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An integrated SOFC plant dynamic model for power systems simulation

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Abstract

The design process of a SOFC plant dynamic model for a power systems simulation (PSS) commercial software package has revealed the trade-off between the satisfaction of the network dynamic requirements and a safe and durable cell operation that the plant controller should implement. This paper describes the initial fuel cell stack and power conditioner modelling methodologies that have addressed such issues. © 2000 Elsevier Science S.A. All rights reserved.

Keywords: Solid oxide fuel cells; Power Systems Simulation; Dynamic modelling; Systems integration

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1. Introduction

A power systems simulator is an extremely valuable tool for electrical utility engineers who need to address critical issues like network expansion, stability, protection, scheduling or quality of service. The use of such a tool is especially critical at present, when a number of countries are undergoing a process of deregulation of their electrical market. This economic process, together with other technical driving factors, has set up the grounds for the installation of generation plants near the places where the load is consumed, so that they have become embedded in the distribution network. This new scenario has been called ‘‘embedded generation’’ or ‘‘distributed generation’’ (DG), and some authors have identified the prospect for fuel cell technology to fit perfectly in this new situation [1,2].

Distributed generation scenarios challenge the majority of classical techniques for electrical network planning, operation and management. Economic and technical considerations change with respect to the classical situation that consisted of large central generation plants, transmission networks and distribution networks (without generators). A simulation tool is essential to deal with the new situation where multiple generators and multiple loads coexist within the same distribution network.

The focus of the project reported here has been to create a simulation model of a fuel cell-based power plant, for use in a particularly well-known PSS commercial package, called PSS/E [3]. However, prior to the production of the final model, a study of how a fuel cell power plant should operate has been undertaken with Matlab™. This includes some of the results taken from this first stage of the project.

2. General characteristics of the model

As described in more detail in Ref. [4], the characteristics of the simulator impose a number of conditions on the model, summarised as follows:

- The dynamics of the model should be expressed in the Laplace transform domain. No facilities are provided for the solution of partial differential equations (PDEs)
- The typical time integration step is 10 ms.
- The model is focused on the system operation in normal conditions. Start-up, shutdown and operation far away from the nominal power production are usually out of the scope.
- The main model outputs must be real power and reactive power. The inputs can be a number of network variables, e.g., busbar voltage, busbar frequency.

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- The internal variables of the model should be initialised in the steady state with knowledge only of the output power.

- The purpose of the model is the description of the system performance rather than to be a helpful tool to the plant designer.

Although the models for PSS/E should meet more requirements, this list should be sufficient to describe the type of model that must be created.

It is always difficult to create a model that is only time-dependent, where the main equations that describe the system are partial differential equations. This situation forces the modeller to make some decisions and assumptions that are only justifiable within the context of a PSS tool. An example of this situation can be found in Ref. [5], where a PSS model for a gas turbine is proposed.

3. Plant structure

Fig. 1 shows the structure of a generic fuel cell plant, as described in Ref. [4], which is perfectly applicable to SOFC technology. The balance of plant (BOP) equipment deals with the fuel and oxidant processing and feeding to the stack, as well as the processing of the stack exhausts. The fuel cell stack performs the fuel oxidation and delivers dc power, but this module can be observed/measured but not controlled directly. The power conditioning unit (PCU) is responsible for the conversion of dc to ac power according to the conditions that the network may require. The PCU is also controllable through the signals sent to solid-state switches.

In this model configuration, the functions of the plant controller are split in two blocks, the first one dealing with the network relationship and issuing commands about the amount of real and reactive power (P and Q respectively) that it is desirable to be injected to the network. This first block is called the network interface controller (NIC). The second part of the controller will execute these commands by sending the appropriate instructions to the balance of plant equipment and PCU. Although this exact structure is not the most suitable for situations where the plant should follow a variable load, it can be valid for the majority of situations where the plant interacts with a reasonably strong network.

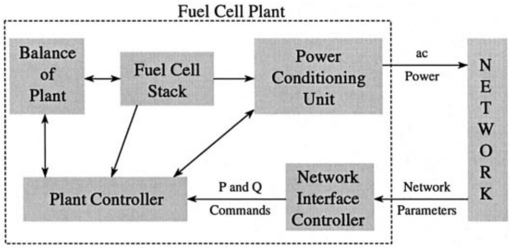

Fig. 1. Structure of a fuel cell power plant.

4. Fuel cell stack model

4.1. Model assumptions

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 of the hydrogen inlet, as a first-order transfer function [6]. 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.

4.2. Characterisation of the exhaust of the channels

According to Ref. [7], 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 a constant temperature, meets the following characteristic:

$$\frac{W}{P_{\mathrm{u}}} = K\sqrt{M}\,, \tag{1}$$

where W is the mass flow [kg/s]; K is the valve constant, mainly depending on the area of the orifice [$\sqrt{\mathrm{kmol\,kg}}$/(atm s)]; P_{u} is the pressure upstream (inside the channel) [atm].

For the particular case of the anode, the concept of fuel utilisation 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:

$$\frac{W_{an}}{P_{an}} = K_{an}\sqrt{(1-U_f)\,M_{H_2} + U_f M_{H_2O}}, \tag{2}$$

where W_{an} is the mass flow through the anode valve [kg/s]; K_{an} is the anode valve constant [$\sqrt{\text{kmol kg}}$/(atm s)]; M_{H_2}, M_{H_2O} 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:

$$\frac{q_{H_2}}{p_{H_2}} = \frac{K_{an}}{\sqrt{M_{H_2}}} = K_{H_2} \tag{3}$$

and

$$\frac{q_{H_2O}}{p_{H_2O}} = \frac{K_{an}}{\sqrt{M_{H_2O}}} = K_{H_2O}, \tag{4}$$

where q_{H_2}, q_{H_2O} are the molar flows of hydrogen and water, respectively, through the anode valve [kmol/s]; p_{H_2}, p_{H_2O} are the partial pressures of hydrogen and water, respectively [atm]; K_{H_2}, K_{H_2O} are the valve molar constants for hydrogen and water, respectively [kmol/(s atm)], the following expression would be deduced:

$$\frac{W}{P_{an}} = K_{an}\left[(1-U_f)\sqrt{M_{H_2}} + U_f\sqrt{M_{H_2O}}\right]. \tag{5}$$

The comparison of Eqs. (2) and (5) shows that for $U_f > 70\%$ 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.

4.3. Calculation of the partial pressures

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

$$p_{H_2} V_{an} = n_{H_2} RT, \tag{6}$$

where V_{an} is the volume of the anode [l]; n_{H_2} 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:

$$\frac{d}{dt} p_{H_2} = \frac{RT}{V_{an}} q_{H_2}, \tag{7}$$

where q_{H_2} is the time derivative of n_{H_2}, 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:

$$\frac{d}{dt} p_{H_2} = \frac{RT}{V_{an}}\left(q_{H_2}^{in} - q_{H_2}^{out} - q_{H_2}^{r}\right). \tag{8}$$

where $q_{H_2}^{in}$ is the input flow [kmol/s]; $q_{H_2}^{out}$ is the output flow [kmol/s]; $q_{H_2}^{r}$ 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:

$$q_{H_2}^{r} = \frac{N_0 I}{2F} = 2K_r I, \tag{9}$$

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_r is a constant defined for modelling purposes [kmol/(s A)].

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

$$\frac{d}{dt} p_{H_2} = \frac{RT}{V_{an}}\left(q_{H_2}^{in} - q_{H_2}^{out} - 2K_r I_i\right). \tag{10}$$

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

$$p_{H_2} = \frac{1/K_{H_2}}{1+\tau_{H_2} s}\left(q_{H_2}^{in} - 2K_r I_i\right), \tag{11}$$

where $\tau_{H_2} = (V_{an})/(K_{H_2} RT)$, expressed in seconds, is the value of the system pole associated with the hydrogen flow.

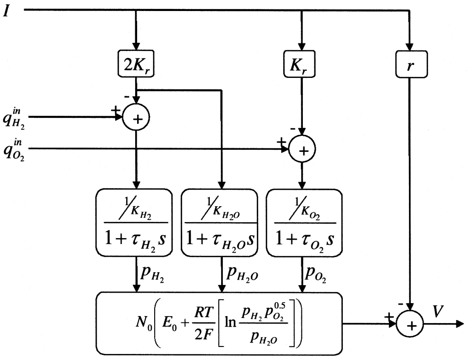

Fig. 2. SOFC stack dynamic model.

Table 1
Constants for model population

Parameter	Value	Unit
N_0	384	
K_{H_2}	8.43e-4	kmol/(atm s)
K_{H_2O}	2.81e-4	kmol/(atm s)
K_{O_2}	2.52e-3	kmol/(atm s)
τ_{H_2}	26.1	s
τ_{H_2O}	78.3	s
τ_{O_2}	2.91	s
r	0.126	Ω

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

4.4. 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:

$$V = N_0\left(E_0 + \frac{RT}{2F}\left[\ln\frac{p_{H_2}\,p_{O_2}^{0.5}}{p_{H_2O}}\right]\right) - rI, \qquad (12)$$

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].

4.5. Dynamic behaviour algorithm and model population

What has been deduced in Section 4.2 can be summarised in the dynamic behaviour algorithm of Fig. 2. However, it is necessary to populate the model with data in order to demonstrate its validity. The majority of data for this model has been extracted from Refs. [8,9] and a commercial leaflet describing the SOFC 100 kW plant operating in 1998 in Westervoort, Netherlands. However, data from those sources has not been enough to populate the model exhaustively, and some of the parameters have had to be estimated within values considered sensible.

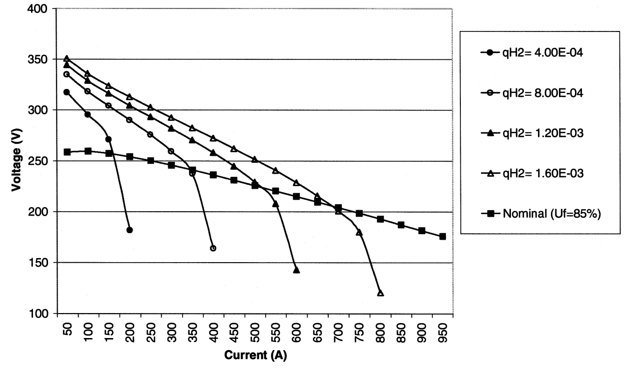

Fig. 3. Voltage–current steady-state characteristics of the SOFC stack model.

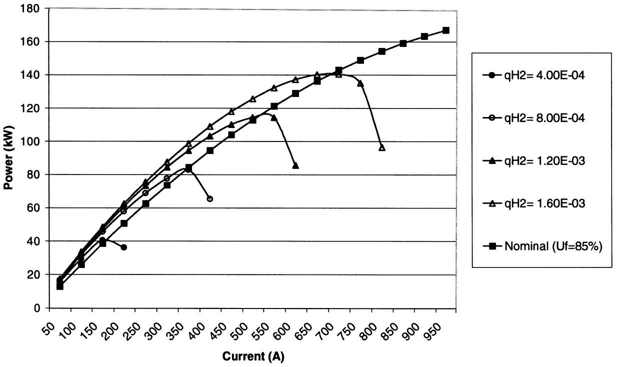

Fig. 4. Power–current steady-state characteristics of the SOFC stack model.

Table 1 contains the values used for the population of the model of a SOFC stack operating at 1000°C. As the data sources are incomplete for the model, these parameters do not intend to model any particular fuel cell stack.

4.6. Steady-state curves generated by the stack model

The stack model can be used to generate voltage–current and power–current curves at different fuel flows. Using data in Table 1, the results are displayed in Figs. 3 and 4. Oxygen excess has been kept constant at 4 times the stoichiometric quantity in the different plots.

5. Power conditioning unit

An integration step of 10 ms is too long to include in the switching model of the solid-state devices. However, what must be included in the model is the direct effect of this switching. In order to do so, the vector control strategy proposed in [10] has been simulated. It is a system that accepts commands in terms of P and Q, and it executes them, by means of several control loops. The air loops control P and Q by means of proportional and integral (PI) compensators. Although the system response time depends on the magnitude of the dc voltage (the stack output), it is capable of responding to P and Q commands in times typically faster than one cycle (20 ms). However, when the PCU response time is so similar to the simulator integration step, it may be preferable not to include any dynamic response of the power conditioner rather than to assume the risk of potential numerical instabilities.

The simulations, however, showed one of the limitations of this configuration of power conditioner. If the output of the cell goes below a certain value, the PCU loses synchronism with the electrical grid, and the generator must be disconnected. This is clearly a situation to be avoided, which must be taken into consideration by the plant controller.

6. Operational limits of the plant

In order to make clear some of the functions that the plant controller should implement, Fig. 3 has been envisaged as an interesting way to define what are the safe operating areas of the plant. As an example, three different limits have been set for Fig. 3:

- Underused fuel. If the fuel utilisation drops below a certain limit (70% in this example), the cell voltage would rise rapidly
- Overused fuel. If the fuel utilisation increases beyond a certain value (90% in this example), the cells may suffer from fuel starvation and be permanently damaged.
- Undervoltage. If the stack voltage output drops beyond a certain point, the power conditioner will lose synchronism with the network and the whole plant will have to be disconnected.

Fig. 5 shows some of the resulting plots derived from the conditions imposed in Fig. 3, including the example operational limits. It can be seen that the figure imposes some operational limitations to certain combinations of the three variables involved: fuel molar flow, output voltage and output current. However, these limits are referred to a situation where the whole system is in steady state. Where dynamics are concerned, to include fuel flow in diagrams like Fig. 5 loses a lot of sense, as the relationship between the fuel flow and the Nernst's equation is not simply algebraic, and dynamics are involved.

7. Response of the plant to load changes

It is necessary to distinguish the different types of response to load changes. On one hand, if the stack is submitted to a current change, this change will be immediate, although this means permanent damage to the stack. On the other hand, there is the control system which, by means of the power flow control capabilities of the PCU, can help to respond to the load change in such a way that avoids the potential dangers to the stack. In this case, the plant will not provide all the power that the load needs instantly.

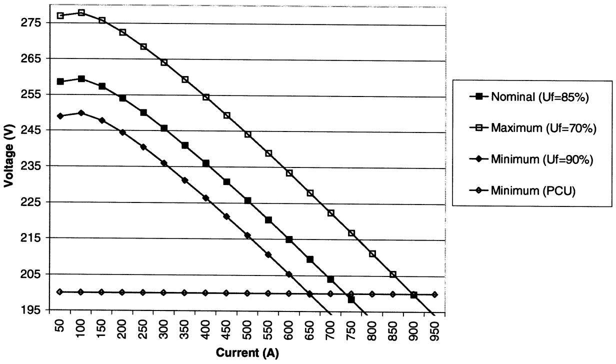

Fig. 5. Voltage–current plots with operating limits.

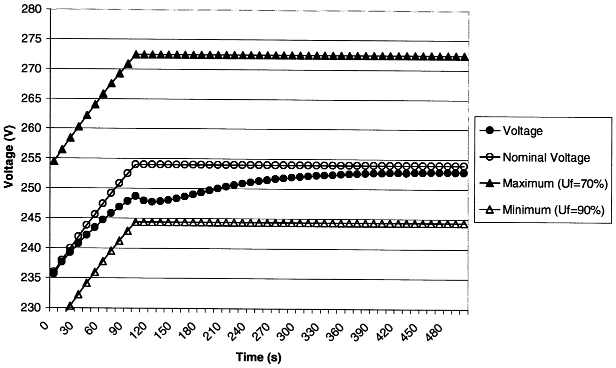

Fig. 6. Stack voltage after current ramp from 400 A to 200 A in 100 s.

The stack model allows the simulation of the event of a load change to the stack. Fig. 6 shows a change in the stack current from 400 A to 200 A in 100 s. This change is backed up with proportional changes in the fuel and air flows. It can be seen that during the decrease of the current, the stack starts following the nominal voltage curve, but soon the response transit beyond the nominal values. In some situations, the voltage output may be situated outside the safe operating area.

The same operation can be plotted in the voltage-current chart of Fig. 7. It can be seen that in this case, the whole transient operation falls into the safe operating area. In simulations similar to the example, some conclusions have been reached:

- When the output current changes, the mere observation of the voltage profile is not sufficient to anticipate the possible consequences of this current change. Some additional variables might have to be monitored.
- If the stack problems associated with a current change are null, the control system may satisfy the demands of the network.

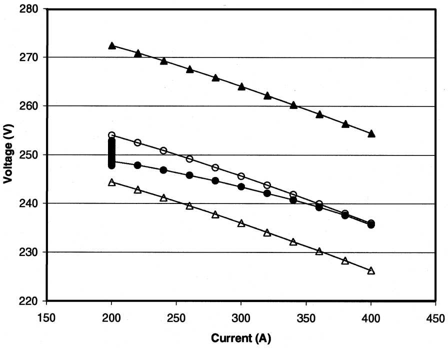

Fig. 7. Stack voltage–current plot after current ramp from 400 A to 200 A in 100 s.

- If the current change indicates stack problems, the network will have to be satisfied at a pace that is sustainable by the stack. This operating mode coincides with what has been proposed by [11].

The purpose of the plant control system will be to identify the likely dangers that any network transients bring, anticipating the transient response that will take place inside the stack, and providing the network with any available power.

8. Conclusions

An SOFC stack model for PSS tools have been proposed, as well as a model for the PCU of the plant. The use of voltage–current and power–current plots has been revealed as an useful tool to define the safe operating areas associated with the stack operation. An example of a transient in the stack has been simulated, and the need for a trade-off between the needs of the network and the integrity of the stack has been highlighted.

Further work in this area will address the ways in which a plant controller can solve these problems.

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