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INTEGRATED SOLID OXIDE FUEL CELL POWER SYSTEM CHARACTERISTICS PREDICTION

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Abstract: The main objective of this paper is to deduce the specific characteristics of the CHP 100kW$_e$ Solid Oxide Fuel Cell (SOFC) Power System from the steady state experimental data. From the experimental data, the authors have developed and validated the steady state mathematical model. From the control room, the steady state experimental data of the SOFC power conditioning are available and using the developed steady state mathematical model, the authors have obtained the characteristic curves of the system performed by Siemens-Westinghouse Power Corporation. As method, the backward and forward power flow analysis has been employed. The backward power flow makes possible to obtain the SOFC power system operating point at different load levels, resulting as the load characteristic. By knowing the fuel cell output characteristic, the forward power flow analysis is used to predict the power system efficiency in different operating points, to choose the adequate control decision in order to obtain the high efficiency operation of the SOFC power system at different load levels. The CHP 100kWe power system is located at Gas Turbine Technologies Company (a Siemens Subsidiary), TurboCare brand in Turin, Italy. The work was carried out through the Energia da Ossidi Solidi (EOS) Project. The SOFC stack permanently delivers constant power in order to supply the electric and thermal power both to the TurboCare Company and to the national grid.

Keywords: solid oxide fuel cell, power conditioning system, mathematical model.

1. INTRODUCTION

Gasoline and coal are being depleted, and are also environmentally unfriendly. Nowadays, these energy sources are the main energy sources for stationary systems and transportation.

The attractive candidates for power production are the fuel cells. In the last years this subject has undergone serious investigation both from the academic and the industrial sectors. This new technology, in which an electrochemical reaction takes place, directly converting the chemical energy of the reactants into electrical energy through an electrochemical process, has the main advantage of obtaining electricity in one step, versus the many energy conversions of the conventional technologies

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used for power generation (Kakaç, *et al.,* 2007; Bove, *et al.,* 2006). Therefore, from this point of view, the expected efficiency by using this new technology is more than the conventional ones. The fuel cells have the possibility of using directly methane by operating an internal reforming. Fuel cells produce very low levels of NOx, becoming a clean, quiet and high efficient advanced alternative to the combustion (Joos, et al., 2000; Mcdermott et al., 2003; Brey, et al., 2002; Enslin, 2003; Enslin, 2005).

There are different types of fuel cells. In this paper the solid oxide fuel cells (SOFC) are under attention.

Planar SOFCs reach larger power densities (because of the smaller current density) than tubular SOFCs, but they present some criticalities due to the seals and their behaviour under thermal gradients. To solve this problem, Siemens Westinghouse has developed the tubular SOFC.

Westinghouse Electric Corporation pioneered the SOFC technology in the late 1970s and continues to lead its development. Westinghouse has concentrated on the development of SOFC with a tubular geometry. The tubular SOFC eliminates the need for high-temperature, high-integrity seals between cells, or between the cells and the *air* and fuel manifolds. It can accommodate small mismatches in the thermal expansion characteristics of the cell components.

The Westinghouse tubular solid oxide fuel cell (SOFC) is an advanced direct conversion electric power generation technology that can transform over 70% of the lower heating value (LHV) of pipeline natural gas into ac electrical power and useful heat. Simple cycle natural-gas-fueled SOFC systems at application ratings of 100 kWe can approach 50% of the electrical generating efficiency (ac/LHV). This high efficiency results in the commensurately low emission of CO2. In addition, since the SOFC electrochemical reaction occurs without exposure to nitrogen, and since the combustion of unreacted fuel within the SOFC module occurs at moderate temperature levels (i.e., < 1000°C), the production of SOFC NOx is very low. Further, since the SOFC utilizes desulfurized fuel, SOx emissions are negligible. SOFC power plants thus represent a environmentally friendly power generation technology that is capable of meeting the increasingly restrictive emission standards that are emerging worldwide. SOFC power generation systems require simple auxiliary systems and promise both long life and low maintenance.

The design/supply of the SOFC module and the field unit equipment that directly supports the module is being done by Westinghouse.
The main components of the fuel cell system are the fuel processing unit or the reformer, the fuel cell stack and the power conditioning unit. The tubular SOFC stack is fueled by natural gas through an internal reformer and air preheating.

Operating on natural gas available at the test site, the function of the field unit is to produce net ac power to be exported to the utility grid, and hot water. At its nominal operating point, the field unit exports 100 kWe net ac power and recovers 40-50 kWth of heat from the SOFC exhaust for the production of hot water. The hot water is supplied to the district heating system. Maximum net ac power capability will be nearly 150 kWe, and the hot-water heat recovery rate at that operating point will be of approximately 120 kWth.

2. SYSTEM DESCRIPTION

The system operation must follow some criteria in order to increase the SOFC stack lifetime. As an example, the load can not be abruptly changed even in case of grid fault or collapse. Therefore, it is necessary to connect some systems to the output of the SOFC generator. Another important point is regarded to the connection of the SOFC generator to the national grid. As the output voltage of SOFC generator is DC, a power conditioning system is demanded. The Power Conditioning System (PCS) shown in Fig.1 is responsible for this task, converting DC power delivered from the SOFC generator module into utility quality AC power and supplies auxiliary AC power to the Electrical Distribution System (EDS). The stationary fuel cell power system is formed by the following primary subsystems (Fig.1): Solid Oxide Fuel Cell Generator (SOFC Stack), Power Conditioning System (PCS), Static Switch (SS), Electrical Distribution System, Dissipation System (DSS), and Auxiliary System (AUX).

There are five operation modes: *Direct Supply from Utility, Precharge Operation, Normal Operation, Island Operation, DC-Dissipator Operation.* The corresponding block diagrams for each operation mode are depicted in (Gaiceanu, *et al.* 2008). In Figure 1, the normal operation mode is shown.

3. NORMAL OPERATION MODE

The experimental and simulation comparative results have been pointed out (Gaiceanu, *et al.* 2007) in order to validate the mathematical model. For each module the power losses are calculated in the backward manner. The authors (Gaiceanu, *et al.* 2008) have developed the energetic model for each primary component. For example, in order to obtain the interface losses, the following procedure can be followed. Knowing the power supplied in the grid PCSKWGRD=P_{grid} and the mains voltage PCSVAC (Fig.4), the grid current PCSIGRID can be obtained. By using the equivalent complex impedance method, it is possible to obtain the inverter output phasors: the voltage phasor, $\underline{V}_{out}^{inv}$, and the current phasor, $\underline{I}_{out}^{inv}$.

The input power of the interface (i.e. the inverter output power) is obtained by means of the three-phase volt-amperes complex power:

$$(1) \qquad \underline{S} = 3\underline{V}_{out}^{inv}\left(\underline{I}_{out}^{inv}\right)^{*}$$

where $\left(\underline{I}_{out}^{inv}\right)^{*}$ is the conjugate of the phasor current. The apparent power is the magnitude of the complex power:

$$(2) \qquad \left|\underline{S}\right| = 3V_{rms}I_{rms}$$

The active power of the inverters output is the real part of the complex power:

$$(3) \qquad P_{outinv} = \Re e\{\underline{S}\}$$

The reactive power is the imaginary part of the complex power:

$$(4) \qquad Q_{outinv} = \Im m\{\underline{S}\}$$

The power factor is the ratio of the active power to apparent power:

$$(5) \qquad k_p = \frac{P_{outinv}}{\left|\underline{S}\right|}$$

or

$$(6) \qquad k_p = \cos\left(angle\left(\frac{\underline{I}_{out}^{inv}}{\underline{V}_{out}^{inv}}\right)\right)$$

The interface losses:

$$(7) \qquad P_{loss,\text{interface}} = P_{out,inv} - P_{PCSout}$$

In the same manner, the entire mathematical model has been developed.

4. DEDUCTION OF THE SOLID OXIDE FUEL CELL POWER SYSTEM CHARACTERISTIC CURVES

As methodology, the backward and forward power flow analysis has been employed.

The backward power flow makes possible to obtain the SOFC power system operating points at different load levels.

The forward power flow analysis is used to predict the power system efficiency in different points of operation.

According to the described methodology and by

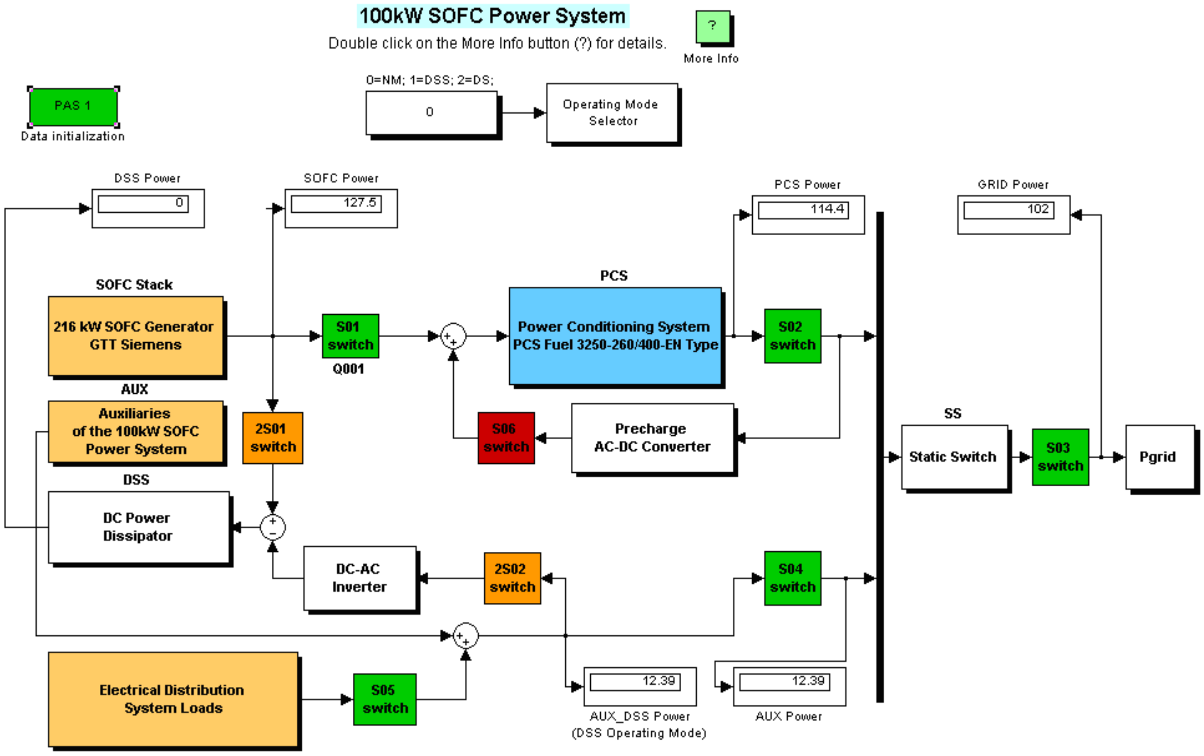

Fig.1. Matlab/Simulink 100kW$_e$ SOFC Power System.

using the developed steady state model of the entire power system (Gaiceanu, *et al.* 2007), the following characteristics have been obtained (Figs.2-9).

The starting point of the electrical power components is the known grid power, PCSKWGRD, of 102kW. By knowing the power delivered to the grid (from the data measurement), the entire system efficiency can be calculated in one operating point.

By varying the reference power delivered to the grid, the efficiency, the losses, the electrical quantities (voltage and current), and the power curves for each module of power system can be deducted (Figs.2-9).

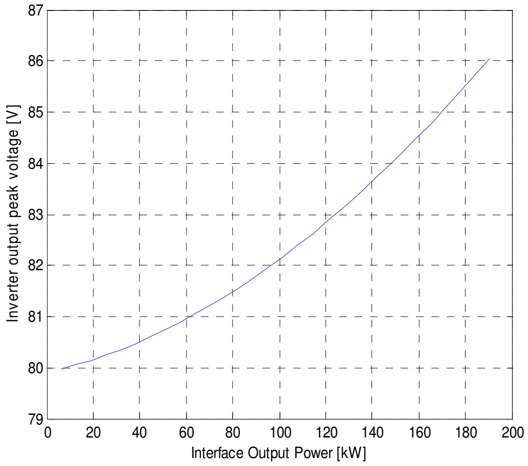

Fig.1. The peak output voltage of the three-phase inverter versus the output power of the interface.

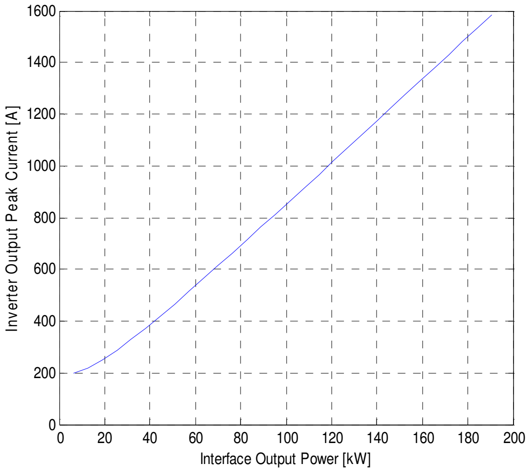

Fig.2. The peak output current of the three-phase inverter versus the output power of the interface.

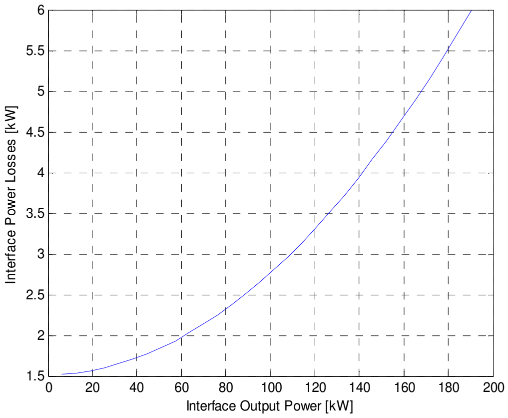

Fig.3. The power losses of the three-phase grid interface versus the output power of the interface.

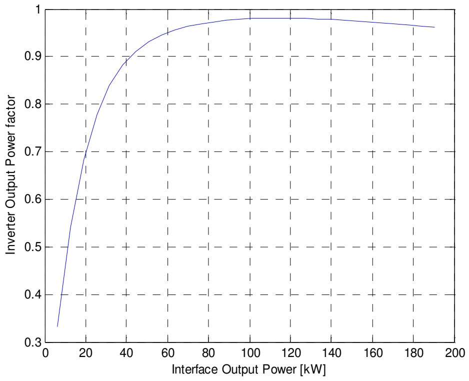

Fig.4. The inverter’s output power factor function on the output power of the interface (the output of the Power Conditioning System).

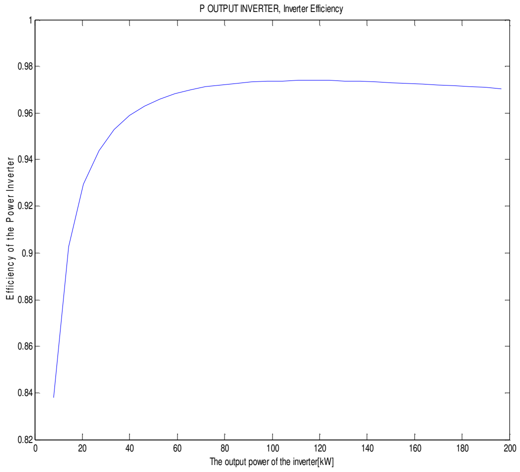

Fig.5. The inverter’s efficiency versus the interface output power from the deduced mathematical model.

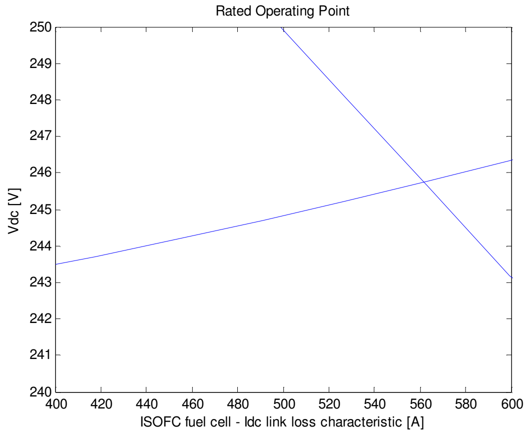

Fig.6. The rated operating point (intersection between the fuel cell polarization characteristic and the dc load characteristic obtained by using the developed steady state model).

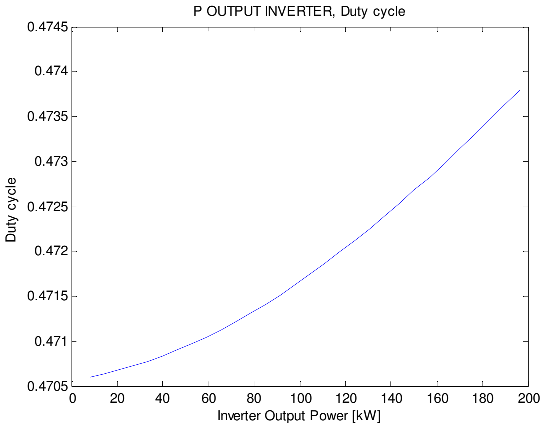

Fig.7. The inverter's duty cycle function on the output power of the inverter.

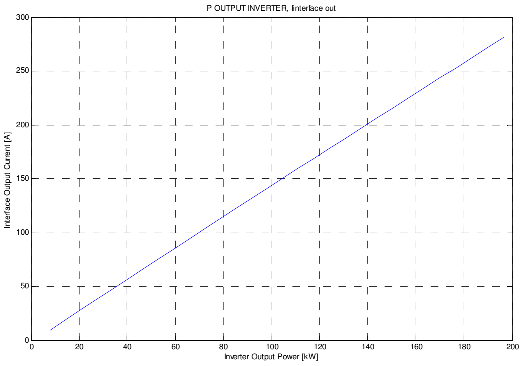

Fig.8. The inverter's output current function on the output power of the inverter.

5. CONCLUSIONS

The characteristic curves of the 100kWe SOFC Power Conditioning System were obtained by the authors using the developed Matlab/Simulink simulator. Starting from the validated steady state mathematical model of the SOFC power plant in normal operation and by varying the reference power delivered to the grid, the efficiency, the losses, the electrical quantities (voltage and current), and the power curves for each module of power system were obtained.

Being modular, friendly and relatively easy to use, the power simulator of the SOFC system is useful in utility applications to choose the adequate control decision in order to obtain the high efficiency operation of the SOFC power system at different level loads. The growing demand in a service area may be met; therefore, the use of power simulator can deliver a lot of system information. The operating modes of the SOFC power system can be selected through the main switch of the simulator (Fig.1), i.e. the main switch will change the states of the individual switches in an appropriate manner. In this way, a costly and extensive time in order to size, design and diagnose the different faults of the power system can be avoided.

Due to the specific operating conditions of the fuel cell power system (the start-up time of the fuel cell power systems can be hours or ten hours, depending on fuel cell type, application, power so on), it is desirable that the entire system work permanently. Under this condition, starting from a specific steady state data and using the developed power system simulator, the human operator can find the adequate operating point for the fuel cell stack to make the right decisions regarding the references of the control system.

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