Modeling of a Small Stand-Alone AC System with the Dynamic Models of Fuel Cells and Solar Panels

Kiran K Chedella[1], Lin Zhao[2] and Zhihao Zhang[3]
[1, 2]Dept. of Electrical & Computer Engineering, Gannon University
[3]UTC Power
[1]phone: (1) 814-384-5768 e-mail: chedella001@gannon.edu
[2]phone: (1) 814-871-5854 e-mail: zhao001@gannon.edu
[3]phone: (1) 860-727-2691 e-mail: zhihao.zhang@utcpower.com

***Abstract*—This paper presents the preliminary study of the modeling of a small stand-alone AC system with the fuel cells and solar panels as energy resources. The solar energy will be the main energy source for electricity generation during the day and will be complemented with the fuel cell when needed. The fuel cell and the battery will be responsible to meet the electricity demand during the night. The dynamic Simulink models of the fuel cell and the photovoltaic cell are implemented and the load characteristics were obtained for both. The system also includes two DC/DC converters to boost the output voltage from both the fuel cell and PV cell to 80V DC. The DC/AC PWM inverter is involved to converter DC to the standard AC voltage suitable for general household appliances. The power management strategy and the load sharing controller are the two main research jobs currently undergoing.**

I. INTRODUCTION

Renewable energy integration with electric power system is one of the major research areas to realize a "green and smart" grid. The rapid depletion of conventional energy resources along with the need to reduce the environmental impacts and the tight constraints over the construction of new transmission lines for long distance power transmission leads to the call of more alternative energy resources and their efficient utilization. Of particular interest are renewable distributed generation systems with free energy resources, such as fuel cells, wind turbines and solar photovoltaic (PV) cells [1][2][3].

The output DC voltages generated by the fuel cell and the PV cell vary in a wide range: the former (e.g. a proton exchange membrane (PEM) fuel cell) depends on the hydrogen flow rate and while the later is highly sensitive to the weather condition. Although a small power system with a single renewable energy system is possible[3][4][5], a small stand-alone power system with the combination of more than one renewable energy resource is more appealing due to the availability of the resources and the sustainable operation of the system[6][7]. The output DC voltage generated by the fuel cell and the PV cell is low in magnitude which needs to be step-up with DC-DC converters. The DC-AC inverters are required if to support ac loads [9][10]. Past research activities of the fuel cells and the PV cells for electricity generation focused either on their dynamic modeling alone [3][11][12][13] or the feasibility and the characteristics of the power system with them assumed to be operated under steady state for most of the cases[14][15][16][17][18].

The presented research work is among the first attempts to include dynamic models in the system level operation. The proposed small stand-alone system consists of two energy resources (PEM fuel cells and PV cells) and a battery as the energy storage device as shown in Fig. 1. When the solar energy is sufficiently high during the day it is used to completely meet the load demands. During nights the fuel cell operates independently supplying the required power demand of the load. When there is no sufficient solar radiation both photovoltaic system and fuel cells operate together to share the load demand. The battery is used to support this system during transients when the response of the system is not quick enough to meet the change in load demand. The dynamic models of the fuel cells and the PV cells will be considered during the system analysis and simulation. This paper presents the preliminary research results of the project including detailed dynamic models of the fuel cell and solar panel and the simulation of the system performance under specific situations. The design and implementation of the power management strategy and the controller (as noted with the red dashed line in Fig. 1) are currently undergoing.

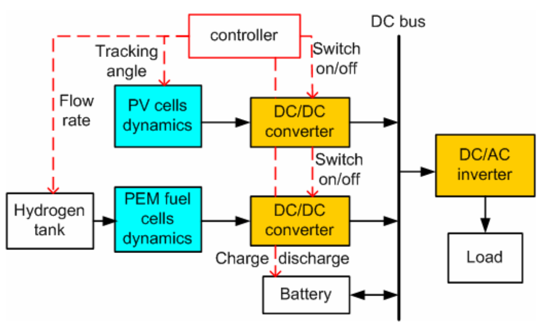

Fig. 1. proposed small stand-alone power system with fuel cells and solar panel

II. SIMULINK DYNAMIC MODEL OF PEM FUEL CELL

The proton exchange membrane (PEM) fuel cell also known as the solid polymer fuel cell was first developed by General Electric (USA) in 1960s for use by NASA. It basically requires hydrogen as fuel and oxygen from ambient air [3]. The fuel cell cannot immediately respond to changes in load because of their slow internal electrochemical reactions, so a battery is required to meet the load demand during transient state. Fuel cell output voltage and power are influenced by the electrochemical and physical properties of fuel cell, such as the capacitance of double layer charge effect, mass diffusion, material conservation, thermodynamics and voltage drops inside the cell.

In this a paper a dynamic model of PEM fuel cell is adopted [3] with the complete full cell voltage equation given as follows

$$V_{fc} = E - V_{act} - V_{conc} - V_{ohm} \quad (1)$$

$$E = E_0 + \frac{RT}{2F}\ln\frac{P_{H_2}\sqrt{P_{O_2}}}{P_{H_2O}} \quad (2)$$

In (1) the activation polarization loss is dominant at the low current density and can be described by the Tafel equation [3]:

$$V_{act} = \frac{RT}{\alpha nF}\ln\left(\frac{i_{fc}}{i_o}\right) \quad (3)$$

At high current densities, slow transportation of reactants is the main reason for the concentration voltage drop:

$$V_{conc} = \frac{RT}{nF}\ln\left(\frac{i_l}{i_l - i_{fc}}\right) \quad (4)$$

The ohmic polarization loss varies directly with current and can be expressed as

$$V_{ohm} = i_{fc}R_{\text{int}} \quad (5)$$

The effects of the thermal dynamics and internal resistance can be expressed as (6) and (7) [3] which are the relations derived from experimental measurement for specific fuel cell model.

$$T = T_0 + (T_0 - T_{ri} + T_{ci}i_{fc})(1 - e^{-t/\tau_T}) \quad (6)$$

$$R_{\text{int}} = A_R + R_0 e^{-i_{fc}/\tau_R} - B_R\ln(i_{fc}) \quad (7)$$

The symbols are defined as follows,
V_{fc} – the output voltage of a fuel cell;
E – the ideal equilibrium potential and can be considered as the open circuit voltage.
P_X – the corresponding partial pressure
E_0 – the ideal standard potential that is the ideal cell voltage under standard conditions such as one atmosphere and 25^0C for the cell reaction.
R – universal gas constant (8.3145 kJ/mol/K);
T – absolute temperature (K);
n – number of electrons participating and equal to 2 if hydrogen is the fuel;
F – Faraday's constant, charge carried by a mole of electrons (96485 coulombs/mol);
α – the electron transfer coefficient which must be in the range from 0 to 1.0;
i_{fc} – fuel cell current (A);
i_o – exchange current density
i_l is the limiting current at the electrode which has the lowest limiting current density
R_{int} - fuel cell internal resistance (ohm)

τ_T and τ_R – time constants
T_X, A_R, B_R and R_0 – empirical parameters [3]

The dynamic model of PEM fuel cell governed by equations (1) to (7) was implemented in Simulink environment as shown in Fig. 2. The fuel cell block represents equations (1) to (5). Equations (6) and (7) were implemented in blocks thermal dynamics and the fuel cell internal resistance respectively. Three inputs (hydrogen flow rate, oxygen/air flow rate, and the load current) and one output (output voltage) connect the fuel cell model with the rest of the system as shown in Fig. 2. Fig. 3 shows the details in the fuel cell subsystem blocks for the cell internal voltage source, the activation, ohmic and concentration voltage drops.

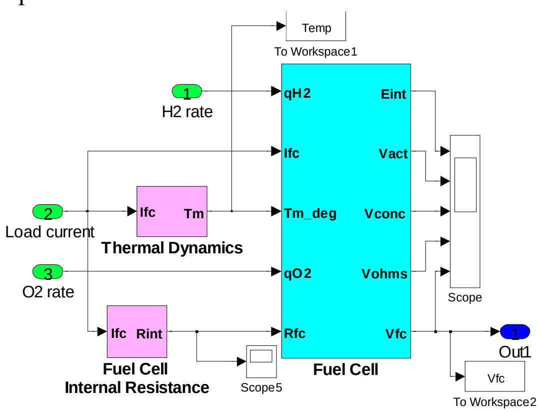

Fig. 2. Dynamic model of fuel cell implementation in Simulink

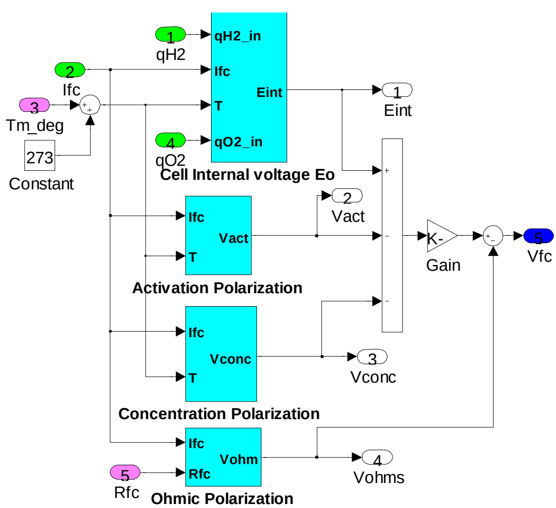

Fig. 3. Fuel cell subsystem

The load characteristics of the fuel cell based on the proposed Simulink model was illustrated in Fig. 4 where both the output voltage and the stack (load) current of the PEM fuel cell are normalized to show the general relationship between them.

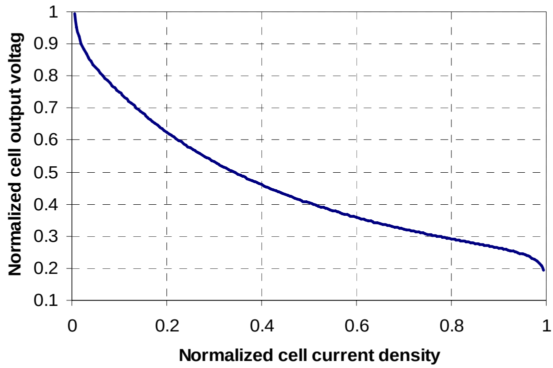

Fig. 4. normalized output characteristics of the PEM fuel cell

III. DYNAMIC MODEL OF PHOTOVOLTAIC CELL

The Simulink model for the PV cell was adopted [11] and modified to fit in the current project. The output characteristics of a PV cell can be represented by [11].

$$V_c = \frac{AkT_c}{q}\ln\left(\frac{I_{ph} + I_0 - I_c}{I_0}\right) - R_s I_c \quad (8)$$

where,
q -- charge of electron (1.602×10^{-19} C)
k -- Boltzmann constant (1.38×10^{-23} J/°K)
I_c -- cell output current (A)
I_{ph} – cell photocurrent, function of irradiation level and junction temperature (A)
I_o -- Reverse saturation current of diode
R_s --series resistance of cell (ohm)
T_c -- reference cell operating temperature (20 °C)
V_c -- cell output voltage (V)

Equation (8) is validated for specific temperature and solar irradiation level. Said so, under a new cell temperature and a new solar irradiation level, the output voltage and the cell photocurrent would become,

$$V_{c\_new} = C_{TV} C_{SV} V_c \quad (9)$$

$$I_{ph\_new} = C_{TI} C_{SI} I_{ph} \quad (10)$$

where, C_{TV}, C_{SV}, C_{TI} and C_{SI} are correction coefficients whose values are dependent on the cell temperature and the solar irradiation level. These coefficients take the forms of

$$C_{TV} = 1 - \beta_T \Delta T,\ C_{TI} = 1 + \frac{\gamma_T}{S_c}\Delta T$$
$$C_{SV} = 1 + \beta_T \Delta S_c,\ C_{SI} = 1 + \frac{1}{S_c}\Delta S_c \qquad (11)$$

with ΔS_c as the solar irradiation level change, ΔT as the corresponding cell temperature change, and the empirical parameters β_T and γ_T . Fig 5 display the Simulink model represent the PV cell subsystem with equation (8) and Fig. 6 shows the details in the PV subsystem block representing (9)-(11).

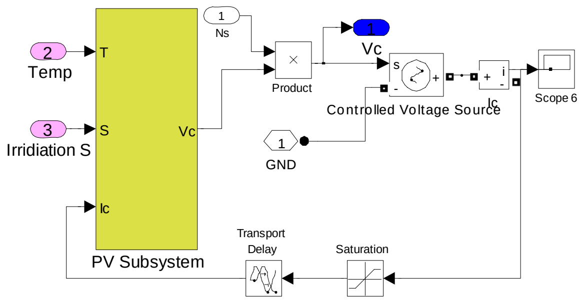

Fig. 5. PV cell system

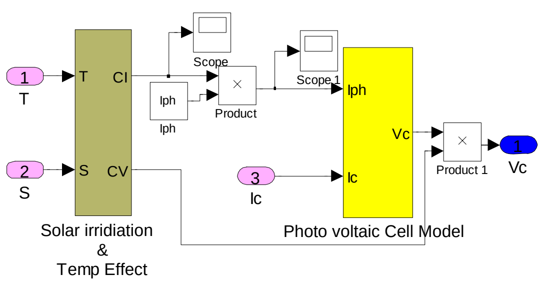

Fig. 6. Solar irradiation level and temperature effect represented by equations (9)-(11)

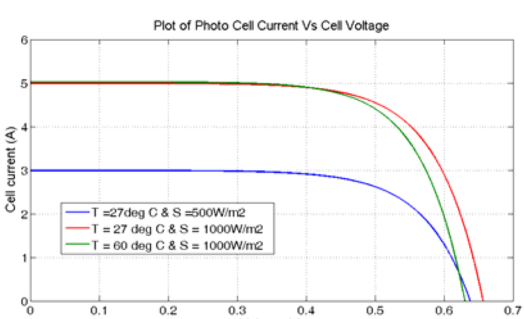

Fig. 7. PV cell load characteristics under different irradiance levels and temperature

Fig. 7 provides the output characteristics of a single PV cell under different solar irradiation levels and different temperature. The nonlinearity at cell high voltage range is evidenced.

IV. OVERALL SYSTEM SIMULATION

The overall system was shown in Fig. 8 with the main components represented as blocks. Two DC/DC converters boost the output voltage of fuel cell module (47 cells) and the PV module (72 cells) to 80V. Each module is protected from the backflow current with a diode. The 80V DC bus is connected with a PWM inverter (three legs/six pulses) to get balanced three-phase. Filters are installed to deal with the harmonics and the three-phase transformer is for isolation purpose. With the power management controller not in place currently, manual adjustment is involved to assign the load sharing. Fig. 9 displays the waveform of the three-phase load voltage.

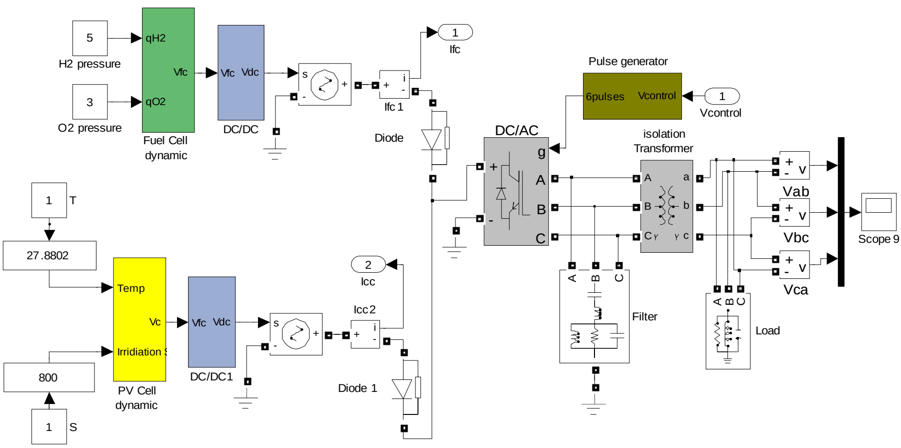

Fig. 8. Overall model of a small stand-alone AC system

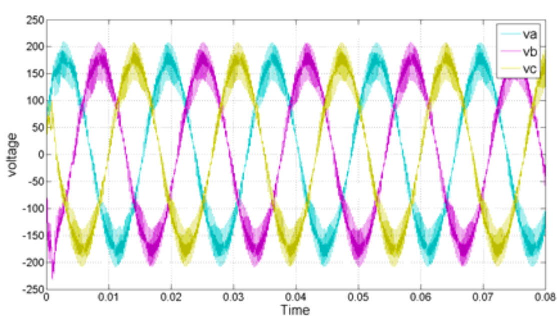

Fig. 9. Output three-phase voltage waveform

V. DISCUSSIONS

The model of a small stand-alone AC system with fuel cell and solar panel was implemented and simulated with Simulink. The preliminary result shows the feasibility of including dynamic models of the renewable energy resources in the analysis of the system performance. The research of the power management strategy and controller is currently undergoing. It will monitor the availability of the renewable energy to determine the switching on or off of the resources to balance the supply and demanding. When both energy resources are involved in electricity generation at the same time, the controller will determine the load share. The controller also can control the angle of the PV cells to track the sun and the flow rate of the hydrogen to meet the power needs.

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