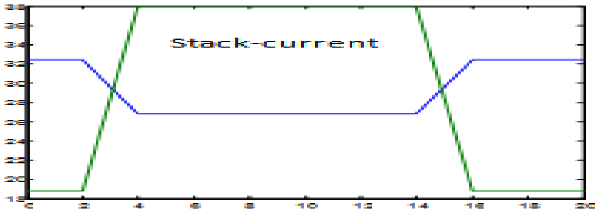


Fig. 6.5: 18.8A-38A-19.2A

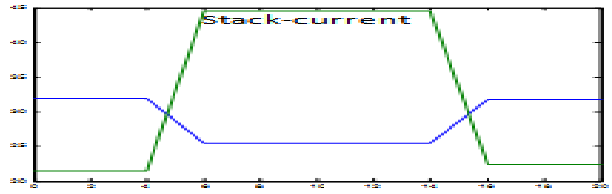


Fig. 6.6: 21.5A-44.5A-22.4A

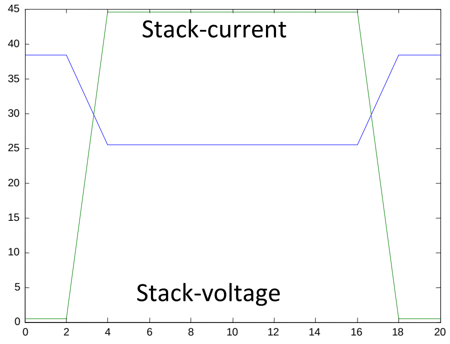


Fig. 6.7: 0.4A-44.5A-0.4A

The proposed model is a good simulation tool to analyze the fuel cell performance during the system design stage. A good correlation between the experimental data and the simulation results proves the validation of the hybrid model. Without complicated mathematics, the proposed model is simple, yet can obtain more than 93% accuracy in evaluating the fuel cell stack steady-state and dynamic performance.

VI. CONCLUSION

At the present time small scale fuel-cell systems offer promise for many applications in electrical power. For applications that can benefit from byproduct heat, fuel cells are especially attractive. It is very clear from the above studies that for stationary, portable power generation & transportation Fuel cell will reach the market with overcoming the existing fuel sources with low cost, high efficiency & less pollution. A good correlation between the experimental data and the simulation results proves the validation of the hybrid model proposed by Xin Kong. Without complicated mathematics, the proposed model is simple, yet can obtain more than 93% accuracy in evaluating the fuel cell stack steady-state and dynamic performance. A good correlation between the experimental data and the simulation results verified the validation of the hybrid model proposed by Junbom Kim. The proposed model is a good simulation tool to analyze the fuel cell performance during the system design stage.

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