Modelling and Control of Grid Connected Fuel Cell System

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Abstract - *As the demand for energy consumption rises, there is need to find alternative means of generation to supplement conventional existing generation facilities. In this regard, distributed generation (DG) will continue to play a critical role in the energy supply demand realm. The common technologies available as DG are micro-turbines, solar photovoltaic systems, fuel cells stack and wind energy systems. In this paper, a dynamic model of solid oxide fuel cell (SOFC) is presented. Fuel cells operate at low voltages and hence need to be boosted and inverted in order to be connected to the utility grid. The interconnection of the SOFC with a DC-DC converter and a DC-AC inverter for interfacing with the grid is presented in this thesis. These models are built in MATLAB/Simulink. The characteristics of grid connected fuel cell system are analyzed and simulation is done under different load conditions.*
The characteristics of the system are then compared with and without fuel cell system under different load conditions. The comparison is also done when the grid voltage is variable. In that case fuel cell connected system gives better voltage regulation as compared to without fuel cell connected to the system.

Key Words: Solid oxide fuel cell; distributed generation; grid integration; voltage regulation; inverter.

1.INTRODUCTION

Today, new advances in power generation technologies and new environmental regulations encourage a significant increase of distributed generation resources around the world. Distributed generation systems (DGS) have mainly been used as a standby power source for critical businesses. For example, most hospitals and office buildings had stand-by diesel generators as an emergency power source for use only during outages. However, the diesel generators were not inherently cost-effective, and produce noise and exhaust that would be objectionable on anything except for an emergency basis. On the other hand, environmental-friendly distributed generation systems such as fuel cells, micro turbines, biomass, wind turbines, hydro turbines or photovoltaic arrays can be a solution to meet both the increasing demand of electric power and environmental regulations due to green house gas emission [1]-[4]. Fuel cells are also well used for distributed generation applications, and can essentially be described as batteries which never become discharged as long as hydrogen and oxygen are continuously provided.

The hydrogen can be supplied directly, or indirectly produced by reformer from fuels such as natural gas, alcohols, or gasoline. Each unit ranges in size from 1-250 kW or larger MW size. Even if they offer high efficiency and low emissions, today's costs are high. Phosphoric acid fuel cell is commercially available in the range of the 200 kW, while solid oxide and molten carbonate fuel cells are in a pre-commercial stage of development. The possibility of using gasoline as a fuel for cells has resulted in a major development effort by the automotive companies. The recent research work about the fuel cells is focused towards the polymer electrolyte membrane (PEM) fuel cells. Fuel cells in sizes greater than 200 k, hold promise beyond 2015, but residential size fuel cells are unlikely to have any significant market impact any time soon [5-6].

2. LITERATURE SURVEY

The fuel cell is a fast growing technology and much research has been going on in this decade. Fuel cells are gaining much attention because of their light weight, compact size, low maintenance, and low acoustic and chemical emissions. They can serve as a potential source for electric power generation for stand-alone as well as for grid-tied applications. Reference [7] provides a basic approach for fuel cell modeling suitable for distributed generation. A model for the proton exchange membrane fuel cell (PEMFC) has been developed by various researchers in [8]-[10] taking its thermodynamic effect into consideration. References [11]-[15] provide the solid oxide fuel cell (SOFC) model taking the temperature effect into account. Hall and Colclaser [11] did not consider the dynamics of the chemical species. Achenbach [12] developed a mathematical model of a planar SOFC which concentrated on the effects of temperature changes on the output voltage response. The same author investigated the transient behavior of a stand-alone SOFC caused by a load change in [13]. A non-linear dynamic model of the SOFC that can be used for dynamic and transient stability studies was developed in [14]. A physically based model for tubular SOFC was developed in [15]. Simplified models of the SOFC have been presented in [16]-[21] considering constant cell temperature. Direct reforming molten carbonate fuel cell (MCFC) stack was developed in [22]-[23]. Fuel cells operate at low DC voltages and hence need to be boosted with the help of a DC-DC converter. Various topologies such as the H-bridge series resonant buck and boost converters have been presented in [24]. The

advantage of the H-bridge resonant converter is its inherited short-circuits protection and no saturation problem of the transformer. These converters provide dc isolation for the inverter. Buck and boost converters can be used if isolation is not required and the voltage conversion ratio is not high. These converters are known as non-isolated DC-DC converters. A current fed push-pull converter has been presented in [25]. This topology decreases the conduction losses in the switches due to the low fuel cell voltage. An interleaved front-end boost converter has been discussed in [26]. This topology considerably reduces the current ripple flowing into the fuel cell. A dual loop control strategy (current and voltage loop) has been used for the interleaved converter. A Z-source converter has been introduced in [27]. This is a new concept in which a shoot-through vector directly steps up the DC source voltage without using a boost DC-DC converter. The boost voltage rate depends on the total duration of the shoot-through zero vectors over one switching period [27].

3. THE FUEL CELL SYSTEM

A fuel cell is an electrochemical device that converts the chemical energy of the fuel (hydrogen) into electrical energy. It is centered on a chemical reaction between the fuel and the oxidant (generally oxygen) to produce electricity where water and heat are byproducts. This conversion of the fuel into energy takes place without combustion. Generally, efficiency of the fuel cells ranges from 40-60% and can be improved to 80-90% in cogeneration applications. The waste heat produced by the lower temperature cells is undesirable since it cannot be used for any application and thus limits the efficiency of the system. The higher temperature fuel cells have higher efficiency since the heat produced can be used for heating purposes.

Operating Principle.

The structure and the functioning of a fuel cell is similar to that of a battery except that the fuel can be continuously fed into the cell. The cell consists of two electrodes, anode (negative electrode) and cathode (positive electrode) separated by an electrolyte. Fuel is fed into the anode where electrochemical oxidation takes place and the oxidant is fed into the cathode where electrochemical reduction takes place to produce electric current and water is the primary product of the cell reaction. Figure 1 shows the flows of reactants in a simplified fuel cell.
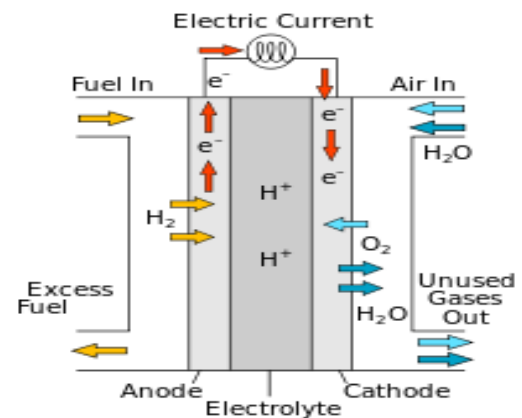

Fig.1. Schematic of an individual fuel cell.

The hydrogen which enters the anode side is broken into hydrogen ions and electrons with the help of the catalyst. In case of lower temperature cells like the PEMFC and the PAFC, the hydrogen ions move through the electrolyte and the electrons flow through the external circuit. The oxygen which enters through the cathode side combines with these hydrogen ions and electrons to form water as shown in the above figure. As this water is removed, more ions are passed through the electrolyte to continue the reaction which results in further power production. In the SOFC, it is not the hydrogen ions which move through the electrolyte, but the oxygen radicals. In case of MCFC, carbon dioxide combines with the oxygen and electrons to form carbonate ions, which are transmitted through the electrolyte. Fuel cells are classified based on the type of electrolyte used. A solid polymer membrane electrolyte is fitted between two platinum catalyzed porous electrodes for PEM fuel cells. MCFCs have a liquid lithium-potassium or lithium-sodium based electrolyte while SOFCs employ a solid yittra-stablized zirconia ceramic electrolyte. The catalyst used for SOFC and MCFC are perovsikites and nickel, respectively, the cost of which is comparatively lower than that used for PEMFC. The typical anode and cathode reactions for a hydrogen fuel cell are given by Equations (1) and (2), respectively.

$$H_2 \longrightarrow 2H^+ + 2e^- \tag{1}$$

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \longrightarrow H_2O \tag{2}$$
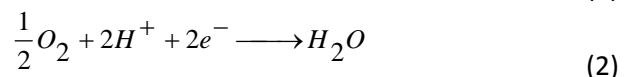
An individual fuel cell produces less than a volt of electric potential. A large number of cells are stacked on top of each other and connected in series (with bipolar connects) to produce higher voltages. Figure 2 shows cell stacks which consists of repeating units, each comprising an anode, cathode, electrolyte and a bipolar separator plate. The number of cells depends on the desired power output.
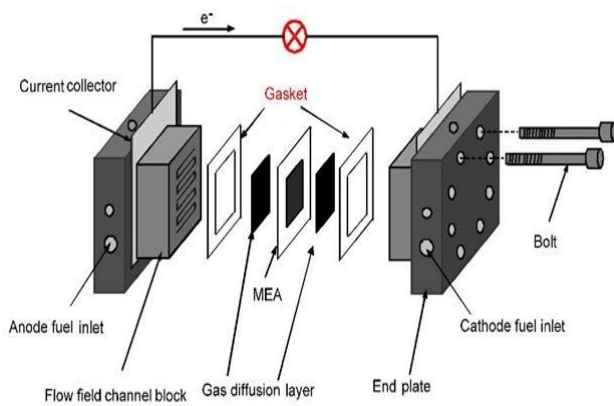
g. 2. Components of Fuel cell stack.

The chemical energy of the fuel cell is defined by enthalpy of formation and Gibbs free energy. Gibbs free energy is the energy available to do external work which involves moving electrons around an external circuit. Enthalpy of formation is the sum of Gibbs free energy and the energy connected with entropy. In fuel cells, change in Gibbs free energy of formation (ΔGf) is considered, as this change is responsible for the energy released. This change is the difference between the free energy of the products and the reactants, as shown in Equation (3).

$$\Delta G_f = G_f \text{ products - } G_f \text{ reactance} \qquad (3)$$

These quantities can be expressed in their 'per mole' form to make the comparisons easier. They are indicated by – over the lower case letter (gf) which is given by Equation (4).

$$\Delta g_f = g_f \text{ products} - g_f \text{ reactance} \qquad (4)$$

For the hydrogen fuel cell, two electrons pass through the external circuit for each water molecule produced and each molecule of hydrogen used, as given in Equation (1). In a lossless system, electrical work done is equal to the change in Gibbs free energy. Further, electrical work done to move a charge of 2F (to move two electrons) for a voltage of E is given by Equation (5).

Electrical work done = -2FE joules   (5)

Therefore E can be written as shown in Equation (6). This voltage is the open circuit voltage of the fuel cell.

$$E = -\frac{\Delta g_f}{2F} \qquad (6)$$

Consider a general reaction given as jJ + kK → mM, where j moles of J and k moles of K react with each other to produce m moles of M. These reactants and products have an activity (a) associated with them. This activity is the ratio of the partial pressure of the gas and the standard pressure. Hence Gibbs free energy can be written as shown in the Equation (7) . $\Delta gf0$ is the change in the Gibbs free energy of formation at standard pressure.

$$\Delta g_f = \Delta g_f{}^0 - RT \ln\left(\frac{a_j^j . a_k^k}{a_M^m}\right) \qquad (7)$$

Equation (7) can be applied to a typical hydrogen fuel cell reaction, where the reactants are hydrogen and oxygen and the product is water. Since activity is the pressure of the gas to its standard pressure, activity can be replaced by pressure in Equation (7). Further, the standard pressure is considered to be unity. Hence, Equations (6) and (7) can be combined together to obtain an equation for voltage as shown in Equation (8), also known as the Nernst equation.

$$E = -\Delta g_f{}^0 / 2F + RT \ln\left(\frac{p_{H2} . p_{02}^{1/2}}{p_{H20}}\right) \qquad (8)$$

4. IMPLEMENTATION AND SIMULATION RESULTS

4.1   System Modelling

The fuel cell stack is connected to the DC-DC converter to boost the DC voltage to connect it to the utility grid via the DC-AC inverter. The fuel cell, DC-DC converter and DC-AC inverter are modeled in MATLAB/Simulink R2015a. Figure 3 shows the block diagram representation of the fuel cell system connected to the utility grid through the transformer and the coupling reactance.
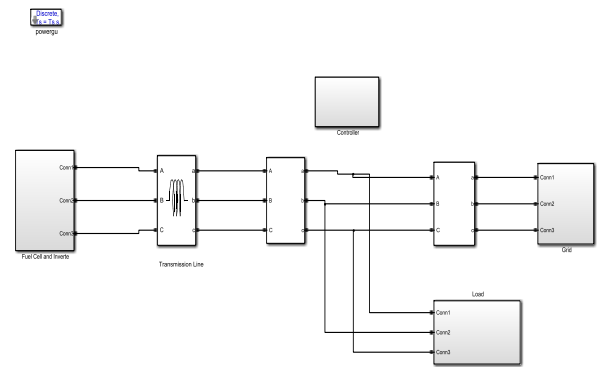

Fig. 3 Grid connected fuel cell system.

The following assumptions have been made in this system:
- The three phase transmission line has been considered to be ideal.
- Reactive power is assumed to be zero (Q).
- Switching losses of the inverter are neglected.

The following constraints have been made for simulating the fuel cell power system:
- The Line-line rms voltage across the inverter constraint is given by Inequality (1). The relationship between the inverter and the transformer voltage is expressed by Equation (9).

$$V_{LLrmsi} \leq \frac{V_0}{\sqrt{2}} \qquad (9)$$

- The maximum fuel cell stack power is limited to 400 kW and it loses stability for any reference power beyond this limit. Higher reference power can be

commanded by either increasing the number of cells, increasing the standard potential or by decreasing the internal resistance of the fuel cell. The simulations corresponding to the breakdown of the fuel cell can be seen in the results section. The maximum stack power is given by Inequality (10).

$$P_{fc\,max} \leq 400kW \qquad (10)$$

- When the reactive power is considered to be zero, the power flow equation is reduced to Equation (11).

$$V_{LLrmsi} = V_{LLrmsi}\cos(\phi_i) \qquad (11)$$

4.2 Simulation Results

The MATLAB/Simulink model of fuel cell connected with the grid is subjected with two perturbations. These are:

- Sag in the grid voltage between time 2.5 sec to 3 sec.
- Change in load at 4 sec.

These two cases will be discussed in the following sub sections.

Sag in grid voltage between 2.5 sec. to 3sec.

For analyzing the grid connected fuel cell system the system is subjected with different perturbations. One of these is sag in the grid voltage. Practically the sag is due to sudden increase in load or due to tripping of any generating station. The voltage dip or sag can affect the system in harmful manner, so it has to be treated accordingly. In this simulation, we have subjected the sag in the grid voltage by changing the grid voltage between time 2.5 sec. to 3 sec. The waveform is shown in figure 4.
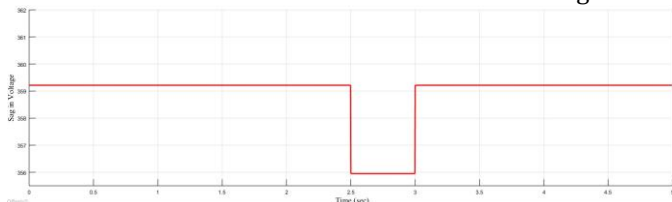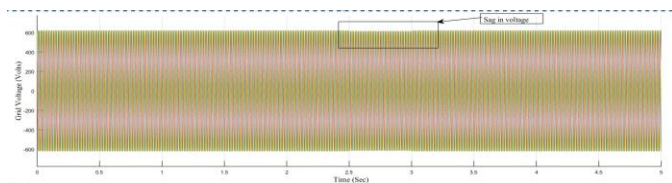

Fig. 4. Sag in grid voltage waveform

Fig.5. Three phase voltage waveform.

Figure 5 shows the waveform of the three phase grid voltage. The change in the three phase grid voltage is visible in the rectangular block inn the figure 5. As the fuel cell system is connected to the grid there is almost negligible change in the three phase grid voltage.

The one of the main aim of this work is to maintain the output voltage across the load. Fuel cell connected grid system does this efficiently and it is shown in the fig.6. From the figure it can be seen that voltage across the load

is almost constant throughout the simulation. The slightest change in output voltage is seen in the figure which can be neglected; otherwise the voltage across the load is constant.
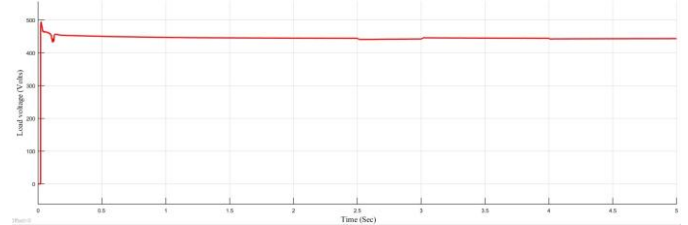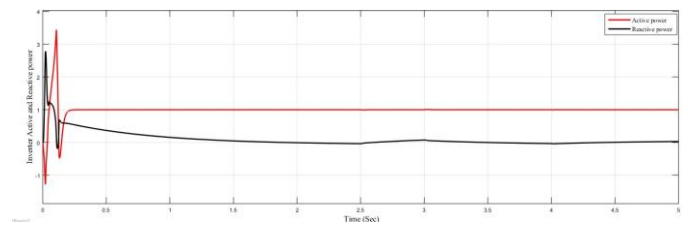

Fig. 6. Voltage across load.

Fig. 7 Active and reactive power to the load.

The figure 7 shows the active and reactive power drawn by the load. Red line shows the active power in kW and reactive power in black line in KVar. As the load is constant and resistive, so there is no change in the active power. As the voltage is dependent on reactive power as mentioned in previous chapter, the voltage dip will cause in the change in reactive power. At 2.5 sec, there is change in the voltage level, to overcome this; the system will draw more reactive power. After the dip is cleared the reactive power requirement will be as it was before time 2.5 sec.
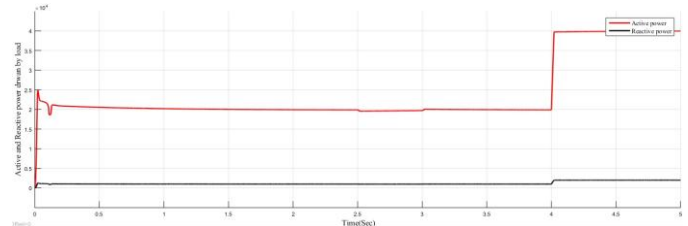
Load increment at time 4 second.

Fig. 8. Active and reactive power drawn from the grid.

5. CONCLUSIONS

A dynamic model of the solid oxide fuel cell (SOFC) was developed in MATLAB 2015 Ra. A DC-DC buck-boost converter topology and its closed loop control feedback system have been built. A three phase inverter has been modeled and connected between the SOFC-DC-DC system on the one side and the utility grid. A control strategy for the inverter switching signals has been discussed and modeled successfully. The fuel cell, the converter and the inverter characteristics were obtained for a reference real power and reactive power. The response of the fuel cell stack power is compared with two perturbations are applied to the system. One at 2.5 sec. with voltage sag in the

grid voltage and other at 4 sec. with load change with both active and reactive power requirement changed.

The interconnection of the fuel cell with the converter boosts the stack voltages and also regulates it for continuous current. The fuel cell stack voltage drops to zero for discontinuous current and the system shuts down. The fuel cell unit shuts off for real power above the maximum limit. The inverter control scheme uses a decoupled PQ control strategy to control the phase angle of the inverter and the voltage across the load. The characteristics for the system have been obtained. The grid and inverter power waveforms have been plotted. The L-L rms voltage measured from the system is compared with the value obtained from the reactive control. The measured voltage oscillates with the average value being equal to that obtained from the control.

The power characteristics of the system have been plotted. A comparison has been made between the response of the fuel cell power, DC-DC converter power and the real power injection into the utility grid. The power conditioning unit improved the slow response of the fuel cell. The response time has been further improved with the three phase inverter connection to the SOFC-DC-DC system.

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