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Modeling and Control of a Grid Connected PAFC System

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Abstract-This paper presents a closed-loop control of a 440kW fuel cell system including power electronics and grid side filters. Simulation results show the dynamics of a phosphoric acid fuel cell (PAFC) and its associated power electronics including grid connection. The proposed model is based on empirical equations and Simulink blocks. The modeling and simulation is done in Matlab/Simulink software with its Power System Blockset (PSB). This model mathematically calculates cell output voltages and their consequent losses. Moreover, this model includes dc power conversion of fuel cell output into ac and grid interface. Presented model is simple and easy to understand.

Keywords-Phosphoric Acid Fuel Cell; Modeling and Simulation; Power Conditioning System; LCL Filters; Distributed Generation

I. INTRODUCTION

Energy is one of the major requirements to develop the economy of a country [1]. The energy demand is increasing and due to a limited resource within few generations affordable fossil fuel reserves will be finished. Non-renewable energy sources have been utilized worldwide for several years [3]. Moreover, energy transition from the conventional fossil fuels to sustainable energy is very important for the existence of future generations and to sustain our economy. This transition can cure the environment and offers a secure future for the generations to come. Among alternative energy solutions, hydrogen based fuel cell energy is one option to address and alleviate the imminent and critical problems [1].

Fuel Cells (FC) are electrochemical devices, which use chemical energy within a fuel. This energy is directly converted into electrical energy 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].

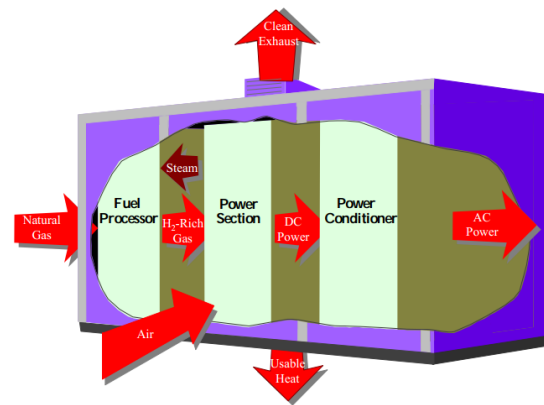


Figure. 1. Fuel Cell Power Plant Major Processes [4]

FCs are broadly classified into five categories based on the type of electrolytic material and the type of chemical operation. They are Alkaline FCs, Proton Electrolyte Membrane FCs, Phosphoric Acid FCs, Molten Carbonate FCs and Solid Oxide FCs [1]. Phosphoric Acid Fuel Cell (PAFC) is one of the most advanced and commercially available technology among all other fuel cells [2].

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 a 440kW 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 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. The error signal is used by the PID controller and PWM generator. Section 2 describes the mathematical model, section 3 describes the proposed model, section 4 shows the simulation results and discussions, and section 5 concludes the paper.

II. MATHEMATICAL MODELING

A valuable insight into the electrochemistry of the fuel cell can be gained by mathematical modeling. It also shows the processes that take place in the system. In this model, the main approach is to keep the ac output fixed so that it can be injected to the grid. It is known that grid requires three phase balanced output and no fluctuation. Another approach is to minimize the losses at different stages of the whole model and to produce 440 kW power at the final stage. The block diagram of the proposed model is given below in figure 2.

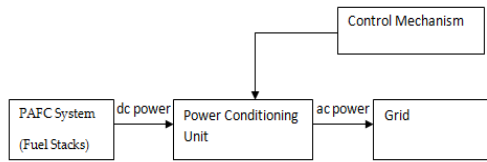


Figure 2. Basic block diagram of the PAFC grid connected model

In this model, the PAFC system consists of 3 fuel stacks and each stack contains 376 fuel cells. The dc power of this PAFC system is converted into ac power through the power conditioning unit. A simple control mechanism controls the whole system through power conditioning unit (PCU). Since the PAFC system of the proposed model is built empirically, only the mathematical modeling of the FC part will be explained. The other three parts of figure 2 i.e. power conditioning unit, control mechanism and grid are built using available blocks available in Matlab/Simulink Power System Blockset (PSB).

The output voltage of an individual PAFC includes Nernst potential, activation loss, ohmic loss and concentration loss. The overview can be observed in figure 3 below [2].

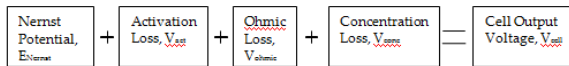


Figure 3. Block diagram of the output of an individual PAFC [2]

Figure 3 can be expressed in an equation form as explained below [2].

$$V_{Cell} = E_{nernst} + V_{act} + V_{ohmic} + V_{conc} \quad [1]$$

A. Nernst Potential

At thermodynamic balance, the thermodynamic potential can be obtained. The equation of Nernst potential explains this voltage. At standard condition (298.15 K, 1atm), the overall reaction result in hydrogen, oxygen and vapor, and produce a thermodynamic potential [2].

$$E_{nernst} = E^0 + \frac{RT}{nF} \ln \left[\frac{p'_{H_2} (p'_{O_2})^{0.5}}{p'_{H_2O}} \right] \quad [2]$$

In equation 2, E^0 is the reference potential at unity cavity (1.229 V at standard state). Here p'_{H_2} , p'_{O_2} and p'_{H_2O} represents the hydrogen, oxygen and vapor partial pressures (atm), respectively. Additionally, T represents the cell temperature (K), R represents the universal gas constant (8.31441 J mol⁻¹ K⁻¹), F represents the Faraday constant (96484.56 C mol⁻¹) and n represents the number of electrons participating in the reaction.

B. Activation Loss

Both electrical and chemical reactions result in activation energy. Reacting species can differentiate between them. Rate parameters and activation energy of one or more rate limiting reaction steps can control the voltage drop during activation loss. The following equation can explain the activation polarization [2].

$$V_{act} = - \frac{RT}{\alpha nF} \ln \frac{i}{i_0} \quad [3]$$

Here α represents the electron transfer coefficient, i represents the current density and i_0 represents the exchange current density.

C. Ohmic Loss

Flowing ions incur resistance in the electrolyte and through the electrode. And ohmic loss occurs due to this resistance. The ohmic over voltage can be expressed by the following equation [2].

$$V_{ohmic} = - IR_{int} \quad [4]$$

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 °C) can be written as below [2].

$$R_{int} = 0.0652 \quad I^{-0.819} \quad [5]$$

D. Concentration Loss

Sometimes a reactant is consumed at the electrode by electrochemical reaction. The products often dilute that reactant and thus concentration loss occurs. The following equation explains the concentration loss [2].

$$V_{conc} = \frac{RT}{nF} \ln \left(1 - \frac{i}{i_L} \right) \quad [6]$$

Here i_L represents the limiting current density.

The following equation will explain the mathematical modeling of a single PAFC stack since 376 fuel cells are connected in series in a single fuel stack [2].

$$V_{stack} = NV_{cell} \quad [7]$$

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

Since three fuel stacks are connected in series in the system, the output voltage of the PAFC system can be expressed with the following equation.

$$V_{3stacks} = N_s V_{stack} \quad [8]$$

Here N_s represents the number of fuel stacks, $V_{3stacks}$ represents the output voltage of the PAFC system and V_{stack} represents the individual stack voltage.

III. PROPOSED MODEL

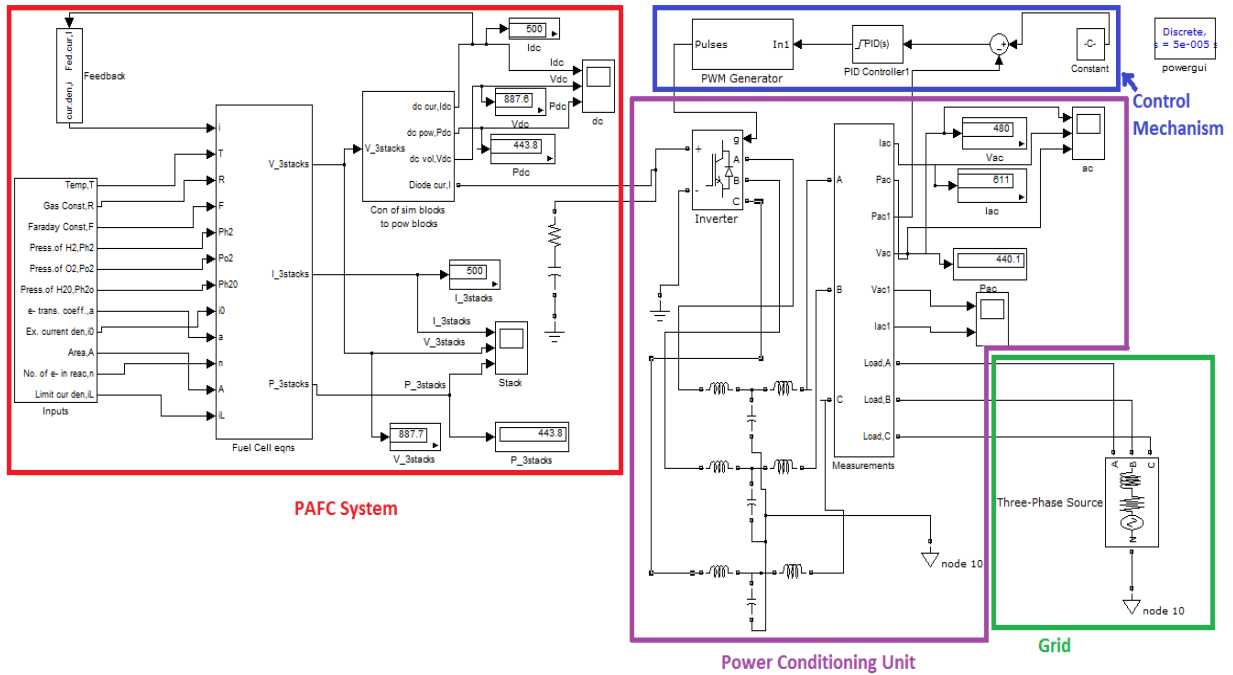


Figure. 4. Proposed Model of PAFC type power plant with grid connection

Figure 4 shows the proposed model in Matlab/Simulink environment. This figure also shows the control mechanism of a 440 kW PAFC type power plant with grid connection. Here a three phase sink is used as grid. Figure 4 is the Matlab/Simulink representation of system shown in figure 2. In figure 4, the PAFC system can be identified by red color block, the PCU by purple color, grid by green color and control mechanism by blue color. The powergui block helps to provide system initial conditions and

run the model with simple power system blocks. The subsystem blocks of the proposed model are 'Inputs', 'Feedback', 'Fuel Cell equations', 'Con of simulink blocks to power blocks' & 'Measurements'. The proposed model will be explained in the following four sections named as PAFC system, PCU, grid and control mechanism.

A. PAFC System

The first block of the PAFC system is 'Inputs' subsystem block. It contains all of the inputs of the model. This subsystem block consists of constants and in-port blocks.

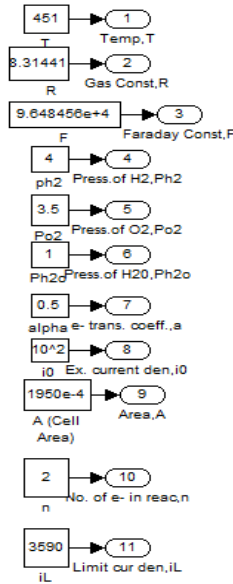


Figure 5. 'Inputs' subsystem block

Figure 5 shows the inputs of the model. All values used in simulation are listed in table 1.

TABLE 1 INPUT PARAMETER VALUES OF THE PROPOSED MODEL

Parameter Name	Parameter Value
Temperature, T	451 K
Gas Constant, R	$8.31441 \text{ J mol}^{-1} \text{ K}^{-1}$
Faraday Constant, F	$96484.56 \text{ C mol}^{-1}$
Partial pressure of hydrogen, p_{H_2}	4 atm
Partial pressure of oxygen, p_{O_2}	3.5 atm
Partial pressure of vapor, p_{H_2O}	1 atm
Electron transfer coefficient, α	0.5
Exchange current density, i_0	10^2 A m^{-2}
Cell area, A	0.1950 m^2
Number of electrons participating in the reaction, n	2
Limiting current density, i_L	3590 A m^{-2}

The second subsystem block is 'Fuel Cell equations' subsystem block. It contains all fuel cell equations of the mathematical modeling section. This block simulates from equation (1) to equation (8). All of the equations are used for each fuel cell of the 376 cells of the PAFC system.

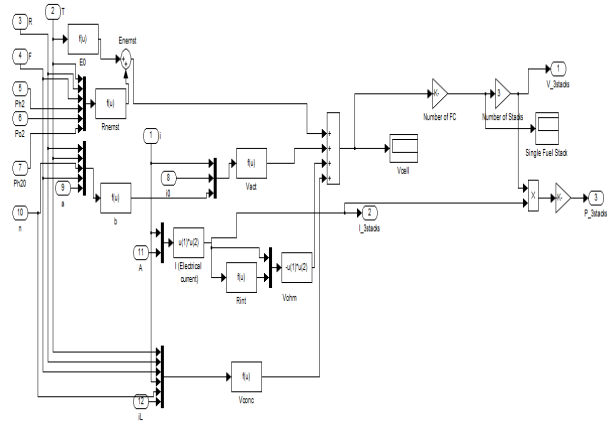


Figure 6. 'Fuel Cell equations' subsystem

Figure 6 shows the 'Fuel Cell equations' subsystem block. The outputs (current, voltage & power of three stacks) of this subsystem block can be observed through the display blocks of figure 4. The system outputs can be investigated through one single window i.e. the 'Stack' scope block of figure 4. The output 'V_3stacks' of figure 6 is connected to the 'Connection of simulink blocks to power blocks' subsystem block of figure 4.

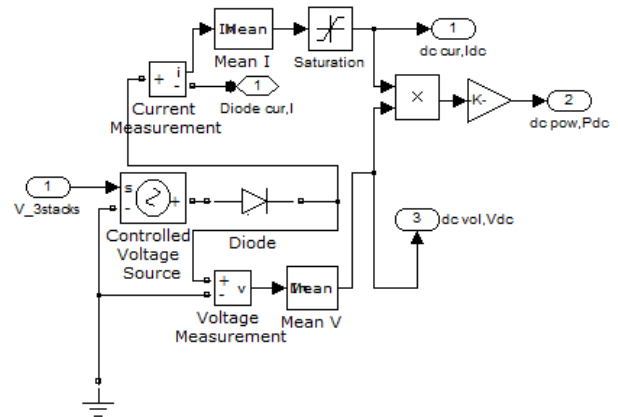


Figure 7. Connection of simulink blocks to power blocks' subsystem block

Basically the 'Connection of simulink blocks to power blocks' subsystem block is the connection between two sections i.e. red colored 'PAFC System' and purple colored 'Power Conditioning Unit'. This subsystem block also connects simulink blocks with power system blocks. From figure 7, it can be seen that the simulink signal ($V_{3stacks}$, stack voltage for three stacks) is input into 'simpowersystem' block i.e. controlled voltage source block. The rectifier diode after the controlled voltage source block makes the

current to flow in one direction. Moreover, the current measurement and voltage measurement blocks can be observed. They measure the current and voltage. The mean blocks calculate the mean value of current and voltage. The saturation block keeps the signal in the range from 500 A to 700 A. This range helps to remove fluctuation from grid. Then the dc power is calculated by multiplying the output of the saturation block with the mean voltage. A gain block is used to convert the watt (power) value into kilowatt (kW) value. In this way, the outputs of the subsystem block are dc outputs current, voltage and power and diode current.

From figure 4, the dc current, voltage and power can be observed through display and scope block. A series RC branch is connected with the diode current. Then the diode current is connected to the power conditioning unit which is another section (purple colored). This RC branch is a DC filter representing a large capacitor and its internal resistance. The value of resistance is taken small to keep the power loss small through this path.

One current feedback can be observed in the red colored 'PAFC System' of figure 4. This is basically the dc current from 'Connection of simulink blocks to power blocks' subsystem block to the 'Feedback' subsystem block.

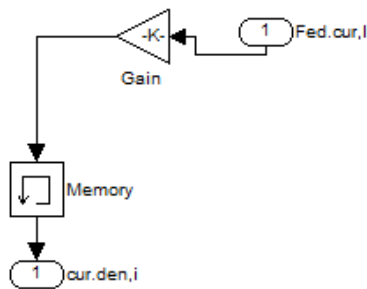


Figure 8. 'Feedback' subsystem block

From figure 8, it can be seen that 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 memory block stores the initial condition i.e. specifies minimum current density observed in the results.

B. Power Conditioning Unit (PCU)

The purple colored power conditioning unit of figure 4 mainly contains an inverter, three LCL filters

and a measurement subsystem block. The positive port of the inverter is connected to the dc signal and the negative port is grounded. It converts the dc signal into ac signal. The inverter is Insulated Gate Bipolar Transistor (IGBT) type. It has three bridge arms (A, B & C) which contain three phase current. Each of these phases (A, B & C) is connected to an LCL filter. These filters are used to reduce harmonics going to the grid. This is an important requirement of the grid. Each filter contains two inductors and a capacitor. The shape of each filter is similar to 'T'. The value of left arm inductance of each filter is same but different from the right arm inductance. Similarly the values of right arm inductance and capacitance are same for each filter. One port of all capacitors is connected to a common point. This common point is connected to the same node which can be observed with the grid in figure 4. The right arm inductances are connected to the 'Measurements' subsystem block.

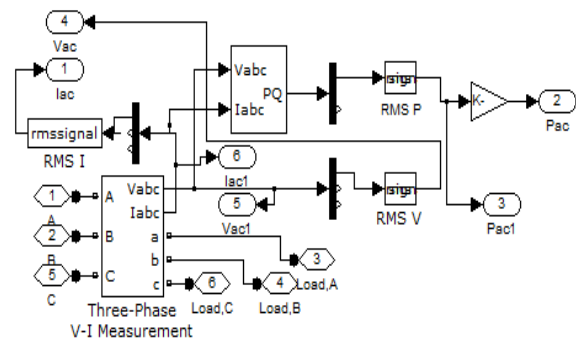


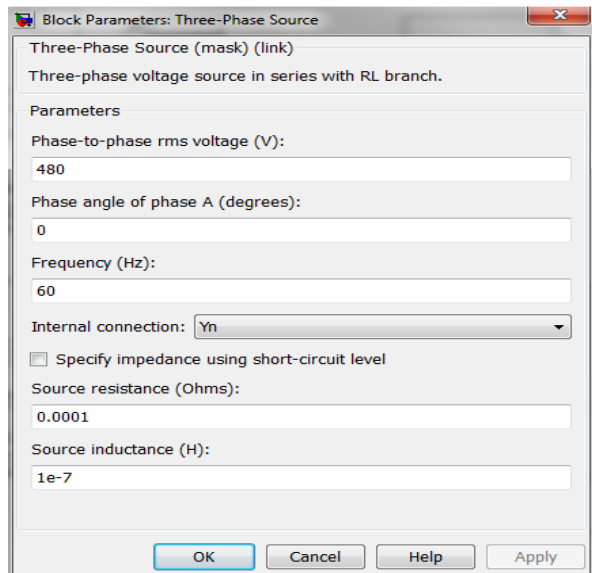
Figure 9. 'Measurements' subsystem block

Figure 9 shows the 'Measurements' subsystem block. In this subsystem, the three input arms are connected to the three phase V-I measurement (phase-to-phase type) block. The V_{abc} and I_{abc} port are demuxed into three outputs. Then each phase voltage and each phase current for the three phase setup can be observed. One phase voltage and one phase current are connected to RMS blocks to calculate the root mean square (rms) values of voltage and current. This rms voltage and rms current are the ac voltage and ac current, respectively in figure 4. Moreover, the V_{abc} and I_{abc} of figure 9 are also entered into the '3 phase instantaneous active and reactive power' block. The output of this block is demuxed from where active and reactive power can be obtained. The active power is connected to an RMS block to calculate the rms power and then to a gain

block to calculate the power in kilowatt (kW). The output of the 'RMS P' block is also sent to the blue colored 'Control Mechanism' section. Additionally, the V_{abc} and I_{abc} are also connected to a scope block in figure 4 to observe the instantaneous voltages and instantaneous currents. Thus the outputs of this PCU section are I_{ac} , V_{ac} & P_{ac} . These values can be measured through display blocks and curves can be observed through the 'ac' scope block.

C. Grid

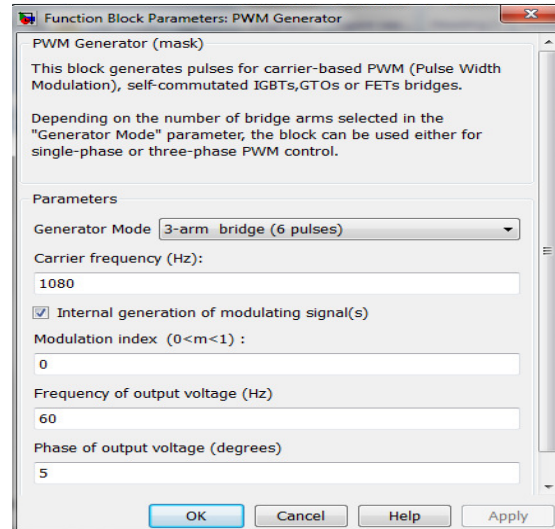
The green colored 'Grid' section contains a three phase sink and a neutral block. The three phase sink represents the grid in figure 4 and 'node 10' neutral indicates the same neutral of PCU section. This type of neutral is a floating type neutral without drawing the connection line between two points. The three phase sink i.e. grid window looks like below.



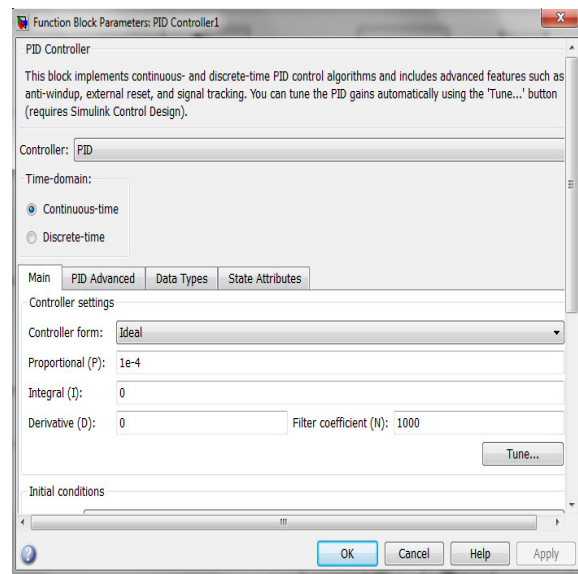
From this window, it can be seen that the phase to phase rms voltage is considered as 480 V (240+240) and the frequency as 60 Hz. Since the grid block is connected to a neutral block, internal connection is chosen as Y_n . Moreover, an ideal grid has no resistance and inductance. So the resistance and inductance values are considered as very small.

D. Control Mechanism

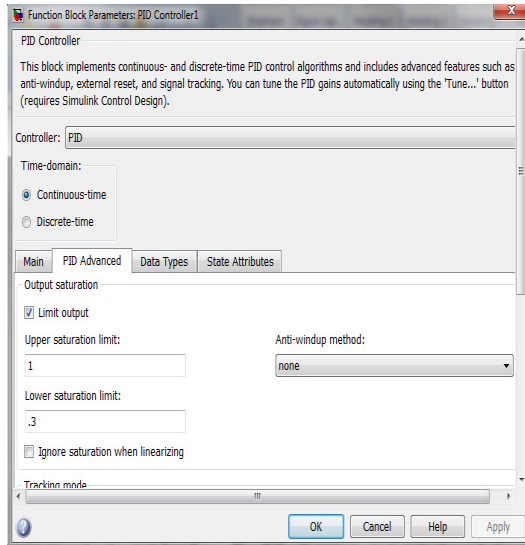
The control mechanism basically consists of a PWM generator, a PID controller, a constant and a sum block. The PWM generator gives an input (g) to the inverter which is a pure ac source. This PWM generator block looks like below.



This window shows that the generator mode is chosen as 3-arm bridge (6 pulses). Because this is a grid connected model. The carrier frequency is considered as 1080 Hz and phase of output voltage as 5 degree. The frequency of output voltage is chosen as 60 Hz, since the frequency of ac current was 60 Hz. The modulation index is controlled by a PID controller. The main window of PID controller looks as below.



Only a small proportional value is taken here. The PID advanced window looks as below.



The upper and lower limits basically indicate the range of the modulation index. The modulation index can vary within this range. The other two windows of this PID controller are kept as such. The input to this PID controller block is an error signal. From figure 4, it can be seen that this error signal is the difference between the reference signal and the power signal from PCU section. The reference signal is indicated by a constant block. The value in the constant block is taken as 440000 which is in watt. This is basically 440 kW which is expected to obtain as output. This reference is compared with the actual output (P_{ac1}) of the model.

IV. SIMULATION RESULTS AND DISCUSSIONS

The proposed model is run for 2 seconds in Matlab/Simulink R2010a to observe the results. Our main objective is fulfilled in this proposed model. The ac output is around 440 kW and it is fixed during the simulation. There is almost no fluctuation. And so, it is safe to inject this power into the grid. Another 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 443.8 kW power and the dc power is also 443.8 kW. So there is no power loss between these two stages. Finally the ac power is measured as 440.1 kW. Here a few kW power loss is observed. 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 look like below.

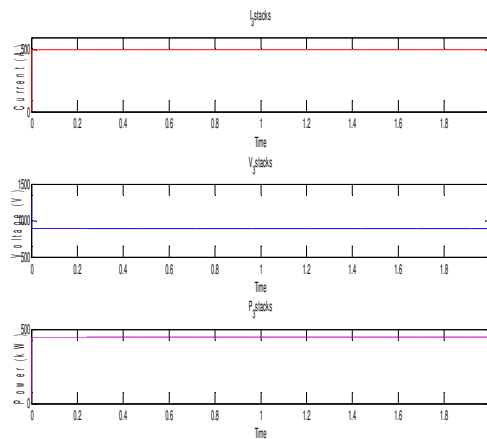


Figure. 10. Stack current, voltage and power as a function of time

Figure 10 shows the steady state condition of current, voltage and power. There is no transient condition for stack parameters.

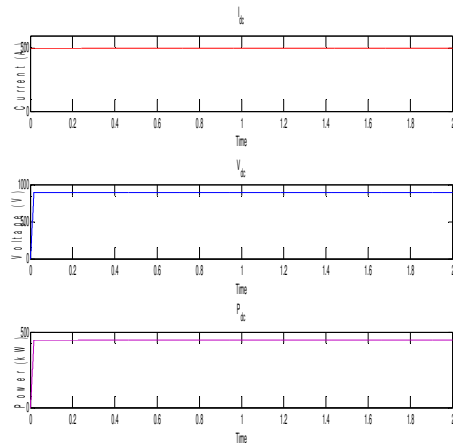


Figure. 11. DC current, voltage, and power as a function of time

Figure 11 shows the output of 'dc' scope. No transient condition can be observed for dc current but initial transients can be observed for dc voltage and dc power. After that they reach a steady value.

Figure 12 shows the output of 'ac' scope. The initial transients and after that steady state values can be observed for ac parameters. This simulation is run for 0.3 seconds to observe the dynamics more clearly. From the above figure, the dynamics of ac power can be observed from $t=0.05$ seconds to $t=0.15$ seconds.

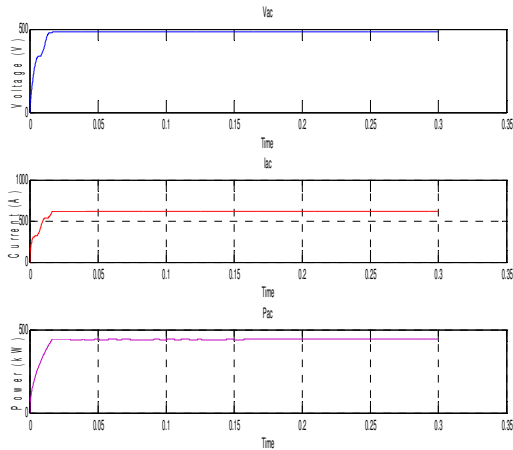


Figure 12. AC current, voltage, and power values

Figure 13 shows the three phase voltages and currents. It can be seen that both voltages and currents are balanced. Since no fluctuation is observed, they are safe to inject into the grid.

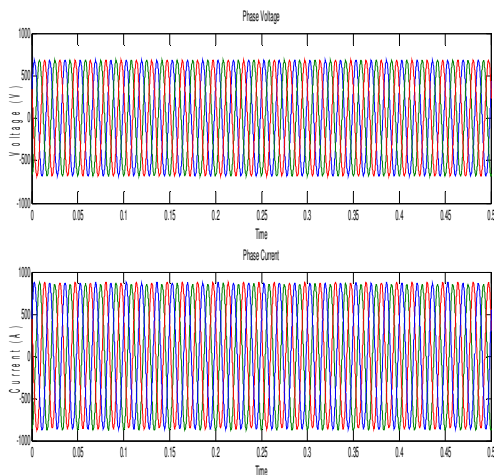


Figure 13. Three phase voltages and currents

V. CONCLUSION

This paper represents a steady state and dynamic model of a 440 kW power plant operated by a PAFC type fuel cell system with grid connection. Moreover, a simple control mechanism is used to control the PWM inverter. Model details and simulation results are discussed in the paper. The proposed model has a simple control mechanism, grid connection and negligible losses and it is simulated in Simulink. Simulation on a Sony i5 based laptop takes few minutes to simulate the system for 2 seconds.

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