Distributed Generation Applications: Polymer Solid Oxide Fuel Cells Systems

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***Abstract* - The ever-increasing need for electrical power generation, steady progress in the power deregulation and utility restructuring, and tight constraints over the construction of new transmission lines for long distance power transmission have created increased interest in distributed power generation. DG sources are normally placed close to consumption centres and are added mostly at the distribution level. They are relatively small in size and modular in structure. These DG devices can be strategically placed in power systems for grid reinforcement, reducing power losses and on-peak operating costs, improving voltage profiles and load factors, deferring or eliminating the need for system upgrades, and improving system integrity, reliability and efficiency.**

The term "alternative energy" is referred to the energy produced in an environmentally friendly way (different from conventional means, i.e., through fossil-fuel power plants, nuclear power plants and hydropower plants). Alternative energy considered in this dissertation is either renewable or with high energy conversion efficiency. There is a broad range of energy sources that can be classified as alternative energy such as solar, wind, hydrogen (fuel cell), biomass, and geothermal energy. Fuel cells (FCs) are static energy conversion devices that convert the chemical energy of fuel directly into DC electrical energy. Fuel cells have a wide variety of potential applications including micro-power, auxiliary power, transportation power, stationary power for buildings and other distributed generation applications, and central power.

Fuel cell systems have high energy efficiency: The efficiency of low temperature proton exchange membrane (PEM) fuel cells is around 35-45%. High temperature solid oxide fuel cells (SOFC) can have efficiency as high as 65%. The overall efficiency of an SOFC based combined-cycle system can even reach 70%. Renewable energy and fuel cell systems are environmental friendly: From these systems, there is zero or low emission(of pollutant gases) that cause acid rain, urban smog and other health problems; and, therefore, there is no environmental clean-up or waste disposal cost associated with them. In this paper we should be bringing up how it is useful to make DG available using high temperature solid oxide fuel cells.

Keywords -Distributed Power Generation, Alternative Energy, Renewable energy, Polymer Electrolyte Membrane Fuel Cells, Proton Exchange Membrane, Solid Oxide Fuel Cells.

I. INTRODUCTION

In a typical fuel cell,fuel is fed continuously to the anode and oxidant is fedcontinuously to the cathode. The electrochemical reactions take place at the electrodes toconvert chemical energy into electricity. Note that anode is the electrode from which Electronsleave (negative) and cathode is the electrode to which the electrons are coming(positive).The most common used fuel for fuel cells is hydrogen, and the oxidant isusuallyoxygen or air. Nevertheless, theoretically, any substance capable of chemicaloxidation that can be supplied continuously (as a fluid) can be used as fuel at the anode ofa fuel cell. Similarly, the oxidant can be any fluid that can be reduced at a sufficient rate.

Among different types of fuel cells, SOFC, PEMFC and MCFC are most likely to beused for distributed generation (DG) applications. Comparedwith conventional power plants, these Fuel Cell Distributed Generation systems have many advantages such as highefficiency, zero or low emission (of pollutant gases) and flexible modular structure. An overview is given on the operating principles solid oxidefuel cells. SOFC is a high temperature fuel cell technology with a promising future.Based on a negative-ion conductive electrolyte, SOFCs operate between 600 C and 1000C, and convert chemical energy into electricity at high efficiency, which can reach up to65%. The overall efficiency of an integrated SOFC-combustion turbine system caneven reach 70%. Despite slow start-up and more thermal stresses due to the highoperating temperature, SOFC allows for internal reforming of gaseous fuel inside the fuelcell, which gives multi-fuel capability to SOFCs. Moreover, their solidnature simplifies system designs, where the corrosion and management problems relatedto liquid electrolyte areeliminated give SOFC a bright future to beused in stationary applications. Figure 1 shows a block diagram of a SOFC. The actions at the anode and cathode are also given in the figure 1.

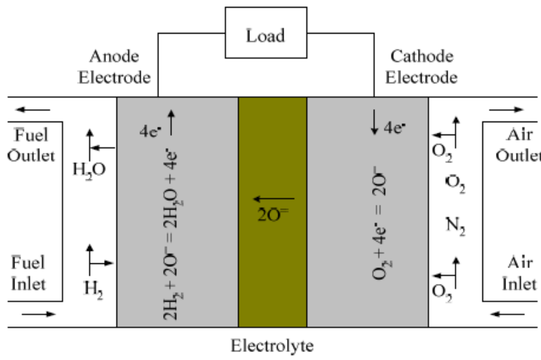

Fig 1: Schematic diagram of a SOFC.

The steady-state terminal V-I curves of a 5kW SOFC model at different temperatures, which are typical of SOFCs, are shownin Figure 2. The activation voltage drop dominates the voltage drop in thelow-current region. As load current increases, the ohmicvoltage drop increases fast andbecomes the main contribution to the SOFC voltage drop. When load current exceeds acertain value, fuel cell output voltage will drop sharply due to the concentration voltagedrop inside SOFC. Figure 2 also shows the effect of temperature on SOFC V-Icharacteristic curve. SOFC output voltage is higher at lower temperature in the lowcurrent zone while the voltage is higher at higher temperature in the high current region.

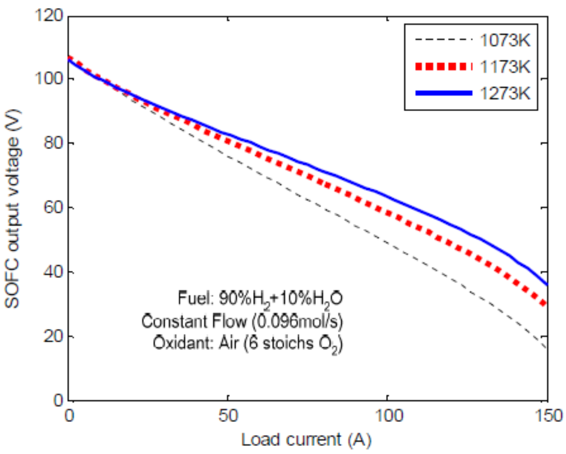

Fig 2: V-I characteristic of a 5kW SOFC stack

II. DYNAMIC MODELS FOR SOFC

Solid oxide fuel cells are advanced electrochemical energy conversion devicesoperating at a high temperature, converting the chemical energy of fuel into electricenergy at high efficiency. They have many advantages over conventional power plantsand show great promise in stationary power generation applications. Theenergy conversion efficiency of a SOFC stack can reach up to 65%, and its overallefficiency, when used in combined heat and power (CHP) applications, i.e., as anintegrated SOFC-combustion turbine system, can even reach 70%. Despite slowstart-up and thermal stresses due to the high operating temperature, SOFC allows forinternal reforming of gaseous fuel inside the fuel cell, which gives its multi-fuelcapability.SOFC modelling is of interest for its performance prediction and controller design.Many SOFC models have been developed; some are highly theoretical and are based onempirical equations, and some are more application oriented. Increased interest in SOFC power plant design and control has led to aneed for appropriate application oriented SOFC models. An integrated SOFC plantdynamic model for power system simulation (PSS) software withthree operation limits of SOFC power plants were addressed in paper in order toachieve a safe and durable cell operation. However, the thermodynamic properties ofSOFCs were not discussed in this paper. A transient model of a tubular SOFC consistingof an electrochemical model and a thermal model is given. However, thedynamic response of the model due to load variations was only investigated in large(minute) time scale.A dynamic model of a tubular SOFC stack is presented based on its thermodynamics and electrochemical properties, and on the mass and energy conservationlaws, with emphasis on the fuel cell electrical (terminal) characteristics.

The SOFC model,implemented in MATLAB/Simulink®, mainly consists of an electrochemical sub-modeland a thermodynamic sub-model. The double-layer charging effect is also takeninto account in the model. The model responses are studied under both constant fuel flowand constant fuel utilization operating modes. The effect of temperature on thesteady-state V-I (output voltage vs. current) and P-I (output power vs. current)characteristics are also studied. The dynamic responses of the model are given anddiscussed in different time scales, i.e., from small time scale (10^{-3}-10^{1} s) to large timescale (10^{2}-10^{3}s). The temperature response of the model is given as well. The SOFCmodel has been used to study the SOFC overloading capability and to investigate theperformance of a SOFC distributed generation system. The model shows the potential to be useful in SOFC related studies such asreal-time control of SOFC and its distributed generation applications.

A. Dynamic Model Development

A mathematical approach is presented for building a dynamic model fora tubular SOFC fuel cell stack. To simplify the analysis, the following assumptions aremade:

- One-dimensional treatment.
- O= conducting electrolytes and ideal gases.
- H2 fuel and large stoichiometric quantity of O2 at cathode.
- H2 and O2 partial pressure are uniformly decreased along the anode channel whilethe water vapor partial pressure is uniformly increased for normal operations.
- Lumped thermal capacitance is used in the thermodynamic analysis, and theeffective temperature of flowing gases in gas channels (anode and cathodechannels) is represented by its arithmetical mean value, Tch gas = (Tin gas-Tout gas)/2 .
- The combustion zone is not model in this SOFC thermal model. The fuel andair are assumed to be pre-heated.
- Parameters for individual cells can be lumped together to represent a fuel cellstack.

A schematic diagram of a SOFC is shown in Figure 3. Two porous electrodes(anode and cathode) are separated by a solid ceramic electrolyte. This electrolyte material(normally dense yttria-stabilized zirconia) is an excellent conductor for negativelycharged ions (such as O=) at high temperatures. At the cathode, oxygen moleculesaccept electrons from the external circuit and change to oxygen ions. These negative ionspass across the electrolyte and combine with hydrogen, at the anode, to produce water.

Effective Partial Pressures - In this part, expressions for H2, O2 and H2O partialpressures at anode and cathode channels and their effective values at actual reaction sitesare derived in terms of the fuel cell operating parameters (e.g., fuel cell temperature, fueland oxidant flow rates, and anode and cathode inlet pressures) and the physical andelectrochemical parameters of the fuel cell. These partial pressure values will be used tocalculate the fuel cell output voltage.

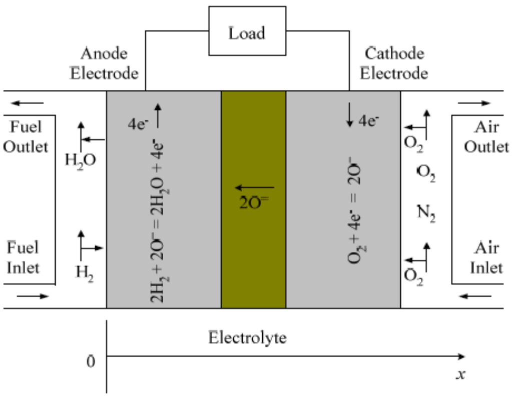

Fig 3: Schematic diagram of a solid oxide fuel cell

As shown in above Figure 3, when load current is being drawn, H_2 and O_2 will diffusethrough the porous electrodes to reach the reaction sites, and the reactant H_2O will diffuse from the reaction sites to the anode channel. As a result, H_2, H_2O and O_2 partial pressuregradients will be formed along the anode and cathode channels when the fuel cell isunder load. Assuming uniform variation of gas partial pressures, thearithmetic mean values are used to present the overall effective gas partial pressures inthe effective partial pressures of H_2 and O_2 at the actual reaction sites will be lessthan those in the gas flow channels due to mass diffusion. In contrast, the vapor partialpressure at reaction sites is higher than that in the anode flow channel. In order to calculate the fuel cell output voltage, the effective partial pressures of H_2, H_2O and O_2at the reaction sites need to be determined. In a gas mixture consisting of N species, the diffusion of component i through the porous electrodes can be described by theStefan-Maxwell formulation:

$$\nabla x_i = \frac{RT}{P} \sum_{j=1}^{N} \frac{x_i N_j - x_j N_i}{D_{i,j}}$$

Where; x_i (x_j) = Mole fractions of species i (j);
$D_{i,j}$= effective binary diffusivity of i-j pair (m^2/s);
N_i(N_j) = Superficial gas flux of species i (j) [mol/($m^2 \cdot s$)];
R = gas constant, 8.3143 J/(mol·K);
T = gas temperature (K);
P = overall pressure of the gas mixture (Pa).

In the anode channel, the gas stream is a mixture of H_2 and H_2O. In theone-dimensional transport process along the x axis, shown in Figure 3 the diffusion ofH_2can be simplified theoretically and the activation voltage drop will be zero when load current is zero. The ohmic and concentration voltage dropsare also zero when the fuel cell is not loaded (i=0). However, even the open-circuitvoltage of a SOFC is known to be less than the theoretical value given.

Ohmic Voltage Drop- The ohmic resistance of a SOFC consists mainly of theresistance of the electrolyte, electrodes and interconnection between fuel cells. In this model, only ohmic losses of electrolyte and interconnection are included while the resistance of electrodes is neglected.

Concentration Voltage Drop-During the reaction process, concentration gradients can be formed due to mass diffusion from the flow channels to the reaction sites (catalyst surfaces). The effective partial pressures of hydrogen and oxygen at the reaction site are less than those in the electrode channels, while the effective partial pressure of water at the reaction site is higher than that in the anode channel. At high current densities, slow transportation of reactants (products) to (from) the reaction site is the main reason for the concentration voltage drop.

Double-layer charging effect -In a SOFC, the two electrodes are separated by the electrolyte (Figure 3) and two boundary layers are formed, e.g. anode-electrolyte layerand electrolyte-cathode layer. These layers can be charged by polarization effect, knownas electrochemical double-layer charging effect, during normal fuel cell operation.The layers can store electrical energy and behave like a super-capacitor. The model forSOFC considering this effect can be described by the equivalent circuit shown in Figure 4.

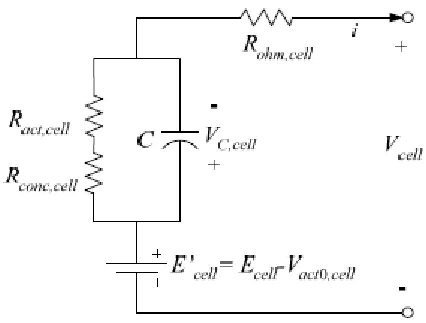

Fig 4: Equivalent electrical circuit of the double-layer charging effect inside aSOFC.

In the above circuit, $R_{ohm,cell}$, $R_{act,cell}$ and $R_{conc,cell}$are equivalent resistances of ohmicvoltage drop, activation and concentration voltage drops, which can be calculated. C is the equivalent capacitance of thedouble-layer charging effect. Since the electrodes of a SOFC are porous, the value of C islarge and can be in the order of several Farads. The voltage across C iscan be calculate the output voltage, Vout, of a SOFC stack.

Energy Balance of the Thermodynamics- The cross section profile and heat transferinside a tubular SOFC are shown in Figure 5. One advantage of thistubular structure is that it eliminates the seal problems between cells since the supporttube of each cell is closed at one end. The air is fed through a central air supplytube (AST) and forced to flow back past the interior of the cell (cathode surface) to theopen end. The fuel gas flows past the exterior of the cell (anode surface) and in paralleldirection to the air.The thermal analysis for fuel reformer and combustor are not included in this model.Heat exchanges between cells are also not considered in this model by assuming thattemperature differences between adjacent cells can be neglected. Heat transport inside thefuel cell occurs mainly by means of radiation, convection and mass flow.

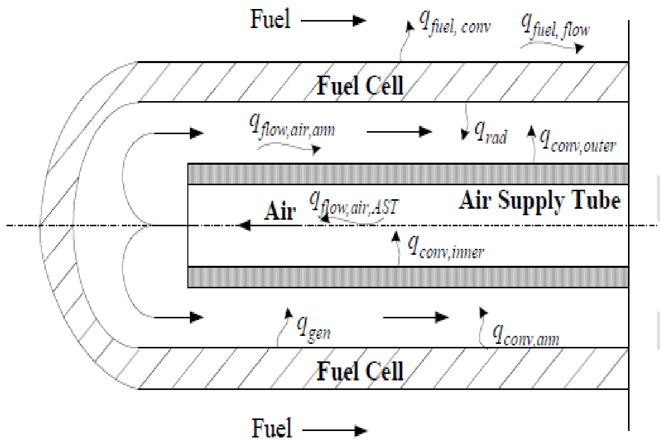

Fig 5: Heat Transfer inside a tubular solid oxide fuel cell.

B. Dynamic SOFC Model Implementation

A dynamic model for a 5kW SOFC hasbeen developed in MATLAB/Simulink, based on the electrochemical and thermodynamic136characteristics of the fuel cell discussed in the previous section. The output voltage of thefuel cell depends on conditions including fuel composition, fuel flow, oxidant flow,anode and cathode pressures, cell temperature, load current and the electrical and thermalproperties of the cell materials. Figure 6 shows the block diagram, based on which themodel has been developed. In this figure, the input quantities are anode and cathodepressures (Pa and Pc), H_2 flow rate (MH_2), H_2O flow rate (**MH_2O**), air flow rate (M_{air})and initial temperature of the fuel cell and air ($T_{fuelinlet}$ and $T_{airinlet}$). At any given loadcurrent and time, the cell temperature $T_{cell}$is determined and both the load current andtemperature are fed back to different blocks, which take part in the calculation of the fuelcell output voltage.In this block diagram, material conservation equations are used tocalculate the partial pressures of H_2, H_2O and O_2 in flow channels. Then, the Nernstequation is employed to determine the internal potential (E) of the fuel cell.Diffusion equations and the material conservation equations will give theconcentration loss of the cell. The ohmic voltage drop andactivation voltage is computed. Eventually, the terminal (output) voltage ofthe fuel cell and the double-layer charging effect are calculated. The thermal model is developed via energy balance equations (4Model Responses under Constant Fuel Flow OperationBoth the steady-state and dynamic responses of the SOFC model under constant flowoperating mode are given). The thermodynamic response of the model andthe impact of the operating temperature are also given. The dynamic responses of themodel are investigated in different time scales.

C. Model Responses under Constant Fuel Flow Operation

Both the steady-state and dynamic responses of the SOFC model under constant flow operating mode are given in this section. The thermodynamic response of the model and the impact of the operating temperature are also given. The dynamic responses of the model are investigated in different time scales.

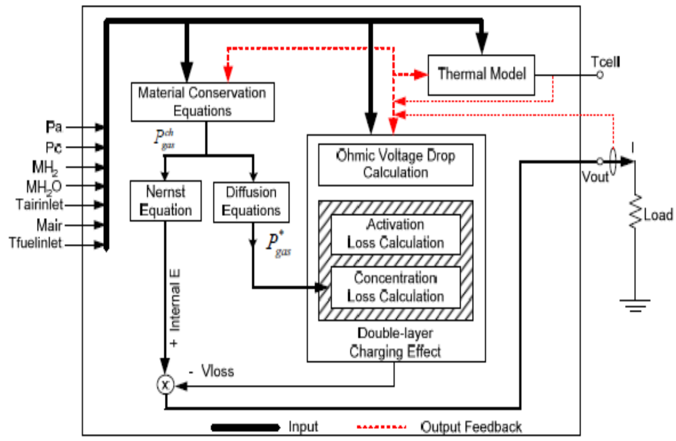

Fig 6: Diagram of building a dynamic model of SOFC in SIMULINK.

The steady-state terminal voltage vs. current (V-I)curves of the SOFC model at different temperatures are shown in Figure 7 Thesecurves are similar to the real test data reported in. The activation voltagedrop dominates the voltage drop in the low-current region. As load current increases, theohmic voltage drop increases fast and becomes the main contribution to the SOFCvoltage drop. When the load current exceeds a certain value (140A for this SOFC model)the fuel cell output voltage will drop sharply due to large ohmic and concentrationvoltage drops inside SOFC. The variations of the above three voltage drops VsLoadcurrent at three different temperatures are shown in Figure 8. .Figure 7 shows the effect of temperature on the SOFC V-I characteristic curve.The SOFC output voltage is higher at lower temperature in the low current zone while thevoltage is higher at higher temperature in the high current region. These simulationresults showing the effect of temperature on SOFC performance are also similar to thetest data. The negative temperature coefficient of theopen-circuit internal potential E0cell, and the temperature-dependentactivation voltage drop and ohmic voltage drop (shown in Figure 8) are the mainreasons for this kind of temperature dependent performance of the SOFC model. As shown in Figure 8, both the activation and ohmic voltage drops decrease as the fuelcell temperature increases.

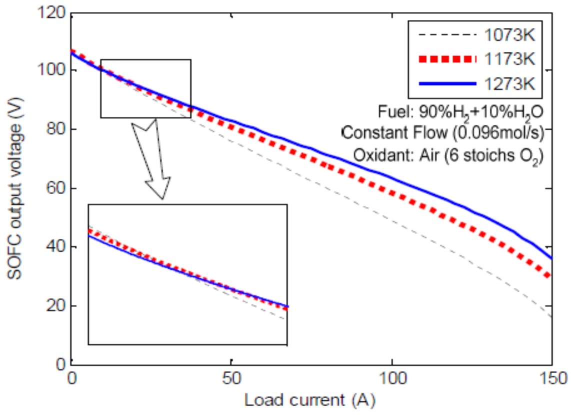

Fig 7: V-I characteristics of the SOFC model at different temperatures.

The corresponding output power vs. current (P-I) curves of the model at different temperatures are shown in Figure 4.22. At higher load currents (I > 40 A), higher output power can be achieved at higher operating temperatures. Under each operating temperature, there is a critical load current point (Icrit) where the model output power reaches its maximum value. For example, Icrit is 95 A at 1073 K, 110 A at 1173 K and 120 A at 1273 K. Beyond these points, an increase in the load current will reduce the output power due to large ohmic and concentration voltage drops.

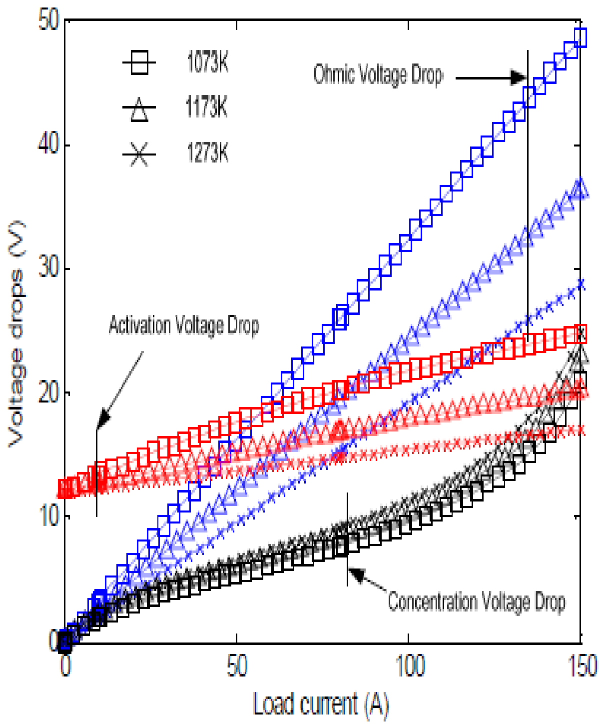

Fig 8:. Three voltage drops at different temperatures.

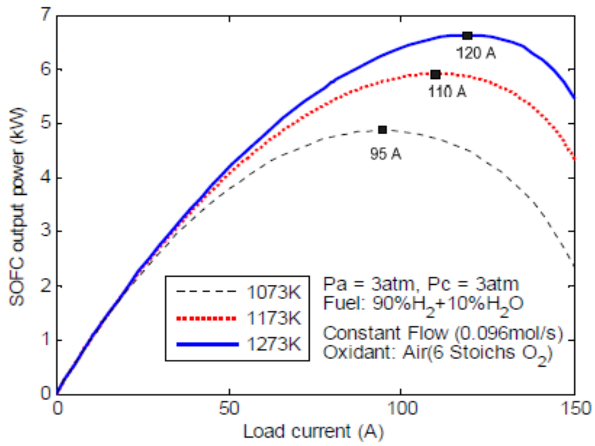

Fig 9: P-I characteristics of the SOFC model at different temperatures

Dynamic Response- The dynamic response of the SOFC model is mainly dominatedby the double-layer charging effect, the time constants Ga and Gc, and the thermodynamic property of the fuel cell. Although the capacitance (C) ofthe double-layer charging effect is large (in the order of several Farads), the time constantGdlc=(Ract,cell+Rconc,cell)C is normally small (in the order of around 10-2 s) because(Ract,cell+Rconc,cell) is small (less than 2.0 mr for a single cell used in this study) when thefuel cell works in the linear zone. Therefore, capacitor C will only affect the modeldynamic response in small time scale, i.e., 10^{-3}-10-1 s. The operating conditions of theSOFC model for this simulation study are listed in Table 1. Figure 10 shows themodel dynamic responses in this small time scale under step current changes. The loadcurrent steps up from 0 A to 80 A at 0.1s and then steps down to 30 A at 0.2 s. The lowerpart of the figure shows the corresponding SOFC output voltage responses with different capacitance values for the double-layer charging effect. When the load current steps up(down), the fuel cell output voltage drops down (rises up) immediately due to the ohmicvoltage drop. Then the voltage drops (rises) “smoothly” to its final value. It is noted thatthe larger is the capacitance C, the slower the output voltage reaches its final valuebecause the larger is the effective time constant Gdlc.

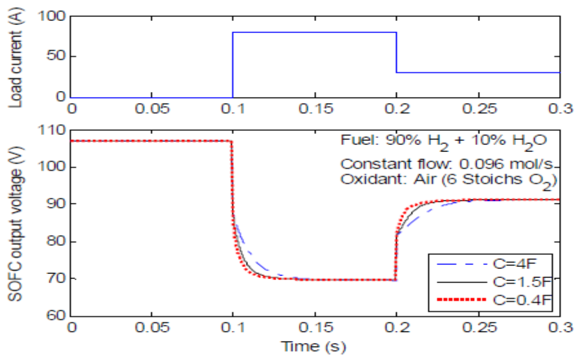

Fig 10: Model dynamic responses with different equivalent capacitance values for
double-layer charging effect in small time scale.

TABLE 1 OPERATING CONDITIONS FOR THE MODEL DYNAMIC RESPONSE STUDIES

Temperature (K)	1173
Anode input pressure (atm)	3
Cathode input pressure (atm)	3
Anode H_2 flow rate (mol/s)	0.0864
Anode H_2O flow rate (mol/s)	0.0096
Oxidant	Air (6 stoichs O_2)

Time constants Ga and Gc are in the order of 10-1-100 s for the model parameters usedin this dissertation. They mainly affect the model dynamic responses in the time scale10-1 to 101 s. Figure 11 shows the model dynamic responses in this medium time scaleunder the same type of step current changes as shown in Figure 10. The load currentsteps up from 0 A to 80 A at 1s and then steps down to 30 A at 11s. The operatingconditions of the model are the same as given in Table 1 except for the operatingpressures. Figure 11 shows the SOFC output voltage responses under differentoperating pressures (Pa = Pc = P). Higher operating pressure gives higher output voltageand also increases time constants Ga and Gc, shown in the figure.

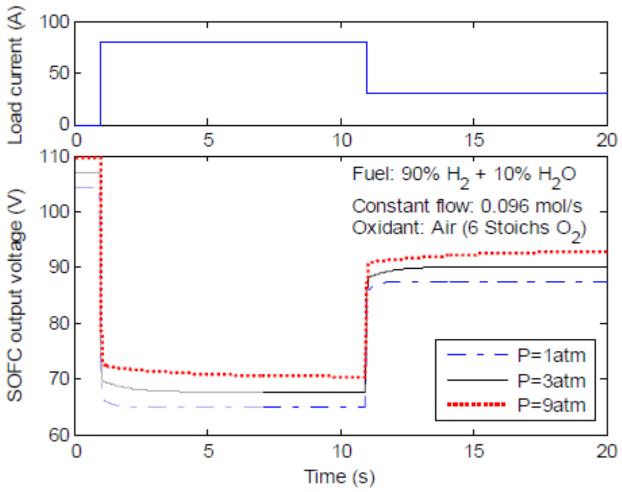

Fig 11: Model dynamic responses under different operating pressures in medium time scale.

The equivalent thermodynamic time constant of a SOFC can be in the order of tens of minutes. Thus, for large time scale (102-103 s), the thermodynamiccharacteristic will dominate the model dynamic responses. Figure 12 shows thetransient response of the SOFC model under load changes. The model was subjected to astep change in the load current from zero to 100 A at 10 min and then the current dropsback to 30 A at 120 min. The operating conditions are also the same as given in Table 4.4except for the varying fuel cell operating temperatures. The fuel and air inlettemperatures are given in the figure. When the load current steps up, the SOFC outputvoltage drops sharply, and then rises to its final value. When the load current steps down,the output voltage jumps up and then drops slowly towards its final value, as shown in Figure 12.

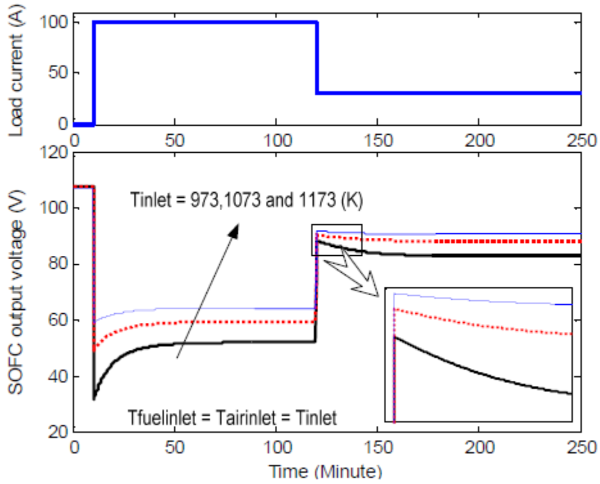

Fig 12: Model dynamic responses under different inlet temperatures in large timescale.

The corresponding temperature responses of the SOFC model are shown in Figure. From this figure, the equivalent overall thermodynamic time constant of the modelis around 15 minutes.

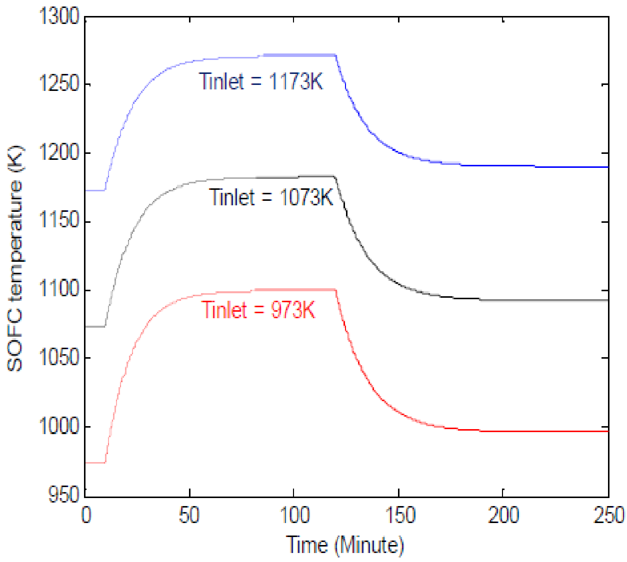

Fig 13: Model temperature responses.

D. Constant Fuel Utilization Operation

The fuel cell can also be operated in constant fuel utilization mode, in which the utilization factor will be kept constant. The direct way to achieve constant utilization operation is to feed back the loadcurrent with a proportional gain 1/(2Fxu) , as shown in Figure 13, to control fuel flow to the fuel processor. As a result, the input H_2 will change as load varies to keep the fuel utilization constant. As shown in Figure 14, the fuel processor is modelled by a simple delay transfer function is set to 5s in this research.

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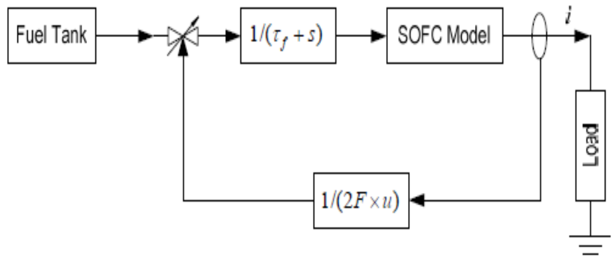

Fig 14: Constant utilization control.

The fuel cell's steady state- characteristics and dynamic responses under constant fuel utilization mode will be discussed. The results will also be compared with those obtained under constant flow operating mode. The utilization factor is set for 0.85 (85% fuel utilization) for this study and other operating conditions are the same as listed in Table1 except the fuel and water flow rates that will change as the load current changes.

Steady-state Characteristics- Figure 15 shows a comparison between the V-I characteristic of the SOFC model with constant fuel utilization and constant fuel flow operating modes. The operating conditions for the constant flow operating mode are listed in Table1. For this specific study, the output voltage under constant flow operating mode is higher than that under constant utilization mode at the same loadcurrent. The voltage difference between the two operating modes keeps getting smaller as the load current increases. The reason for this is that the utilization factor of the constant flow operation will be getting closer to the utilization factor (0.85) of the constant utilization operation as load current increases. The corresponding P-I curves, also given in Figure 15, show that the SOFC can provide more power under constant flow operation.

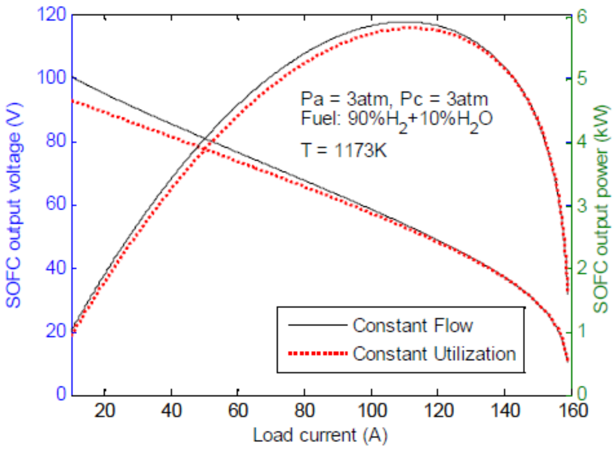

Fig 15: V-I and P-I characteristics of the SOFC model under constant fuel utilizationand constant fuel flow operating modes.

Figure 16 shows the curves of input fuel versus load current for both operation modes. It shows that the constant flow operation mode requires more fuel input, especially at light loading. But the unused H_2 is not just wasted; it can be used for other purposes or recycled to use again.

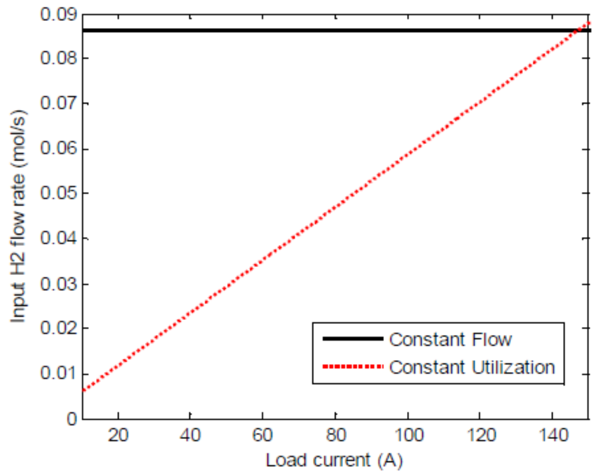

Fig 16: H_2 input for the constant utilization and constant flow operating modes.

*Dynamic responseof the SOFC model-*In small time scale is dominated by the double-layer charging effect and in large time scale is mainly determined by the thermodynamic properties of the fuel cell. Both the double-layer charging effect and the thermodynamic characteristics of the fuel cell are determined by the fuel cell's physical and electrochemical properties. These properties are normally not affected by whether the SOFC is operating under constant fuel flow mode or constant fuel utilization mode. However, the dynamic response in medium time scale will be affected by the operating mode since the fuel flow rate will change as load varies under constant utilization operating mode. This load-dependent fuel flow rate will give a load-dependent time constant Ga as well. Therefore, only the dynamic response in this time scale will be discussed for the constant utilization operating mode.

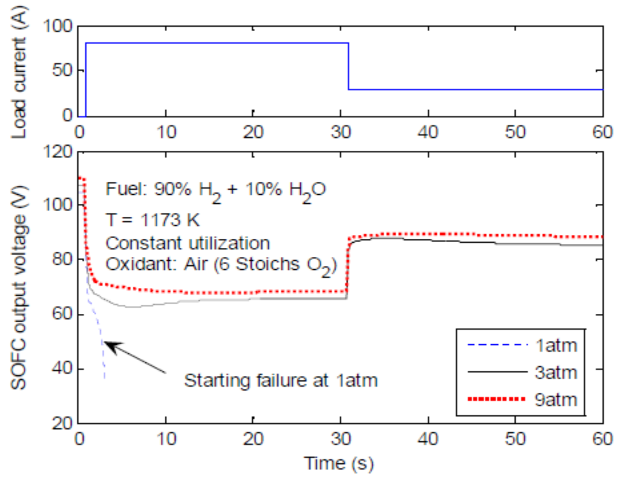

Fig 17: Model dynamic responses under different operating pressures in the medium time scale
with constant utilization operating mode

Figure 17 shows the model dynamic responses in the medium time scale under similar stepcurrent changes used in the constant fuel flow operating mode. The load current steps up from 0 A to 80 A at 1s and then steps down to 30 A at 31 s. The lower part of Figure 17 shows the corresponding SOFC output voltage responses under

different operating pressures. Similar to what is shown in Figure 11 for constant fuel flow operating mode, a higher operating pressure results in a higher output voltage and larger time constants Ga and Gc. In this case, the dynamic responses are not determined only by Ga and Gc, but also by the dynamics of the fuel processor. The output voltage curves (Figure 17) show the typical characteristic of a second order system while the dynamic responses in medium time scale for the constant flow operating mode (Figure 11) exhibit the characteristic of a first order system. Figure 17showsthat the SOFC output voltage drops as the load current steps up, undershoots, and then rises back to its final value. While the load current steps down, the voltage rises up, overshoots, and then drops back to its final value. It is note that the fuel cell fails to start up at 1 atmospheric operating pressure due to the delay in the fuel processor, which causes insufficient fuel supply.
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III. CONCLUSIONS

For a SOFC array, its configuration can be determined in a similar way. According to the SOFC V-I and P-I characteristics, when its load current is over 110 A, the SOFC stack is in the concentration zone, where its output voltage will decrease sharply as load current increases. In order to leave some safe margin, the fuel cell is operated around the point where its current is 100 A (rated operating point), and its output voltage (VSOFC) is about 55 V. Therefore, the number (Ns) of fuel cell stacks we need to connect in series to get a voltage of 220 V is 4.

The total power rating of the series connection of 4 SOFC stacks (5 kW each) is 20 kW. The number (Np) of these 20 kW SOFC units that need to be connected in parallel to compose a 40 kW fuel cell array is 8 SOFC stacks (5 kW each). Super-capacitors or battery banks are connected to the DC bus to provide storage capability and fast dynamic response to load transients. A 3-phase 6-switch inverter interfaces the DC bus with a 120/220 V AC power system. An LC filter is connected to the output of the inverter to reduce the harmonics introduced by the inverter. A 220V/12.5kV step up transformer connects the fuel cell power system to the utility grid through a coupling inductor and a short transmission line. The coupling inductor isneeded to control the real and reactive power flow between the fuel cell DG system and the utility grid and to limit disturbance and fault currents. The controllers for the boost DC/DC converters are designed to keep the DC bus voltage within an acceptable band (±5% in this study). Therefore, the input to the 3-phase inverter can be considered as a fairly good constant voltage source. The inverter controller controls the real and reactive power flows to the utility grid. P, Q power flows follow their respective reference values, which can either be set as fixed values or to follow a certain load demand.

In SOFC DG, The output voltage and current curves of each 40 kW SOFC array (input to each DC/DC converter) for the above heavy loading, when the system output power reaches its pre-set value, the fuel cell output current ripple is about 10% and the fuel cell output voltage ripple is around 3%. These relatively small variations of the current and voltage are indicative of the healthy operation of fuel cells. The DC bus voltage (output voltage of the boost DC/DC converter) is the DC bus voltage comes up to its reference value (480V) though the fuel cell terminal voltage is much lower than its no-load value under this heavy loading condition. The voltage ripple at the DC bus is about 1.5%, which is within the acceptable range.

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