Modeling and Grid Connection of a Solid Oxid Fuel Cell (SOFC) based on *P-Q Theory* for Stationary Loads

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***Abstract*—This paper presents the dynamic modeling of a Solid Oxid Fuel Cell (SOFC) and the device necessary to perform its grid connection. Since there is a voltage drop with increasing load, the DC/DC Converter boosts the cell's output voltage and keeps it regulated. The DC/AC inverter interfaces the DC output of the converter side with the AC grid side. In order to control the injection of active and reactive power into the grid, the inverter control is based on the *p-q theory*. It is also shown that the inherent slow response of the fuel cell would make it improper for sudden load changes, but the addition of power electronics makes the presented set feasible for such load behaviors. Simulation in Power System Computer Aided Design (PSCAD) helps validate the stated above, including the attempt to generate more power than the cell's rated power capacity, which is taken into consideration.**

***Index Terms*—Distributed generation, fuel cells, *p-q theory*, SOFC, renewable energy.**

I. INTRODUCTION

As the consumption of energy around the world increases and with the fact that fossil fuels are finite, Distributed Generation (DG) prevenient from renewable energy sources can play an important role regarding costumers' energy supply. Benefits from DG include higher power quality, possibility of using renewable resources and lesser technical losses in transmission and distribution, due to the proximity between generation and demand [1].

A SOFC is a fuel cell that operates in high temperatures (from 800ºC to 1000ºC), making it suitable for stationary applications. Its efficiency varies from 45% to 50%. When cogeneration is considered (*i.e.,* combined with a gas turbine), it is expected to reach efficiencies over 70% [2].

The output voltage produced by a single fuel cell is low, approximately 1 V. Therefore, there are, as a matter of fact, several fuel cells (*i.e.*, a stack) connected in series to obtain a higher voltage [1,3]. Nonetheless, this output voltage needs to be boosted and regulated so that the inverter can accomplish the connection to the grid. The control of the DC/AC inverter is based on the *p-q theory*. Shortly, instantaneous currents are calculated from the grid voltages and from the desired injection of active and reactive power into the grid. The reference currents are compared with the injected currents, determining the duty cycle signals of the Pulse-Width Modulation (PWM) inverter [4]. Fig. 1 shows the block diagram of the SOFC connected to the grid.

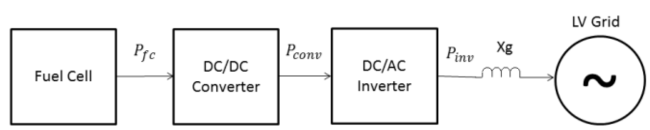

Fig. 1 Fuel Cell connection system

It is important to highlight that in this paper, reactive power set point is taken as zero (Q=0).

The remainder of this paper is organized as follows. Section II presents the modeling of the SOFC and the design of the converter. Section III details the design of the inverter and shows its control scheme based on *p-q theory*. Section IV contains the simulation results and Section V draws the conclusion of the paper.

II. SOFC AND DC/DC CONVERTER: MODELS

A. SOFC

The operating voltage of the SOFC can be obtained by applying Nerst's equation and considering the losses [1,5]:

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

$$E = N\left[E^0 + \frac{RT}{2F} ln\left(\frac{p_{H_2}\sqrt{p_{O_2}}}{p_{H_2O}}\right)\right] \quad (2)$$

Where:

V_{fc}: output voltage of the fuel cell (V)
E: reversible open circuit voltage (V)
V_{act}: voltage drop due to activation losses (V)
V_{conc}: voltage drop due to concentration losses (V)
V_{ohm}: voltage drop due to ohmic losses (V)
E^0: standard reversible cell potential (V)
N: number of cells in stack
R: Universal gas constant, 8.314J/ (mol K)
T: Stack temperature (K)
F: Faraday's constant, 96487 C/mol
p_i: partial pressures of the species i (Pa)

The slow rate of the electrochemical reaction between the fuel and the oxidant causes the activation losses. In other words, to initiate the reaction, part of the generated voltage is lost. Also, as the reactants are consumed at the surface of the electrodes, their concentration is slightly reduced. This causes a drop in the partial pressures, resulting in a voltage drop. These are the concentration losses [6]. In this paper, both activation and concentration losses are neglected to simplify the model. If they were taken into consideration, the fuel cell would accomplish lower voltages and would have a slower response at the start-up process. The ohmic losses are due to the resistance of the electrodes, as well as to the resistance to the flow of ions in the electrolyte [6,7]. The ohmic losses can be calculated in

$$V_{ohm} = rI_{fc} \,. \quad (3)$$

Where r is the internal resistance and I_{fc} is the current of the fuel cell.

B. DC/DC Converter

Fuel cells have a long time constant. Therefore, their response to fast load changes is slow. Besides, as the load increases, V_{fc} tends to lower. Hence, to improve the system's response to load step changes and regulate the voltage at $600\ V$, a DC/DC converter is required. In this paper, a buck-boost converter was chosen due to smoother output voltage [8].

The control scheme of the converter is shown in Fig. 2. The output voltage of the converter (V_{out}) is filtered and then compared with a reference ($600\ V$). The error goes through a PI controller, generating a Closed Loop Trigger signal (CLT). This signal is compared with a sawtooth wave, originating the pulses (G) for the converter.

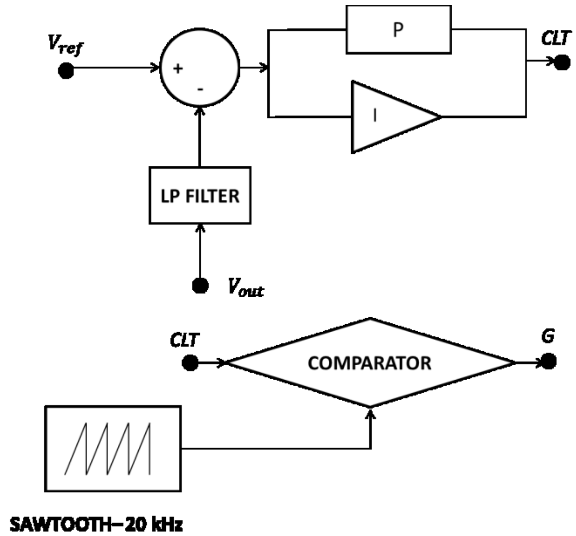

Fig. 2 Control strategy for the DC/DC Converter

III. DC/AC INVERTER

To perform the connection to the grid, a three phase Voltage Source Inverter (VSI) is used. The VSI is composed by three legs; each one consisted of two forced commutated IGBTs and anti-parallel diodes. Fig. 3 presents a simplified scheme of the converter and the VSI tied to the 220 Vrms grid.

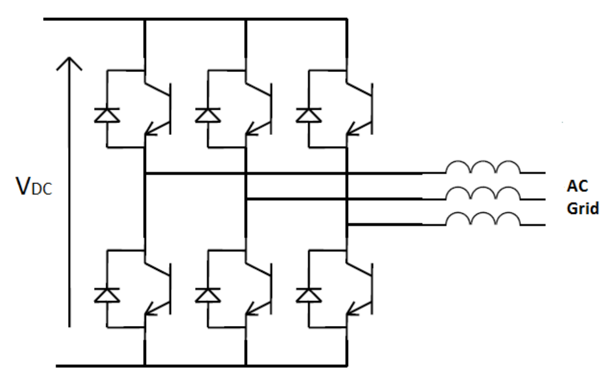

Fig. 3 Grid-tied VSI

In order to generate the gate signals, *p-q theory* is applied [4, 9, 10]. Fig. 4 shows the control strategy for the VSI. The voltage grids (V_{apu},V_{bpu},V_{cpu}) pass through a positive sequence detector, generating V_{apll}, V_{bpll} and V_{cpll}. Next, Clarke Transformation is applied, from which V_{alfa} and V_{beta} are obtained. The following step is to calculate the instantaneous currents, I_{alfa} and I_{beta}. For that, the references of active (P_{set}) and reactive power (taken as zero) to be injected into the grid are necessary. The Inverse Clarke Transformation is applied to the instantaneous currents, generating currents I_a, I_b and I_c. The PWM block uses these currents, the currents from the grid (I_{apu},I_{bpu},I_{cpu}), and the voltages from the detector to generate the gating signals properly.

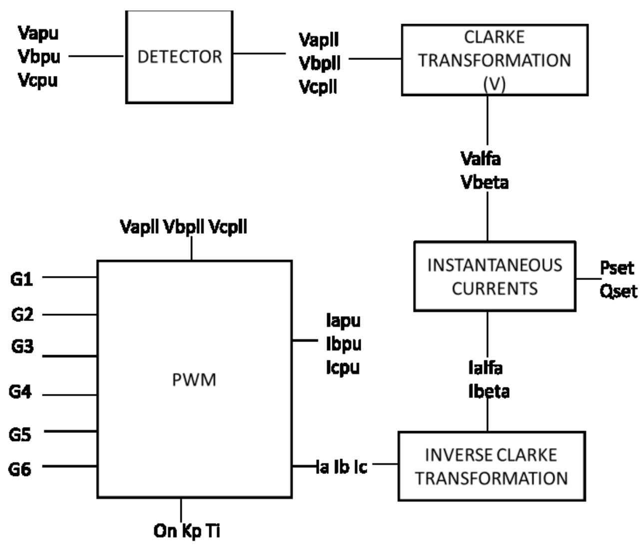

Fig. 4 P-Q based control scheme of the VSI

IV. Simulation Results

In order to test the presented set, the following simulation shows the performance of the grid-tied fuel cell in the face of changes in the reference power (P_{ref}). Table 1 indicates the most important simulation parameters [5].

	Representation	*Unit*	*Values*
N	Number of cells in stack		384
T	Stack temperature	K	1273
P_{max}	Maximum stack power	kW	400
V_{out}	DC/DC Converter output voltage	V	600
V_{grid}	Grid voltage	V (rms)	220
S_{base}	Power base	kVA	400

TABLE I. SIMULATION PARAMETERS.

A. DC/DC Converter Characteristics

The output voltage of the fuel cell tends to lower when the load increases, as discussed previously and shown in Fig. 5.

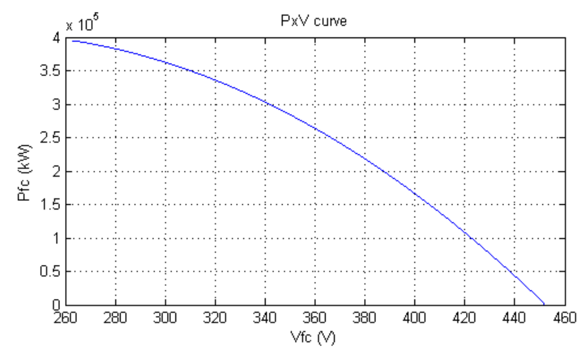

Fig. 5 Fuel cell voltage and converter output voltage

Fig. 5 shows that, at maximum load, the output voltage is approximately 260 V. At no-load situation, V_{fc} is about 450 V. Fig. 6 shows the behavior of V_{fc} and V_{out} with increasing loads up to 80% of the maximum stack power (320 kW).

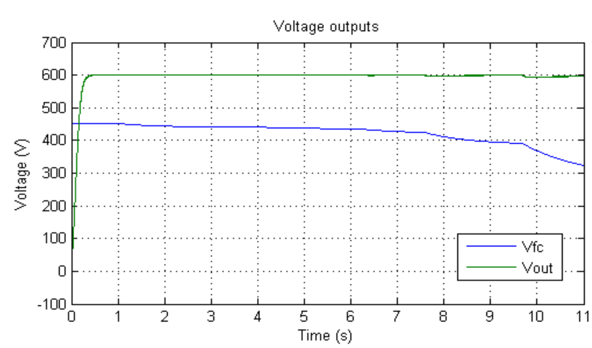

Fig. 6 Fuel cell voltage and converter output voltage

As shown in Fig. 6, from no load to 320 kW, the fuel cell's voltage (V_{fc}) decreases from 450V to 320 V, approximately. It is also shown that, when V_{fc} drops, the control of the DC/DC converter adjusts its gating signals, generating the proper regulated voltage (V_{out}) at 600V. In this simulation, *Vout* presented a ripple of 0.42%.

B. DC/AC Inverter Characteristics

Fig. 7 shows the system's behavior when the commanded power is step changed from 50 kW (0.125 pu) to 200 kW (0.5 pu).

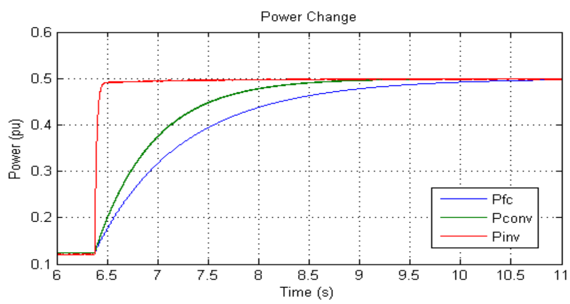

Fig. 7 Power Characteristics for a step change

C. Maximum output power

The maximum output power of the SOFC is influenced by the resistance of the electrode. As mentioned previously, the fuel cell's maximum output power is 400kW. When a step change in the reference power is commanded, a change in the flow of reactants occurs. Fig. 8 shows the attempt to change the commanded power from 400 kW to 500 kW.

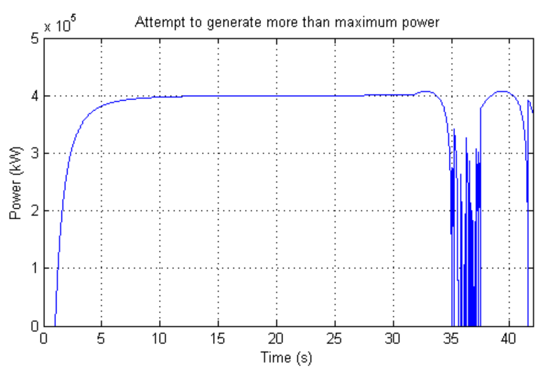

Fig.8 Attempt to generate 500 kW

As shown in Fig. 8, in t=30s, the reference power is changed from 400 kW to 500 kW. It is clearly seen that the SOFC loses stability. If it is possible to reduce the resistance of the electrodes from 0.126Ω to 0.09Ω, for instance, the SOFC will be able to generate 500 kW, as shown in Fig. 9. Stack resistance can be reduced by using higher conductivity electrode or by making it as thin as possible [1].

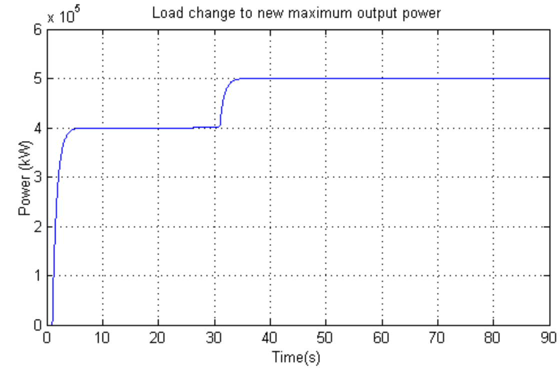

Fig.9 SOFC generating 500 Kw

D. Fuel and oxygen flows

Aside from the parameters shown previously, some other variables, such as fuel (hydrogen) flow, oxygen flow and fuel utilization are worth discussing.

The results in Fig. 10 and Fig. 11 show the fuel and the oxygen flows, respectively, for different power loads.

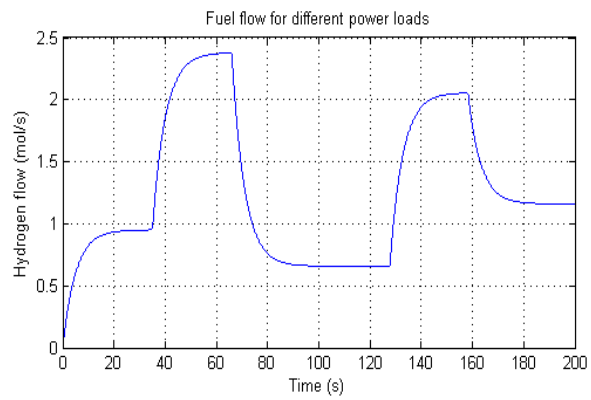

Fig.10 Fuel flow

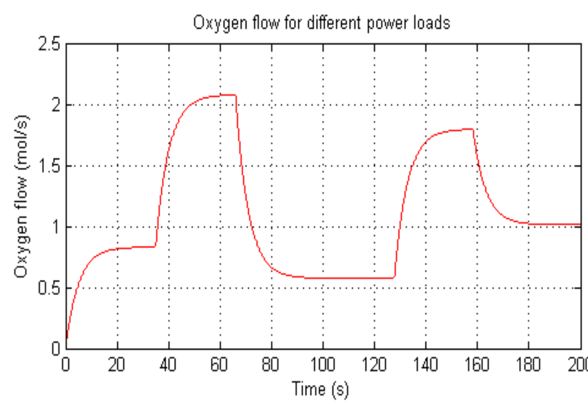

Fig.11 Oxygen flow

From Fig. 10 and Fig. 11, it is possible to see that the flows grow with load increase. When the load decreases, they also do. The reason why both flows have the same waveform is due to parameter *r*, which is the ratio between hydrogen and oxygen in the fuel cell reaction. This ratio is 1.125.

For the same simulation, Fig. 12 shows the fuel utilization rate, which expresses the amount of hydrogen injected into the fuel cell that reacts.

In Fig. 12, it is shown that the fuel rate stays approximately at 0.85 (85%), which is the optimum fuel utilization. When load changes, this rate is disturbed, but when the transient is over, the rate reaches 0.85 again.

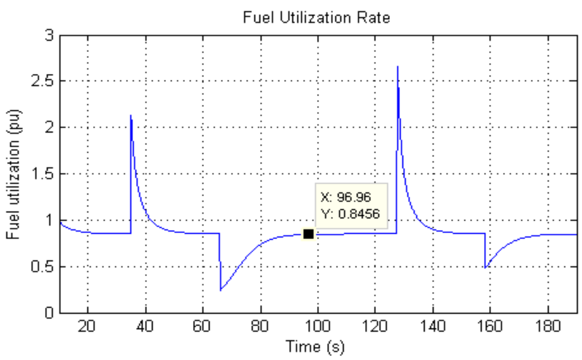

Fig.12 Fuel rate

V. CONCLUSION

In this work, a SOFC and its power electronic device have been modeled in PSCAD to simulate a grid-tied application. It has been shown that before the inverter, a DC device is required in order to regulate the fuel cell's output voltage V_{fc}. The inverter control strategy based on *p-q theory* in one of the several controls in existence, with advantages that it is valid for both steady-state and transient simulations, suitable for general current and voltage waveforms, alongside from its calculation, using only algebraic operation.

Simulation has shown that power conditioning units allow the use of SOFC for stationary applications, since the response time of the set is improved by approximately 98%, making it attractive in the DG domain. Moreover, it has been presented that the decrease of the electrode's resistance is able to alter the maximum output power of the SOFC.

The main limitation on the presented model is it considers an infinite amount of available fuel. Future work will include the modeling of a limited hydrogen tank. Simulation in isolated systems will also be taken into consideration.

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