Modeling and Control of a Grid Connected PAFC-Ultracapacitor Hybrid System

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Abstract—This paper presents a closed-loop control of an 800W fuel cell power system consisting of phosphoric acid fuel cell (PAFC), an ultracapacitor, power controlling unit and grid side filters. Simulation results represent the dynamics of the PAFC and its related power conditioning devices including grid connection. The proposed model is based on mathematical equations. The modeling and simulation is done in MATLAB/Simulink environment. This model mathematically computes cell output voltages and losses. The model includes dc power conversion of fuel cell output into ac and grid interface. Proposed model is lucid and simple.

Keywords— Phosphoric Acid Fuel Cell; Ultra-Capacitor; Modeling and Simulation; Power Conditioning unit; LCL Filters; Distributed Generation

I. INTRODUCTION

Energy is one of the major requirements to develop the economy of a country [1]. With the growing energy demand added with the limited reserve of various energy resources, within few generations, affordable fossil fuel reserves will be depleted. The world has been dependent on Non-renewable energy sources for several years [2]. Moreover, energy transition from the Non-renewable fossil fuels to Renewable energy is very important for the existence of the future generations and to have a sustained economic development. This transition would have a positive impact on the environment and could offer a secure future for the generations to come. Among alternative energy solutions, hydrogen based fuel-cell technology provides bright perspective to address and alleviate the impending and critical problems [1].

Fuel Cells (FC) are static energy conversion devices that convert the chemical energy of fuel directly into electrical energy. This energy conversion takes place via an electrochemical reaction. The main components of an FC based power system are fuel processing unit (reformer), FC stack and Power Conditioning Unit [1].

FCs are broadly classified into five categories based on the type of electrolyte and the type of chemical operating condition.

<table>
<thead>
<tr>
<th>Electrolyte</th>
<th>PEFC</th>
<th>AFC</th>
<th>PAFC</th>
<th>MCFC</th>
<th>SOFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Temp.(°C)</td>
<td>80°C</td>
<td>65°C - 220°C</td>
<td>205°C</td>
<td>650°C</td>
<td>600-1000°C</td>
</tr>
<tr>
<td>Charge carrier</td>
<td>H⁺, OH⁻</td>
<td>H⁺, OH⁻</td>
<td>H⁺, CO₃⁻</td>
<td>O⁻⁻</td>
<td></td>
</tr>
<tr>
<td>External Reformer</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

FC based system requires power conditioning circuits to condition its output DC voltage and convert the DC output into AC voltage. For a grid-connected system, an inverter is used with a FC. This must be synchronized with the grid in terms of voltage and frequency [1].

This paper represents a model and a control mechanism of an 800 W PAFC system including power electronics and grid filters. A modeling of PAFC system including dc to ac power conversion and grid connection is proposed. The FC model is based on empirical equations. Power electronics and grid demand added with the limited reserve of various energy resources, within few generations, affordable fossil fuel reserves will be depleted. Moreover, energy transition from the Non-renewable fossil fuels to Renewable energy is very important for the existence of the future generations and to have a sustained economic development.
This transition interface is modelled in Simulink. This model includes fuel stacks to produce dc power, a dc to ac inverter to produce ac power, filters to eliminate fluctuation, grid connection and a closed loop control mechanism to maintain a constant output power. The closed loop control mechanism basically compares the inverter output with the reference and controls the PWM inverter. Section II describes the mathematical model, section III describes the proposed model, section IV shows the simulation results and discussions, and section V concludes the paper.

II. FUEL CELL POWER SYSTEM

Due to a fluctuation of FC output voltage, its voltage has to be regulated, boosted with power converters, for most of its applications. Coupled with energy storage devices like a batteries and/or ultra-capacitors FCs can meet the transient load demand. Therefore, FCPS consists of the FC System, a power conditioning unit and the controller [4].

The schematic block diagram of Fuel cell based power system (FCPS) for testing of dynamic load demands is given in Fig. 1. FCPS comprises of a FC stack, power converter, Ultracapacitor, power controller and FC controller. According to the load power and FC current requirement, the power controller will generate a reference signal for flow control.

\[ V_{cell} = E_{nernst} + V_{act} + V_{ohmic} + V_{conc} \]  

Where \( E^0 \) is the ideal voltage at unity activity (≈1.229V under standard conditions)

\[ E_{nernst} = E^0 + \frac{RT}{nF} \ln \left( \frac{p_{H2}p_{O2}^{1/2}}{p_{H2O}} \right) \]  

Where \( E^0 \) is the ideal voltage at unity activity (≈1.229V under standard conditions), \( T \) is the Universal gas constant, \( n \) is number of exchanged electrons, \( F \) is the Faraday’s constant, \( p_{H2}, p_{O2}, p_{H2O} \) are partial pressures of Hydrogen, Oxygen and water respectively. However, the practical output voltage of fuel cell is slightly lower than the Nernst’s voltage due to inherent activation (\( V_{act} \)), ohmic (\( V_{ohmic} \)) and concentration (\( V_{conc} \)) losses under load conditions.

The power output from a PAFC is affected by the changes in the temperature and reactant flow rates. Fuel cell performance changes with temperature which, in turn, influences the water removal and reactants activity. Another temperature dependent parameter is the ion conductivity of the electrolyte. The performance of fuel cells is also influenced by the variation of relative humidity at the electrodes. Concentration of oxygen in diffusion layer also affects the performance of the cell [7].

The model of PAFC for dynamic power characteristics is implemented in MATLAB/Simulink®. The partial pressures of reactants and products are obtained by considering that the molar flow rate of gas through the valve is proportional to its partial pressure [8].

\[ p_{H2} = \frac{1}{1 + K_{H2}} q_{H2}^{in} \] \[ p_{O2} = \frac{1}{1 + K_{O2}} q_{O2}^{in} \] \[ p_{H2O} = \frac{1}{1 + K_{H2O}} q_{H2O}^{in} \]  

where \( q_{H2}, q_{O2}, q_{H2O} \) are molar flow rates, \( p_{H2}, p_{O2}, p_{H2O} \) are partial pressures, \( K_{H2}, K_{O2}, K_{H2O} \) are valve molar constants of hydrogen and water, respectively.

Substituting these equations of dynamic partial pressure terms in (1), we can obtain the Nernst potential for dynamic model.

The electrochemical reactions involve activation energy. The activation loss is governed by using Tafel equation which explains the part of the voltage that is used up in driving the chemical reaction that moves the electrons to the respective electrodes.
Tafel equation gives a correspondence between the over-voltage at the surface of an electrode and the natural logarithm of the current density and can be used to determine the activation voltage loss for the fuel cell. Rate parameters and activation energy of one or more rate limiting reaction steps can control the voltage drop during activation loss. The following equation explains the activation polarization [3].

$$V_{act} = -\frac{rT}{nF} \ln \left( \frac{i}{i_0} \right)$$  \hspace{1cm} (6)

Here ‘α’ is the electron transfer coefficient, ‘I’ represents the current density and ‘i_0’ represents the exchange current density.

Ohmic Loss

The flow of ions is met with resistance in the electrolyte and through the electrode which causes the ohmic loss. The ohmic over voltage can be expressed by the following equation [3].

$$V_{ohmic} = -I R_{int}$$  \hspace{1cm} (7)

Here ‘I’ represents the electrical current and $R_{int}$ represents the internal resistance. The developed equation of $R_{int}$ at the temperature of 451 K (178 0C) can be written as below [6].

$$R_{int} = 0.0652 I^{-0.819}$$  \hspace{1cm} (8)

Concentration Loss

Concentration losses occur due to inadequate concentration of reactants at the electrode with increase in the current drawn from the FC. The products often dilute that reactant and hence the concentration loss occurs. The concentration loss is given by the following equation [8]

$$V_{conc} = \frac{RT}{nF} \ln \left( 1 - \frac{i}{i_l} \right)$$  \hspace{1cm} (9)

Here $i_l$ represents the limiting current density.

The final stack voltage is given by the following equation:

$$V_{stack} = N V_{cell}$$  \hspace{1cm} (10)

Here N represents the number of fuel cells and $V_{stack}$ represents the stack voltage for a PAFC.

III. PROPOSED MODEL

Proposed model is developed in Matlab/ Simulink environment, as shown in the Figure II, which shows the control mechanism of an 800 W PAFC based power plant with grid connection. Here a three phase sink acts as grid. Figure II is the Matlab/Simulink implementation of system shown by the block diagram in figure I. In the figure, the PAFC system can be identified by orange coloured block, the ultracapacitor by magenta colour and control mechanism by grey colour. The powergui block is essential for providing system initial conditions and to run the model with simple power system blocks. The subsystem blocks of the proposed model are 'PAFC', 'Feedback' & 'Measurements'. The proposed model is explained in the following four sections namely PAFC system, PCU, grid and control mechanism.

A. PAFC System

The first block of the PAFC system is 'Inputs' subsystem block, which contains the values of various inputs of the model as given in the table below.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>N ( No.of cells)</td>
<td>14</td>
</tr>
<tr>
<td>N.E0 (Open circuit voltage, V)</td>
<td>9.86</td>
</tr>
<tr>
<td>$K_{H2}$ (kmol/s.atm)</td>
<td>8.38 x 10^4</td>
</tr>
<tr>
<td>$K_{O2}$ (kmol/s.atm)</td>
<td>2.55 x 10^5</td>
</tr>
<tr>
<td>$K_{H2O}$ (kmol/s.atm)</td>
<td>2.79 x 10^6</td>
</tr>
<tr>
<td>$\tau_{H2}$ (s)</td>
<td>1.24</td>
</tr>
<tr>
<td>$\tau_{O2}$ (s)</td>
<td>2.95</td>
</tr>
<tr>
<td>$\tau_{H2O}$ (s)</td>
<td>7.79</td>
</tr>
<tr>
<td>$m$ (constant)</td>
<td>0.045</td>
</tr>
<tr>
<td>n (constant)</td>
<td>0.01</td>
</tr>
</tbody>
</table>
The second block is ‘PAFC’ subsystem block. It contains all the equations from the mathematical modeling part. This block simulates the equations from (1) through (10).

**Figure III. PAFC Sub-System**

Figure III shows the ‘PAFC’ subsystem block. The outputs (current, voltage & power of the stacks) of this subsystem block can be observed through the display blocks of figure II. The output voltage of figure III is connected to the ‘Ultracapacitor’ subsystem block of figure II.

A current feedback can be observed in the ‘PAFC System’ of figure 4. This is basically the dc output current from the ‘PAFC System’.

**Figure IV. Feedback Sub-System**

From figure IV, the feedback current (I) is converted into current density ‘i’ through a gain block. Then it is sent as an input to the model. The function of the memory-block is to store the initial condition i.e. specifies minimum current density observed in the results.

**B. Ultracapacitor**

Ultracapacitors are highly promising power-augmentation devices, capable of providing better dynamic response. In the ultracapacitor sub-system block, an in-built non-ideal ultracapacitor has been used. The SPS blocks are used to convert the Simulink signals into power signals. The block diagram is shown below. The output is connected to the inverter in Power conditioning unit.

**Figure V. Ultracapacitor Sub-System**

**C. Power Controlling Unit (PCU)**

The power conditioning unit of figure II mainly contains an inverter, LCL filters and a measurement subsystem block, shown in grey. The positive port of the inverter is connected to the dc signal and the negative port is grounded in order to converts the dc signal into ac signal.

The inverter is Insulated Gate Bipolar Transistor (IGBT) type. Each of the phases (A, B & C) is connected to the LCL filter. These filters are used to check the harmonics entry into the grid. This is an essential requirement of the grid. Each filter contains a pair of inductors and a capacitor in ‘T’ formation. The value of left arm inductance of each filter is same for each other but different from the right arm inductance. Similarly the values of right arm inductance and capacitance are same for each filter. One terminal of all the capacitors is connected to a common point. One terminal of both the arm inductances are connected to the 'Measurements' subsystem block [9].

**Figure VI. Voltage and Current Measurement Sub-System**

Figure VI shows the 'Measurements' subsystem block. In this block, the two input arms are connected to the three phase V-I measurement block. The \(I_{ab} \) port is demuxed into two outputs. One is fed to the rms bock, and the other goes to the three phase power measurement block, whose output is ac active power.
D. Grid

A three phase sink is used as the ‘Grid’. The 'node 10' neutral indicates the same neutral of PCU section. This is a floating type neutral that helps connect two points without drawing the connection line between them. The three phases sink i.e. grid window looks as shown below.

![Figure VII. Three phase sink](image)

From this window, it can be seen that the phase root mean squared voltage is assumed to be 500 V and the frequency as 50 Hz. The internal connection is chosen as ‘Yn’. The resistance and inductance values are considered as very small as ideally grid has negligible resistance and inductance.

E. Control Mechanism

The control mechanism contains of a PWM generator block, a PID controller block, a constant reference block and a sum block. The output of the PWM generator is fed to the inverter which is produces ac. This PWM generator block is given below. The modulation index is adjusted by this control mechanism.

![Figure VIII. PWM generator window](image)

The generator mode is chosen to be 3-arm bridge (6 pulses). Because this is a grid connected model. The carrier frequency is 1080 Hz. The PID controller takes care of the modulation index. The main window of PID controller is shown below.

![Figure IX. PID settings](image)

Proportional value is taken as $10^{-4}$. The upper and lower saturation limits are assumed as 1 and 0.3 respectively which indicate the range of the modulation index. From figure II, it can be seen that this error signal is the difference between the reference signal and the power signal from PCU section and this is fed to the PID as input. The reference signal is indicated by a constant block.
IV. SIMULATION RESULTS AND DISCUSSION

The proposed model is run for 0.25 seconds in Matlab/Simulink R2013a to obtain the results. The ac output is around 800 W and it is fixed constant throughout the simulation. Moreover, there is negligible fluctuation in it, hence it is safe to inject this power into the grid. The second main objective is to reduce losses at each stage. Measurements are done at three stages of the proposed model to meet this objective. Firstly, the measurement is done after the fuel stacks, secondly after the connection of power block i.e. diode (dc measurement) and thirdly after converting the dc power into ac (ac measurement). The display blocks show that the fuel stacks can produce 789 W and the dc power is also approximately 789 W. So there is no power loss between these two stages. Finally the ac power is measured to be 788 W which shows negligible power loss due to inverter. This loss occurs due to inverter and filters which is reasonable. The output of ‘stack’ scope i.e. wave shapes of current, voltage and power after the fuel stacks are shown below.

As can be seen, there is hardly any fluctuation in the DC values.

The current remains constant, but voltage and power show initial transient.

Figure X shows the output of ‘ac’ scope. The initial transient and the following steady state condition can be observed.
Figure XIV: Three Phase Voltages & Currents

Figure XV shows the three phase ac line to line voltages and line currents from the grid side. The transient at the initial stage dies quickly and the resultant balanced waveform can be fed into the grid safely.

V. CONCLUSION

The paper proposes a steady state and dynamic model of a fuel cell-ultracapacitor hybrid plant with grid connection. A simple control mechanism is employed to control the inverter based on pulse width modulation (PWM) technique. The measurements at various stages show negligible losses, with three phase balanced output which can be safely fed into the grid. It can also be concluded that use of ultracapacitor against the battery has also provided satisfactory results.

REFERENCES


