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Full Length Research Paper

Control and Operation of a Solidoxide Fuel-Cell Power Plant in an Isolated system

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A dynamic model for a solid oxide fuel cell power plant has been constructed. The concept of a feasible operating area for a solid oxide fuel-cell power plant is introduced by establishing the relationship between the stack terminal voltage, fuel utilization, and stack current. By controlling the input hydrogen fuel in proportion to the stack current, constant utilization control can be accomplished. The effectiveness of the proposedschemes is illustrated through simulation.

Keywords: Distributed generation, SOFC, Load tracking.

INTRODUCTION

In Recent Years, environmental and economic considerations have resulted in much increased interest in the applicationof distributed generation (DG) (IEEE Standard, 2002), (Hatziargyriou et al., 2000). DG, such asinternal combustion engines, micro turbines, fuel cells, photovoltaic, and wind turbines are typically of 10 kW–10 MW incapacity. As these generators are to be incorporated into powersystems, their impacts on network reliability and security havecome under close scrutiny (Lee,(1998).

FUEL CELLS (FC) are modular, high-efficiency; environmentally friendly energy conversion devices that have become a promising option to replace the conventional fossil fuel- based electric power plants (Ellis, 2001). Among the several kinds of FC, the low-temperature proton exchange membrane fuel cell (PEMFC) is the most widely used type and has been commercialized for the portable, vehicular, and residential applications (Oman, 2002). However, due to the lower efficiency and the dependency on pure hydrogen as the fuel input, PEMFC has not been considered for stationary power applications.

Another kind of FC under active research is thehightemperaturesolid oxide fuel cell (SOFC). SOFC presents an attractiveoption for the DGtechnology,which generates electricity at or near the load site.The current main challenges to develop this DG technologyare to reduce the installation cost, to improve overall efficiency, and to explore the avenues of increasing the durability to more than 40 000 h for stationary power applications.

The feasibility of using FC power plant for stationary power supply has been studied by many researchers (Kyoungsoo and Rahman, 1998). In orderto ensure that the SOFC would operate successfully in a power system,

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it is necessary to examine, among other issues, its ability to perform load tracking and its impact on power quality. Central to the studies is the need to have a credible analytical model of the SOFC plant. Thus, building a suitable FC dynamic model is one important aspect in the study of SOFC DG system.An appropriate FC dynamic model should consider the electrochemical-thermodynamic process and electrical performance. A number of models for simulating FC-based power plant have been developed. Lukas *et al.* provided a nonlinear mathematical model for molten carbonate FC (MCFC) (Lukas et al., 1999). This model is, however, complex and is difficult to be implemented for power system analysis purposes. Hatziadoniu*et al.* derived a reduced-order MCFC dynamical model for dynamic stability analysis (Hatziadoniu et al., 2002). (Padullés et al., 2000) created a simulation model of a solid oxide FC (SOFC) power plant intended fora power system analysis package. Their paper shows that the electrochemical and thermodynamic process could be approximated by first-order transfer functions. Based on the results of (Padullés et al., 2000), Zhu *et al.* included the SOFC fuel processor in their investigation and used the model to study SOFC load tracking ability (Zhu and Tomsovic, Provide year).

SOLID OXIDE FUEL-CELL MODEL

A. Fuel Cell Stack Dynamic Model

The stack model will be based on the following assumptions.

- The gases are ideal.
- The stack is fed with hydrogen and air. If natural gas instead of hydrogen is used as fuel, the dynamics of the fuel processor must be included in the model, upstream ofThe hydrogen inlet, as a first-order transfer function (Kreutz and Ogden, 1998). The transfer function gain should reflect the changes in composition occurring during the process. The effect of the fuel processor in the model will be tested in the future.
- The channels that transport gases along the electrodes have a fixed volume, but their lengths are small, so that it is only necessary to define one single pressure value in their interior.
- The exhaust of each channel is via a single orifice. The ratio of pressures between the interior and exterior of the channel is large enough to consider that the orifice is choked.
- The temperature is stable at all times.
- The only source of losses is ohmic, as the working conditions of interest are not close to the upper and lower extremes of current.
- The Nernst equation can be applied.

B. Characterization of The Exhaust of The Channels

According to (Blackburn, 1960), an orifice that can be considered choked, when fed with a mixture of gases of average molar mass M (kg/kmol) and similar specific heat ratios, at aconstant temperature, meets the following characteristic:

$$\frac{W}{p_u} = K\sqrt{M} \qquad (1)$$

Where W is the mass flow (kg/s); K is the valve constant, mainly depending on the area of the orifice; P_u is the pressure upstream (inside the channel) [atm].For the particular case of the anode, the concept of fuel utilization $U_f$can be introduced, as the ratio between the fuel flow that reacts and the fuel flow injected to the stack. $U_f$is also a way to express the water molar fraction at the exhaust. According to this definition, Eq.(1). can be written as:

$$\frac{W_{an}}{p_{an}} = K_{an}\sqrt{(1-U_f)M_{H2} + U_f M_{H20}} \qquad (2)$$

Where W is the mass flow through the anode valve [kg/s]; K_{an} is the anode valve constant; M_{H2}, M_{H20} are the molecular masses of hydrogen and water, respectively [kg/kmol]; P_{an} is the pressure inside the anode channel [atm]. If it could be considered that the molar flow of any gas through the valve is proportional to its partial pressure inside the channel, according to the expressions:

$$\frac{q_{H2}}{p_{H2}} = \frac{K_{an}}{\sqrt{M_{H2}}} = K_{H2} \qquad (3)$$

and$$\frac{q_{H2O}}{p_{H2O}} = \frac{K_{an}}{\sqrt{M_{H2O}}} = K_{H2O} \qquad (4)$$

Where q_{H2}, q_{H2O} are the molar flows of hydrogen and water, respectively, through the anode valve [kmol/s];p_{H2} , p_{H2O} are the partial pressures of hydrogen and water, respectively [atm]; K_{H2} , K_{H2O} are the valve molar constants for hydrogen and water, respectively [kmol/(s atm)], the following expression would be deduced:

$$\frac{W}{p_{an}} = K_{an}[(1-U_f)\sqrt{M_{H2}} + U_f\sqrt{M_{H2O}}] \qquad (5)$$

The comparison of Eqs. (2) and (5) shows that forU_f> 70% the error is less than 7%. It is possible to redefine slightly Eqs. (3) and (4) so that the error is even lower. This error shows that it may be reasonable to use Eqs. (3) and (4). The same study for the cathode shows that the error in that valve is even lower, because of the similar molecular masses of oxygen and nitrogen.

C. Calculation of The Partial Pressures

Every individual gas will be considered separately, and the perfect gas equationwill be applied to it. Hydrogen will be considered as an example.

$$p_{H2}V_{an} = n_{H2}RT \qquad (6)$$

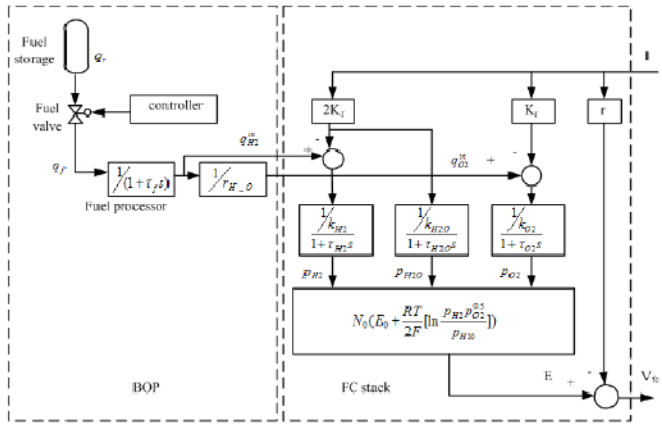

Figure 1 SOFC dynamic model

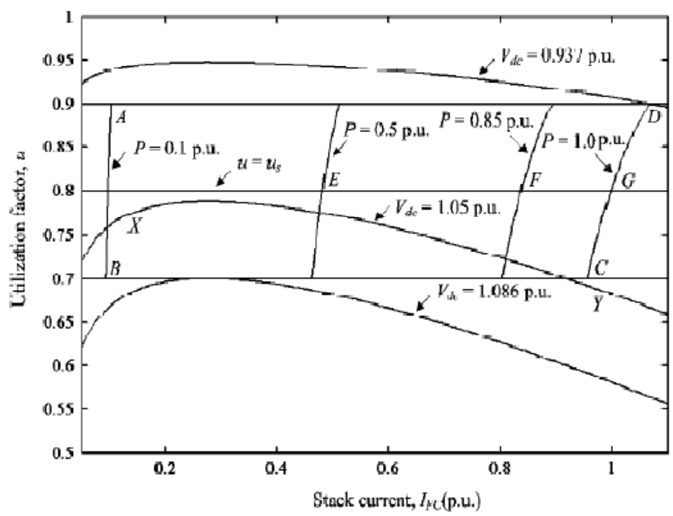

Figure 2 FeasibleOperating Area of a SOFC [10].

Where, V_{an} is the volume of the anode (Thorogood, 1995); n_{H2} is the number of hydrogen moles in the anode channel; R is the universal gas constant [l atm./(kmol K)]; T is the absolute temperature [K].It is possible to isolate the pressure and to take the time derivative of the previous expression, obtaining:

$$\frac{d}{dt} p_{H2} = \frac{RT}{V_{an}} q_{H2} \qquad (7)$$

Where, q_{H2} is the time derivative of n_{H2} , and represents the hydrogen molar flow [kmol/s]. There are three relevant contributions to the hydrogen molar flow: the input flow, the flow that takes part in the reaction and the output flow, thus:

$$\frac{d}{dt} p_{H2} = \frac{RT}{V_{an}} (q_{H2}^{in} - q_{H2}^{out} - q_{H2}^{r}) \qquad (8)$$

Where, q_{H2}^{in} is the input flow [kmol/s]; q_{H2}^{out} is the output flow [kmol/s]; q_{H2}^{r} is the hydrogen flow that reacts [kmol/s].According to the basic electrochemical relationships, the molar flow of hydrogen that reacts can be calculated as:

$$q_{H2}^{r} = \frac{N_0 I_{fc}}{2F} = 2K_r I_{fc} \qquad (9)$$

Where, N_0 is the number of cells associated in series in the stack; F is the Faraday's constant [C/kmol]; I is the stack current [A]; K is a constant defined for modeling purposes [kmol/(s A)].

Returning to the calculation of the hydrogen partial pressure, it is possible to write:

$$\frac{d}{dt} p_{H2} = \frac{RT}{V_{an}} (q_{H2}^{in} - q_{H2}^{out} - 2K_r I_i) \qquad (10)$$

Replacing the output flow by Eq. (3), taking the Laplace transform of both sides and isolating the hydrogen partial pressure, yields the following expression:

$$p_{H2} = \frac{1/K_{H2}}{1+\tau_{H2} s} (q_{H2}^{in} - 2K_r I_i) \qquad (11)$$

Where,$\tau_{H2} = (V_{an})(K_{H2} RT)$expressed in seconds, is the value of the system pole associated with the hydrogen flow.

A similar operation can be made for all the reactants and products.

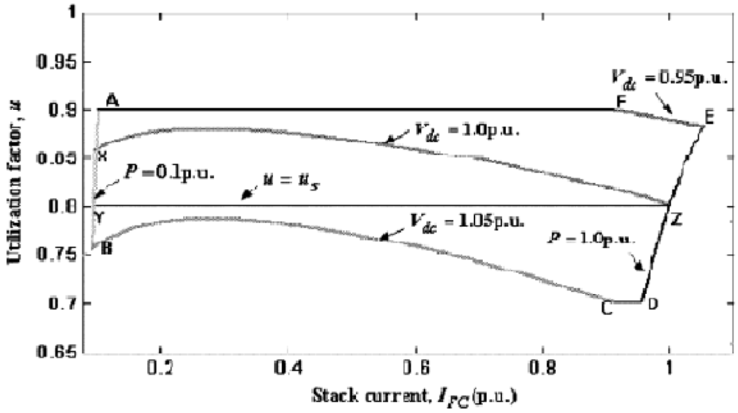

Figure 3 Constant fuel utilization and constant voltage-control schemes in the FOA [10].

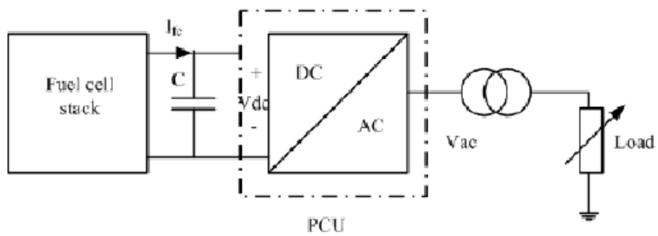

Figure 4 SOFC Power Plant in an isolated system

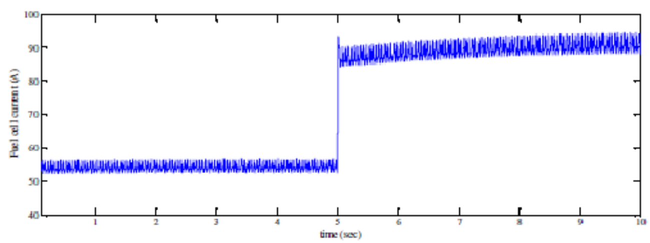

Figure5fuel cell current variation with time

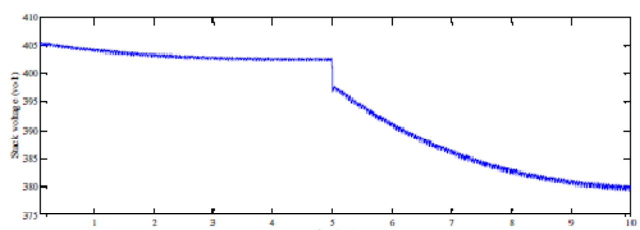

Figure6fuel cell voltage variation with time

D. Calculation of The Stack Voltage

Applying Nernst's equation and Ohm's law (to consider ohmic losses), the stack output voltage is represented by the following expression:

$$V_{fc} = N_0\left(E_0 + \frac{RT}{2F}\left[\ln\frac{p_{H2}p_{O2}^{0.5}}{p_{H2O}}\right]\right) - rI_{fc} \qquad (12)$$

Where E_0 is the voltage associated with the reaction free energy [V]; R is the same gas constant as previous, but care should be taken with the system unit [J/(kmol K)]; r describes the ohmic losses of the stack [Ω].

By including the function of the fuel processor, an SOFC power plant dynamic model based on (Padullés et al., 2000) and (Zhu and Tomsovic, Provide year) is

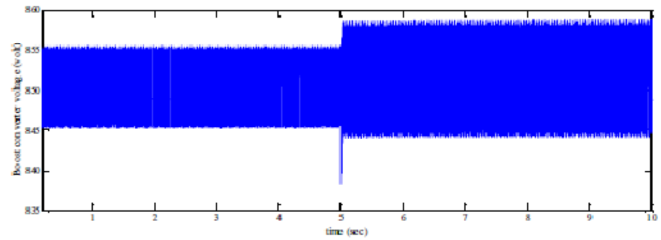

Figure7 Boost converter voltage variation with time

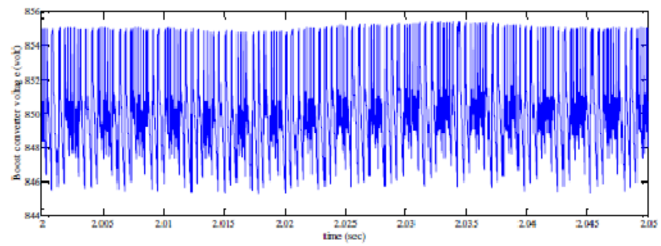

Figure8 Boost converter voltage variation with time(zoomed version)

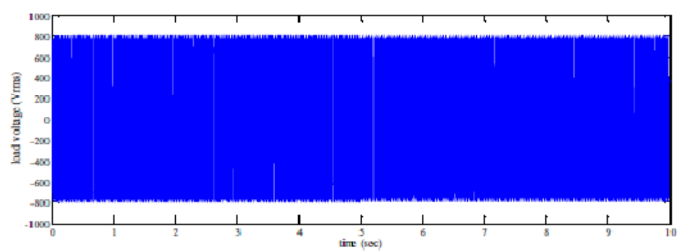

Figure9 Load voltage variation with time

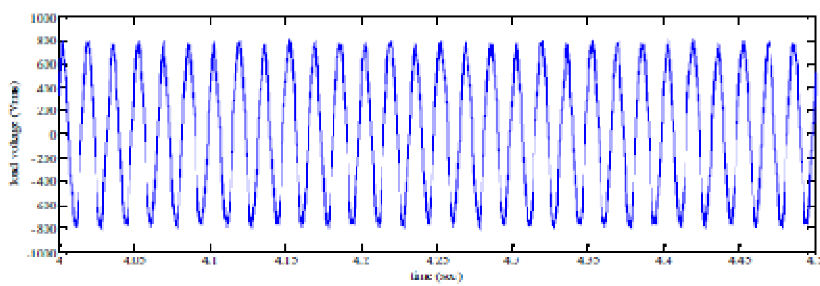

Figure10 Load voltage variation with time (zoomed version)

shown in Fig. 1. The model is seen to be suitable for inclusion into a power system computer simulation package. Two main parts can be readily identified in this model. Starting from the fuel input end, one encounters the part of the model representing the so-called balance of plant (BOP) while downstream of which isthe FC stack. The balance of plant (BOP) consists of the natural gas fuel storage, fuel valve controlled by its controller, and the fuel processor that reforms the natural gas input q_f to the hydrogen-rich fuel q_{H2}^{in} . The fuel processor is represented simply by a first-order lag model of time constant τ_f . The natural gas input to the fuel processor q_f is controlled according to the current drawn from the FC stack by the feedback controller of the fuel valve. In the SOFC, the output of the fuel processor is directly fed to the FC stack, which is the second part of the plant shown in Fig. 1.

It can be seen from this figure that the hydrogen and oxygen molar flows with the ratio r_{H-O} are sent to the FC stack where the reactions described by (1) occur. In order to allow for oxygen to completely react with hydrogen and maintain the pressure difference between the electrodes below a certain

Threshold value, excess oxygen q_{O2}^{in} is provided. This means that $r_{H-O} < 2$ (Zhu and Tomsovic, Provide year). The partial pressures of the three reactants are generated as the outputs of three first-order transfer

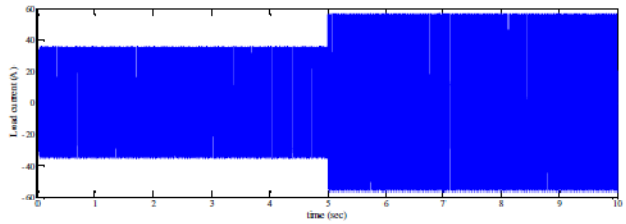

Figure 11Load current variation with time

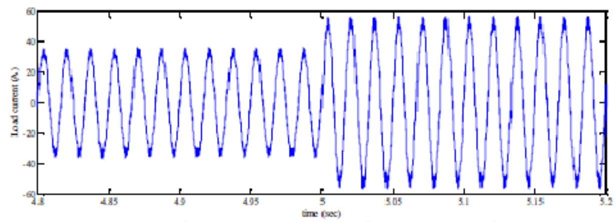

Figure 12 Load current variation with time (zoomed version)

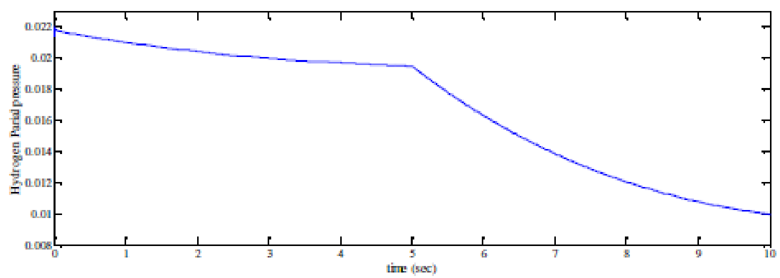

Figure13Hydrogen partial pressure variation with time

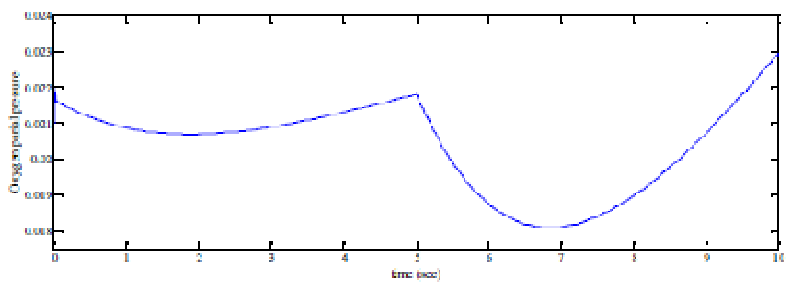

Figure14 Oxygen partial pressure variation with time

functions where K_{H2},K_{O2} , and K_{H2O} are the valve molar constants and

τ_{H2}, τ_{O2} , and τ_{H2O} are the respective temperature-dependant time constants for hydrogen, oxygen, and water, respectively. Typical values of the time-constants are of the order of 3 to 80 s. The production of internal EMF E by N_0 number of cells in series is represented by the block with the Nernst equation given in (12).

Furthermore, there are three types of losses in the generated EMF, namely, the ohmic loss due to the resistance to the flow of ions and electrons, the activation loss due to sluggish electrode kinetics, and the concentration loss due to the concentration gradient formed at the electrodes (Blomen and Mugerwa, 1993). The activation loss is dominant during very low stack currents and the concentration loss is dominant at very high stack currents. The ohmic loss occurs at all levels of currents. In the model shown in Fig. 1, these losses are represented by the resistance r. In order to limit mathematical complexity, a constant resistance is assumed in this paper. If increased accuracy is desired, all three losses can be accounted by a nonlinear resistance r, which is a function of the operating current level as in (El-Sharkhet al., 2004).

To maintain plant efficiency and to avoid breakage of cell material, it is necessary to keep the operating

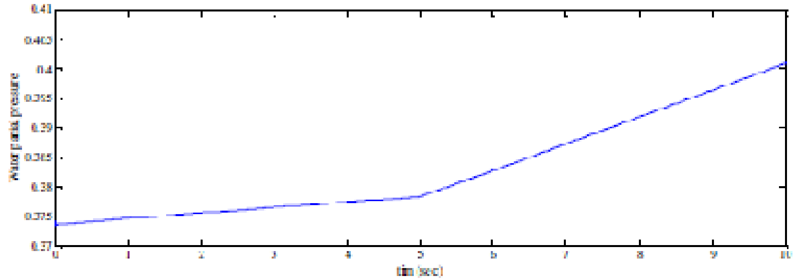

Figure15Water partial pressure variation with time

TABLE 1 PARAMETERS OF SOFC POWER PLANT

Symbol	Representation	Value
P_{rated}	Rated power	50KW
$V_{dc\ rated}$	Rated FC terminal voltage	450 V
T	Operating Temperature	1273 K
E_0	Ideal standard potential	1.18 V
N_0	Number of series cells in stack	450
K_r	Modeling constant	0.993e-3 mol/(s.A)
u_s	Fuel utilization factor	0.85
K_{H2}	Hydrogen valve molar constant	8.43e-4 Kmol/(s.atm)
K_{H2O}	Water valve molar constant	2.81e-4 Kmol/(s.atm)
K_{O2}	Oxygen valve molar constant	2.53e-3 Kmol/(s.atm)
τ_{H2}	Hydrogen flow response time	26.1s
τ_{H2O}	Water flow response time	78.3s
τ_{O2}	Oxygen flow response time	2.91s
τ_f	Fuel processor response time	5s
r	Ohmic resistance	3.28e-4Ω
$r_{H\text{-}O}$	Ratio of hydrogen and oxygen	1.145

temperature (T) of the FC stack within a limited range around its rated value by the thermal management system of the plant (Krumdieck et al., 2004). Therefore, the paper also assumes that T is constant. This operation with relatively constant temperature also places a lower limit on the FC output power (Krumdieck et al., 2004).

The stack voltage Vfc is the actual voltage available at the terminals after considering the losses. The current drawn from the stack I_{fc} acts as a feedback to adjust the partial pressures of the reactants according to the reaction rate.

E. Feasible Operating Area

One of the most important operating variables that may affect the performance of FC is its utilization factor u. The utilization factor, which is not shown explicitly in Fig. 1, is defined as

$$u \equiv (q_{H2}^{in} - q_{H2}^{out})/q_{H2}^{in} \quad (13)$$

From (Padullés et al., 2000), it can be shown that u can be expressed in terms of I_{fc} as follows:

$$u = \frac{2K_r I_{fc}}{q_{H2}^{in}} \quad (14)$$

Where, K_r is a modeling parameter which has a value of (N0/ 4 F).The electrical parameters defining the operating status are V_{fc} and I_{fc} as shown in Fig. 1. Specifically, the FC must operate within its rated power and has to be kept within the range described earlier. Furthermore, in practice, has u to be constrained to a certain range to meet the voltage specifications of the ac load. These variables are related in a rather complex way, through the Nernst equation. Under steady state, the reaction output partial pressure from Fig. 1 is

$$p_{H2,0} = (q_{H2}^{in} - 2K_r I_{fc})/K_{H2}$$

$$p_{H2O,0} = 2K_r I_{fc}/K_{H2O} \quad (15)$$

$$p_{O2,o} = ({q_{H2}^{in}}/{r_{H-O}} - 2K_r I_{fc})/K_{O2}$$

Substituting the above three terms into (equa) and considering the definition of u, FC emf can be written as

$$E = N_o E_o + E_f\{\ln\left[\left(\frac{K_{H2O}}{K_{H2}}\right)\left(\frac{K_r}{r_{H-O}K_{O2}}\right)^{0.5}\right] + 0.5\ln[I_{fc}\left(\frac{1}{u} - 1\right)^2\left(\frac{2}{u} - r_{H-O}\right)]\} \quad (16)$$

Where E_f=N_0RT/2F and FC emf should also satisfy

$$E = V_{fc} + rI_{fc} \quad (17)$$

Therefore, combining (16) and (17), yields

$$\left(\frac{1}{u} - 1\right)^2\left(\frac{2}{u} - r_{H-O}\right) = \frac{\exp\,(\gamma + 2rI_{fc}/E_f)}{I_{fc}} \quad (18)$$

Where

$$\gamma = \frac{2(V_{fc} - N_0 E_0)}{E_f} - 2\ln\left[\frac{K_{H2O}}{K_{H2}}\left(\frac{K_r}{r_{H-O}K_{O2}}\right)^{0.5}\right] \quad (19)$$

Equation (18) governs the steady-state operating condition of the SOFC.Another useful way to explain the steady-statefeasible operating area (FOA) is through Figure 2.Based on the typical SOFC data given in [9], Figure 2 shows a family ofcurves describing the relationship between u and I_{fc} obtained through the application of (18) for a range of V_{fc}. In this example, it has been assumed that V_{fc} is constrained to within 0.95–1.05 p.u. Hence, the curves are drawn with these two limits in mind. Superimposed onto the curves are the constraints on u, assumed to be within 0.7–0.9.The constraints placed on are shown by the straight boundary lines AF and CD. Finally, the FC output powerP_{fc}, which is simply the product $V_{fc}I_{fc}$, has been assumed to be confined to within the 0.1–1.0-p.u. range.

These are shown by the curves AB and DE. Taking all of these into consideration, the FOA of the SOFC must therefore be within the area ABCDEFAof Figure 2. Any operating point outside of FOA will reduce the cell life and is deemed unacceptable. From (7) or Figure 2, it is obvious that it is impossible for the SOFC to maintain a simultaneous constant u and V_{fc} constant operating regime for a range of I_{fc}

Constant Fuel Utilization Control

If the possible range of the FC output power is known, one can select a suitable preset utilization value u_s such that any variation in the load will result in the final steady-state operating condition to be within the FOA. For example, this means the selection of a constant u_s corresponding to that of the line YZ shown in Figure 3. This can be achieved by feeding back the stack current with a proportional gain ($2K_r/u_s$) to adjust the fuel input as (q_f= $2K_rI_{fc}/u_s$). A PWM inverter in the PCU can easily handle the resulting small change of voltage on the FC terminals while supplying the ac load with a constant voltage.

Power-Conditioning Unit

Unless the load supplied by the FC plant is of dc type, the power generated by the FC stack invariably has to be converted to ac form by using a power-conditioning unit (PCU). Since the FC terminal voltage varies with the supplied current and the loads are normally designed to operate under constant voltage, the PCU need not only transform dc to ac but should also possess voltage controllability.This can be readily achieved by using a pulse width-modulation (PWM) inverter as shown in Figure 4. If the FC voltage varies in a large range or the inverter does not possess sufficient voltage controllability, a dc/dc converter is also needed in between the FC terminals and the inverter (Mohan et al., 1993). In conjunction with the PCU, the primary objective of having the capacitor C in between the FC stack and the PCU is to filter out the harmonic components generated by the PCU.

Since the PCU keeps the load voltage constant despite changes in FC terminal voltage, a change in real power demand of the ac load appears as a change in dc load current at theFC terminals. Thus, the ac load can be modeled as a variable resistor for the purpose of analyzing the system behavior

SIMULATION RESULTS AND DISCUSSION

The example in this section is used to illustrate how the control system of an SOFC power plant can be designed to track the variations of load. The example is made on the data given shown in table 1. The controller design is is based on the nonlinear SOFC model shown in figure 1. The simulation is performed using MATLAB/SIMULINK.At initial condition the FC is operating at its rated operation point. In thefollowing illustration, the load resistance has the following variation. The resistive load is adjusted for 25KW and still constant until the simulation time reaches five seconds, then the load is resistive load is increased to 40KW. The load voltage is 575Vrms. The controller is designed to adjust constant load voltage under load change. A boost converter is used and controlled to give average voltage of 850V under FC voltage change.

From simulation results, figure 5 shows the change of the fuel cell current with time when the load power changed from 25KW to 40KW after five second from simulation. Figure 6 shows variation of the stack voltage with time and shows that with increase in fuel cell current the output voltage will decrease.

A boost converter is used to raise the output stack voltage and the reference value of the converter output voltage is set to 850V. figure 7 shows the boost converter output voltage and figure 8 shows a zoomed version of the output voltage and it is shown that the voltage has an average value of 850V. Load voltage is shown in figure 9 and a zoomed version of load voltage is shown in figure 10, which shows that the line to line load voltage approximately equal to (575*sqrt(2)). Figure 11 shows the load current and figure 12 shows a zoomed version which shows that the load current changes as the load power at constant voltage and power factor. Figure 13 and figure 14 show Hydrogen and Oxygen partial pressure variation with time respectively. As current drawn from fuel cell increases Hydrogen and Oxygen partial pressure will decrease as more Hydrogen and Oxygen will consumed in the chemical reaction, when the current drawn tends to be constant the partial pressure will increase. The opposite action will appear in Water partial pressure variation as shown in figure 15.

CONCULOSION

A simplified SOFC dynamic model is derived and it is used to study the FC load-tracking capability in an isolated powersystem. The concept of FOA is introduced in which it becomes a simple tool to assess the possible operating regime
of the FC. Power conditioning unit control system keeps constant load voltage under load power variation.

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