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# Solid oxide fuel cell hybrid system: Control strategy for stand-alone configurations

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ABSTRACT

The aim of this study is the development and testing of a control system for solid oxide fuel cell hybrid systems through dynamic simulations. Due to the complexity of these cycles, several parameters, such as the turbine rotational speed, the temperatures within the fuel cell, the differential pressure between the anodic and the cathodic side and the Steam-To-Carbon Ratio need to be monitored and kept within safe limits. Furthermore, in stand-alone conditions the system response to load variations is required to meet the global plant power demand at any time, supporting global load variations and avoiding dangerous or unstable conditions. The plant component models and their integration were carried out in previous studies. This paper focuses on the control strategy required for managing the net electrical power from the system, avoiding malfunctions or damage. Once the control system was developed and tuned, its performance was evaluated by simulating the transient behaviour of the whole hybrid cycle: the results for several operating conditions are presented and discussed.

## 1. Introduction

Hybrid fuel cell systems are considered a good candidate for future power generation [1] because of their high efficiency and ultra-low emissions. They can reach a very high efficiency level [2–4] (over 60% – electrical efficiency on a natural gas LHV basis, in a mid-term perspective), even in small size plants. Solid Oxide Fuel Cell (SOFC) hybrid systems especially seem to be the right answer for overcoming the main limitations of traditional power plants. Besides the high efficiency energy conversion performed inside the fuel cell stack (not restricted by Carnot efficiency), SOFC high temperature exhaust flow is naturally considered a good heat source for a gas turbine bottoming cycle [5]. Moreover, hybrid system technology produces exhaust gases at high temperature condition, useful for co-generative applications [6–8].

In the last few years (and currently), many authors have discussed different SOFC hybrid cycles at full, part load, and transient conditions [9–14]. While a study of SOFC hybrid systems at on-design and off-design conditions is necessary for assessing cycle performance and understanding safe operative limits of plants, the transient analysis is mandatory for implementing the control system and studying critical aspects over time. It is extremely useful for avoiding malfunctions or damage to key components of the plant, especially during start-up/shutdown or during fast load variations. In an SOFC hybrid system the main risk situations to be avoided by control system performance are, for instance, (I) excessive temperature in the fuel cell, (II) excessive pressure difference between the cathodic and the anodic sides, (III) too low a Steam-To-Carbon Ratio (STCR) value in the reformer or on the cell, (IV) excessive microturbine rotational speed, (V) an operating condition too close to compressor surge line (surge margin) or (VI) excessive thermal stress in the heat exchanger and the cell. All these constraints need to be coped with during both load variations and start-up/shutdown procedures. In particular, the main difficulty in implementing such a control system is due to the great difference between the time-scales of the transient phenomena [15]. For this reason, the combination of the high thermal capacitance of SOFC systems and the short-term response of the turbine rotor requires a specially designed control strategy, able to protect the machine from overspeed or unstable conditions.

Several studies [16–19] have been developed (or are under development) on control systems for SOFC hybrid plants at both academic and industrial level. In this paper a new control system, able to support global load variations avoiding dangerous or unstable conditions, is presented by showing plant performance and the most critical parameters. Although the control system development problem for this kind of hybrid systems has already been investigated [16–19], it is important to emphasise that the control strategy presented here is innovative because it allows the global power demand to be met at any time, an important advantage if a grid connection is not available.

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### Nomenclature

*Acronyms*

| | |
|---|---|
| AC | alternate current |
| C | compressor |
| DC | direct current |
| DS | desulfurizer |
| EFmGT | externally fired micro gas turbine |
| FC | fuel cell |
| HS | hybrid system |
| M | motor |
| MCFC | molten carbonate fuel cell |
| mGT | micro gas turbine |
| PI | proportional integral controller |
| PID | proportional integral derivative controller |
| SOFC | solid oxide fuel cell |
| Tu | turbine |
| TPG | thermochemical power group |

*Variables*

| | |
|---|---|
| Coeff | power sharing-out coefficient [–] |
| FO | valve fractional opening |
| LHV | Low Heating Value [J kg$^{-1}$] |
| $K_p$ | surge margin |
| $i$ | electrical current density [A m$^{-2}$] |
| $m$ | mass flow rate [kg s$^{-1}$] |
| $n$ | molar flow rate [mol s$^{-1}$] |
| $P$ | power [W] |
| $p$ | pressure [Pa] |
| $\Delta p$ | differential pressure [Pa] |
| STCR | Steam-To-Carbon Ratio [–] |
| $T$ | temperature [K] |
| TIT | Turbine Inlet Temperature [K] |
| $t$ | time [s] |
| $U_f$ | fuel utilization factor [–] |

*Greek symbols*

| | |
|---|---|
| $\beta$ | compression ratio |
| $\eta$ | efficiency |

*Subscripts*

| | |
|---|---|
| diff | diffuser |
| 0 | on-design |
| FC | Fuel Cell |
| in | inlet |
| out | outlet |
| s.l. | surge line |
| t | total |

The results presented in this work refer to the classic scheme of a hybrid system based on the coupling of a pressurized tubular SOFC with a recuperated micro Gas Turbine (mGT). This plant was previously investigated at design and off-design conditions [20] producing "Open loop" transient results [21] essential for control system design. In particular, the time-scale characterization [21] of the Hybrid System based on a Solid Oxide Fuel Cell (SOFC-HS) transient phenomena was very helpful in choosing a control strategy and setting the control system parameters.

## 2. The plant model

The hybrid system studied in this paper (Fig. 1) is a plant of about 300 kW net electrical power, employing a microturbine integrated with a tubular pressurized SOFC [22,23]. The plant design (the order of magnitude of flow properties) is based on the Siemens-Westinghouse plant developed at Irvine (CA, USA) [10]. However, this study does not refer to an actual plant because it is a theoretical analysis. The cell cathode receives air from a pre-heater downstream of the compressor, and the anodic side uses the gas mixture coming from the reformer, which converts the fuel (methane) into hydrogen. The SOFC exhaust gases are fed into an off-gas burner to increase turbine inlet enthalpy. A part of the exhaust anodic flow is mixed back with the fuel and recirculated at the anodic inlet. This is necessary for generating the right temperature for reforming reactions and avoiding carbon deposition inside the reformer and the stack (if the STCR value inside this component is reduced, carbon deposition irreparably damages both the reformer and the cell stack). The recirculation system, mainly composed of a single-stage ejector where the fuel is introduced through the primary nozzle, was studied in previous works at design, off-design [24] and transient conditions. This is an important system to be carefully analysed because the ejector performance (recirculation ratio, pressure rise) affects SOFC behaviour and its safe management. The ejector pressure rise is essential to maintain the flow through the fuel cell anodic ducts, and a high recirculation ratio is important to avoid STCR low values (carbon deposition has to be prevented at both steady-state and transient conditions).

The hybrid system transient model was implemented using the TRANSEO tool [25] developed at TPG in the MATLAB®-Simulink® environment [25,26]. It is a visual, user-friendly, modular program, based on an easy-access library [27], implemented for the off-design, transient and dynamic analyses of advanced energy systems based on microturbine technology. TRANSEO applies both the interconnecting volume and the mass continuity approach [27]: in this paper the former is employed because it is more accurate, although it is more time-consuming [27]. While each component calculates its own mass inflow or mass outflow, each plenum defines the boundary conditions in terms of pressure and temperature [27].

All the SOFC hybrid system components are modelled with the "lumped volume" technique that was explained, for the ejector, in [28,29]. Hence, they consist of an off-design model and a constant area pipe for the fluid dynamic delay. This simplified calculation scheme, which is necessary for achieving a reasonable calculation time, generates satisfactory results for plant simulations. This simplified approach is able to furnish correct answers for plant level design activities, without the high detail level suitable for component optimisation (not for plant development). It is important to stress that all the component models take into account the heat exchange with the walls and the variation in chemical composition over time, using the algorithm presented in [28] (in this kind of system the chemical composition of the streams undergoes significant changes over time, affecting the matching of fuel cell and turbomachinery at both steady-state and transient conditions).

The compressor and turbine models, based on the characteristic non-dimensional curves, the quasi 2-D recuperator model and the average SOFC temperature model, based on the tubular geometry shown in [30], were presented and validated in previous studies where a detailed description can be found [25–29]. For instance, in [31,32] TRANSEO approach to microturbine-based systems was completely validated against experimental data; the ejector model experimental verification was carried out in [33] and the simplified fuel cell approach was successfully tested in [34]. Fig. 2 shows an example of this validation campaign, focusing on ejector model performance. This illustration shows the comparison, at room temperature, between the model results and the experimental data during a start-up of an anodic ejector operating at open circuit configuration. It shows the effect on the diffuser outlet mass flow rate due to fast opening of the valve located upstream of the ejector primary duct [33]. It is important to note that the characteristic time of the unsteady phenomenon is calculated with good accuracy by

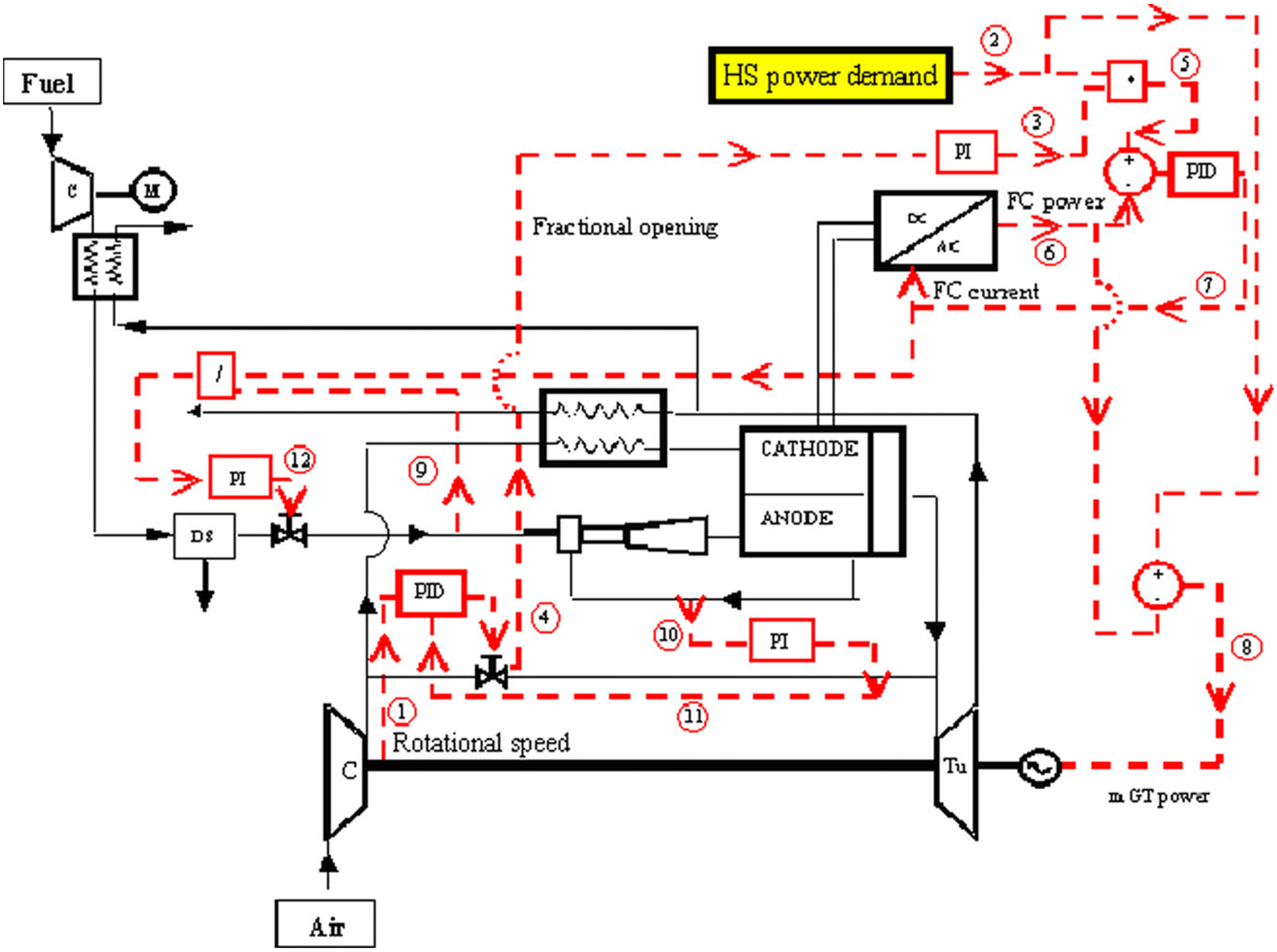

**Fig. 1.** Plant and control system layouts (the numbers in red circles refer to the closest dotted line related to the control system, and all the abbreviations are shown in nomenclature). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

the model. The oscillations in the experimental data are not due to a physical phenomenon, but come from instrument noise. To obtain a fast time response in transducer behaviour (in order to record the transient phenomena with enough accuracy [33]) no data filtration are used for the transducer setting [33].

## 3. The control system

In this paper, the model of the entire control system was developed with PID (Proportional, Integral, Derivative) controllers of TRANSEO [25]. However, the time-scale of the SOFC-HS transient phenomena makes it often possible to use slow response controllers avoiding the derivative part, retaining only the Proportional and Integral (PI) part (derivative coefficient in the TRANSEO Proportional, Integral and Derivative (PID) block equal to zero). So, the control system model (as shown in Fig. 1) is based on two PID and three PI controllers. The time-scale characterization of the plant transient phenomena, presented in [33], was essential for choosing the control strategy and setting the control system parameters.

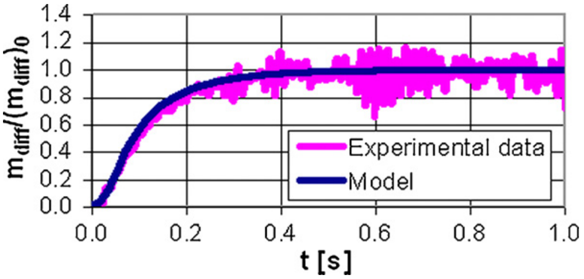

**Fig. 2.** Model validation example: the anodic ejector.

The main difficulty found in implementing the SOFC-HS control system (Fig. 1) is the difference between the small mechanical inertia of the microturbine shaft and the very high thermal capacitance of the fuel cell stack [35]. For this reason, to control the mGT rotational speed (point 1 in Fig. 1), a bypass valve, with a small Fractional Opening (FO) at design condition (FO = 0.05) which is necessary for controlling the mGT rotational speed during load increases, was introduced. This solution was based on the control strategy developed for Externally Fired micro Gas Turbine (EFmGT) plants (already studied by TPG staff [31]): the rotational speed is controlled by bypassing part of the compressed air directly to turbine inlet.

The input signal is the global net power requested from the whole system (point 2 in Fig. 1). The power-sharing between the stack and the turbine is obtained through a sharing-out coefficient (point 3 in Fig. 1) calculated by a slow response PI. This controller operates with the objective of keeping the bypass valve fractional opening at the set point position (point 4 in Fig. 1), fixed at the design value (0.05). The sharing-out coefficient multiplies the input signal to calculate the power requested from the SOFC (point 5). This coefficient is essential to keep the net efficiency high over time and at part-load conditions: it is necessary to vary the power ratio between the SOFC and the mGT system to avoid too high bypass

**Table 1**
Measured properties for control system operation.

| Property | Point (see Fig. 1) |
|---|---|
| Rotational speed [rpm] | 1 |
| Bypass FO | 4 |
| FC power [kW] | 6 |
| FC current [A] | 7 |
| Fuel mass flow rate [kg s$^{-1}$] | 9 |
| Fuel cell average temperature [K] | 10 |

valve mass flow rate at part load conditions. A very fast response PID, then, simulates the inverter controller, calculating the SOFC current (point 7 in Fig. 1) with the objective of nullifying the difference between the power requested from the SOFC and the power effectively generated by the cell stack (point 6 in Fig. 1). The remaining power is requested from the microturbine generator (point 8 in Fig. 1). Fuel is controlled by an apt valve whose fractional opening (point 12 in Fig. 1) is calculated by a slow response PI with the objective of keeping the ratio between the SOFC current and the fuel mass flow rate constant (point 9 in Fig. 1). This approach is necessary in order to obtain a high fuel utilization factor (Eq. (1)) inside the cell at part-load conditions too. The parameters of this controller were optimized after several trial simulations to avoid excessively low STCR values over time. Even if, to obtain good stability, the response of this controller needs to be an order of magnitude slower than the rotational speed PID controller, the fuel mass flow rate decrease, after a power step reduction, needs to be quick enough to avoid an initial low STCR. The last controller is a very slow response PI in order to calculate the rotational speed set point (point 11 in Fig. 1) to keep the SOFC average temperature (point 10 in Fig. 1) constant.

$$U_f = \frac{[n(\mathrm{H_2}) + 4 \cdot n(\mathrm{CH_4}) + n(\mathrm{CO})]_{\mathrm{FC\_in}} - [n(\mathrm{H_2}) + 4 \cdot n(\mathrm{CH_4}) + n(\mathrm{CO})]_{\mathrm{FC\_out}}}{[n(\mathrm{H_2}) + 4 \cdot n(\mathrm{CH_4}) + n(\mathrm{CO})]_{\mathrm{FC\_in}}} \quad (1)$$

Table 1 reports the measured properties necessary to control the system with the strategy just presented.

## 4. Results

To demonstrate the capabilities of the control system, a net plant power step decrease was studied. As a critical stress to test a real load variation, the power requested from the whole hybrid system by the grid was reduced by a step of ten percent, starting from the design value of about 285–256 kW (constant ambient conditions: 60% relative humidity air at 288.15 K and 1.013 bar). To obtain the following results, many simulations were performed. In this kind of system the main difficulty to overcome is the need to obtain good stability by maintaining the critical properties in the correct ranges. So, the controllers were gradually introduced and tested with different simulations to evaluate the parameters necessary for obtaining the good performance shown in the following figures.

Fig. 3 shows the main capability of this control strategy, presenting the power-sharing between the stack and the turbine after the 10% load step decrease. The hybrid plant, equipped with the control system presented in the previous paragraph, is able to meet the external power demand at any time, an important benefit if the grid connection is not available. So, although the control system problem for this kind of hybrid systems has already been investigated in previous studies [16–19], this is a significant solution for a stand-alone plant configuration.

While the first part of the results (10–20 s after the load step) deals with the fast microturbine response dominated by the mechanical inertia of the shaft, deduced (as the machine maps) in accordance with the available data [37], the second part (the following seconds) is concerned with the long-term response due to the influence of the high thermal capacitance of the cell stack. To show this kind of behaviour, Fig. 4 reports a rapid rotational speed oscillation followed by a longer time-scale decrease. The initial speed increase is controlled through the bypass valve FO increase and the following slow decrease is due to the speed set-point decrease (point 11 in Fig. 1) necessary for keeping the average temperature of fuel cell stack constant. While in the “Open loop” analysis, presented in [22,36] and shown in Fig. 5 with a dotted line, the average SOFC temperature shows only a decrease dominated by the stack thermal delay time-scale (about 300 s), in this paper (“Closed loop” line in Fig. 5) the control system prevents this phenomenon reducing the mGT rotational speed set-point to recover the initial temperature inside the cell. The initial temperature values shown in Fig. 5 are not the same for some design changes due to the bypass valve introduction (fuel cell power and current was reduced of about 7 kW). Fig. 6 shows the bypass valve FO values following the 10% load step decrease (net plant power step decrease). The initial sudden increase (up to about 0.20) is necessary to control the rotational speed increase (Fig. 4), mainly due to the decrease in cell fuel utilization, preventing machine overspeed; then, the FO is mainly driven by the sharing-out coefficient variation.

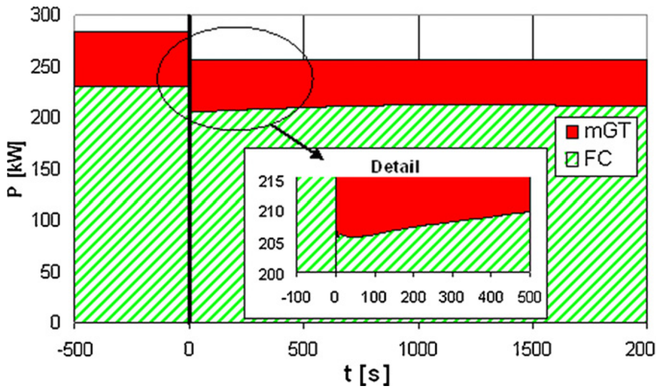

**Fig. 3.** 10% load step decrease: system power sharing-out.

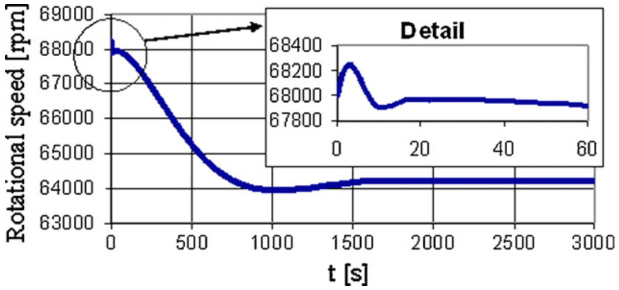

**Fig. 4.** 10% load step decrease: microturbine rotational speed.

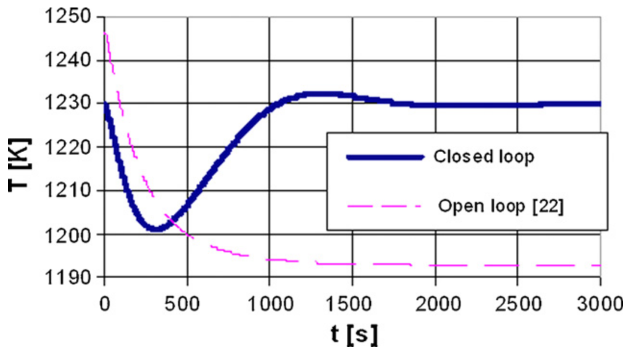

**Fig. 5.** 10% load step decrease: average temperature of solid oxide fuel cell.

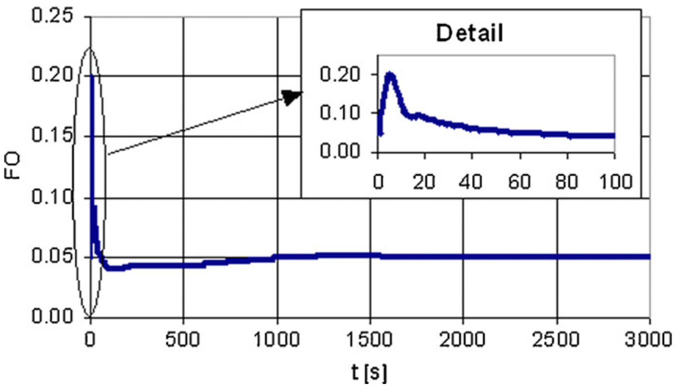

**Fig. 6.** 10% load step decrease: bypass valve fractional opening.

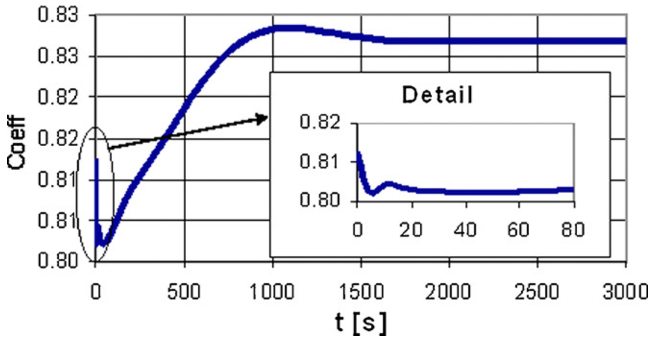

**Fig. 7.** 10% load step decrease: power sharing-out coefficient.

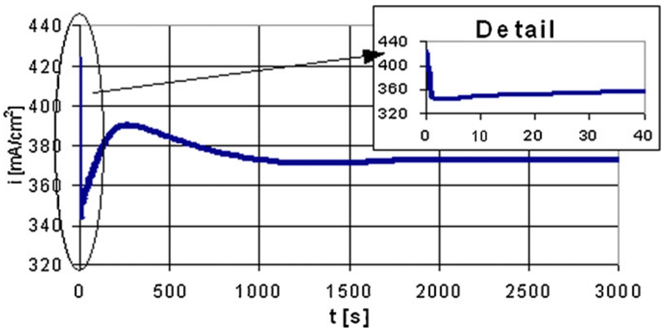

**Fig. 9.** 10% load step decrease: fuel cell average current density.

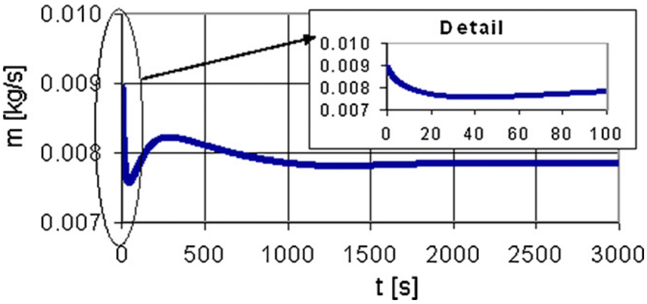

**Fig. 10.** 10% load step decrease: fuel mass flow rate.

After the rotational speed control, the by-pass valve FO reaches the design value of 0.05 because of the effect of the sharing-out coefficient (Fig. 7). It has to split the requested power between the SOFC and the mGT with the objective of keeping the bypass valve FO at set-point to ensure high efficiency. For this reason, Fig. 7 shows (after an initial oscillation) a slow increase of this coefficient value to recover the design condition of bypass valve FO. Comparing Fig. 8 control system results with the "Open loop" analysis [22,36], shown in Fig. 8 with a dotted line, the results show the importance of the control system in preventing low efficiency performance at part-load conditions. Also in this case the efficiency design values are not the same for the changes due to the bypass valve introduction.

Fig. 8 shows the initial sudden efficiency decrease, because of the initial average current density reduction (Fig. 9), followed by a maximum value corresponding to the fuel mass flow rate minimum (Fig. 10). Then, the net plant efficiency trend is completely driven by the time-dependent temperature behaviour (the time-scale of the final part of efficiency variation is the same of temperature trend). Figs. 9 and 10 show an initial sudden decrease followed by an oscillation due to fuel cell temperature variation. While the initial decrease is extremely fast for the current density (the power step directly affects the cell through the PID controller for current managing), the fuel controller PI generates a delay of about 15 s (time to reach 63.2% of the total variation) for the fuel variation response.

The initial fuel mass flow rate decrease is obtained by setting the fuel valve PI controller to avoid Steam-To-Carbon Ratio values that are too low at the beginning of the transient (Fig. 11). The subsequent increase, driven by temperatures, is necessary to keep the ratio between the SOFC current and the fuel mass flow rate constant in order to reach high fuel utilization factor values (Fig. 12), also at off-design conditions. The initial fast reduction in the fuel utilization factor value does not generate high thermal stresses for the turbine. In details, in spite of the fast initial increase in the bypass fractional opening, the Turbine Inlet Temperature (TIT) augmentation (about 3 K) during the first simulated seconds is not a problem for the turbine (Fig. 13). Then, Fig. 13 shows a TIT decrease, due to the fuel drop, followed by a slow increase, due to the air mass flow rate decrease for the effect of machine rotational speed variation.

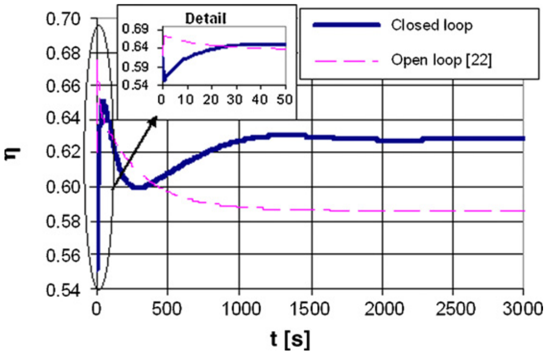

**Fig. 8.** 10% load step decrease: plant net efficiency.

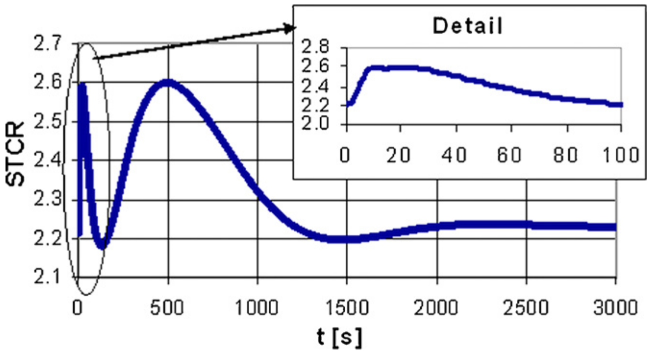

**Fig. 11.** 10% load step decrease: fuel cell anodic inlet Steam-To-Carbon Ratio.

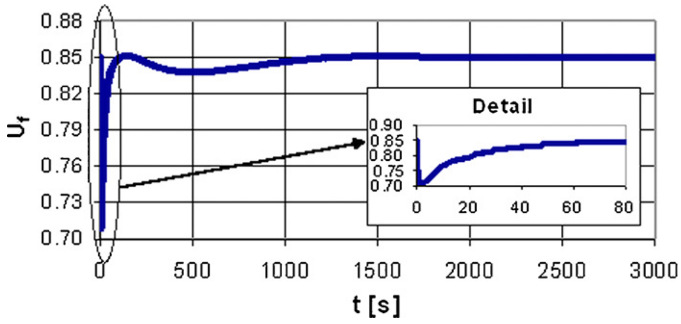

**Fig. 12.** 10% load step decrease: fuel utilization factor.

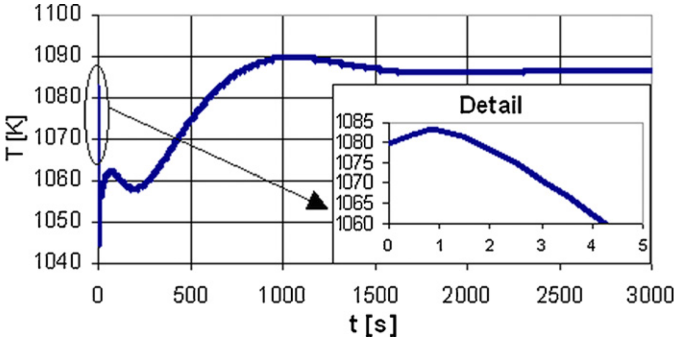

**Fig. 13.** 10% load step decrease: turbine inlet temperature.

The main objective of this transient analysis is the verification of the stack behaviour inside the entire plant, since fuel cell is the most expensive component affected by relevant operational constraints. For this reason, some stack parameters were carefully checked at both steady-state and transient conditions. For instance, the fuel cell anodic inlet STCR (Fig. 11) is always within an acceptable range (STCR ≥1.8 [24]) and the differential pressure between the anodic and the cathodic sides (Fig. 14) is never too high (30 mbar is considered acceptable [29]; however, usually this differential pressure limit value depends on SOFC technology and is not available for confidentiality reasons). It is important to emphasize that, because of the reforming reaction behaviour, the fuel cell anodic inlet STCR is lower and, therefore, more critical than that inside the reformer. So, it is enough to monitor its value at the cell anodic inlet in order to prevent carbon deposition not only inside the stack, but also inside the reformer.

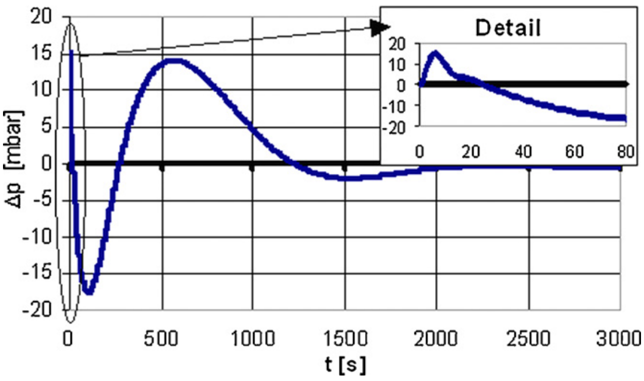

**Fig. 14.** 10% load step decrease: differential pressure between the anodic and the cathodic sides.

To show the behaviour of the cathodic side, Fig. 15 reports the transient performance on the compressor characteristic map. The thin blue lines represent the curves at constant value of the following parameter: $(N/\sqrt{T_{t\_in}})/(N/\sqrt{T_{t\_in}})_0$ (in detail: this parameter value is 1.0 for the curve on the right). Furthermore, $\beta$ is the ratio between compressor outlet and inlet pressures, and the subscript "0" refers to machine design values. After the first variation around the design point, which is not exactly at the unitary coordinate point because of the introduction of the bypass valve (see Fig. 15 detail), the transient curve on the map shows the slow rotational speed decrease necessary to keep the average temperature of the SOFC constant. To complete the study of the compressor over time, Figs. 16 and 17 show the air pressure ratio and mass flow rate curves, respectively. Both figures show a transient behaviour due to the rotational speed trend (Fig. 4). The initial part of the property variations is related to the fast microturbine oscillation (10–20 s) and the second part is concerned with the fuel cell stack long-term response.

As expected from Fig. 15, the reduction in plant power does not create problems for the compressor because it moves away from the surge line. So, the surge margin value, defined in Eq. (2), both at steady-state and unsteady conditions, assumes larger values than at the design point (Fig. 18).

$$K_p = \frac{\beta_{s.1.} \cdot m}{\beta \cdot m_{s.1.}} \tag{2}$$

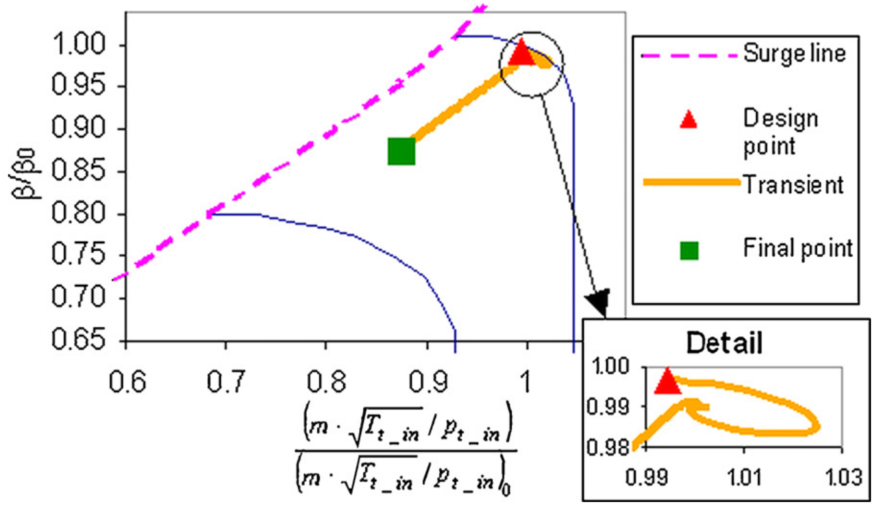

**Fig. 15.** 10% load step decrease: compressor characteristic map and operative points (the property ratio at the bottom of the figure is the *x* axis).

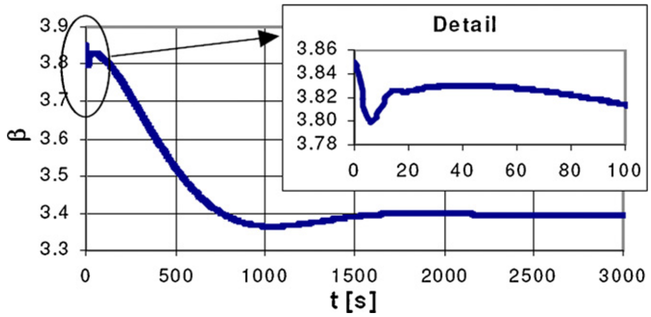

**Fig. 16.** 10% load step decrease: compressor pressure ratio.

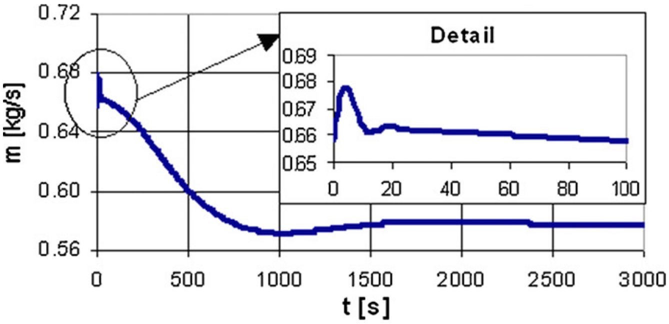

**Fig. 17.** 10% load step decrease: compressor mass flow rate.

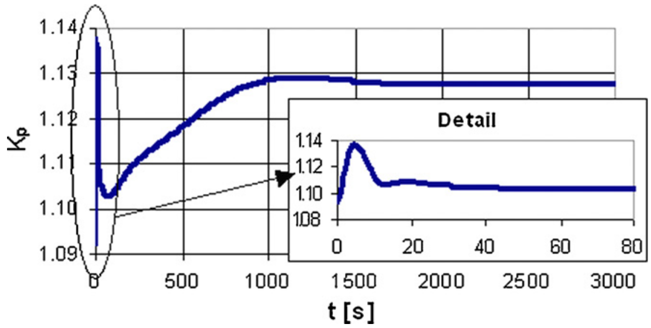

**Fig. 18.** 10% load step decrease: surge margin.

Different load step decreases were tried in order to analyze the hybrid system transient behaviour: a 20% net plant power decrease was compared with the previous results. Also in this case the critical variables, such as the mGT rotational speed (Fig. 19), the SOFC

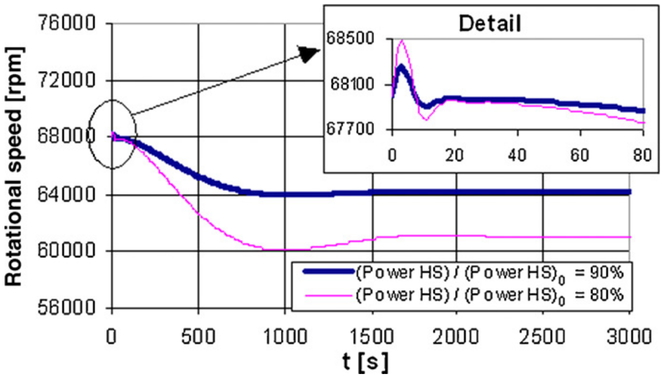

**Fig. 19.** Rotational speed comparison (10% and 20% load step decreases).

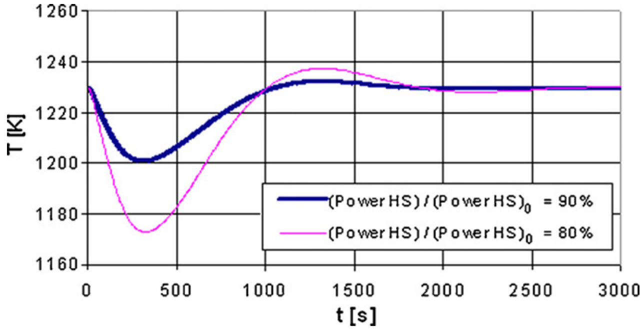

**Fig. 20.** Comparison of average temperature of fuel cell stack (10% and 20% load step decreases).

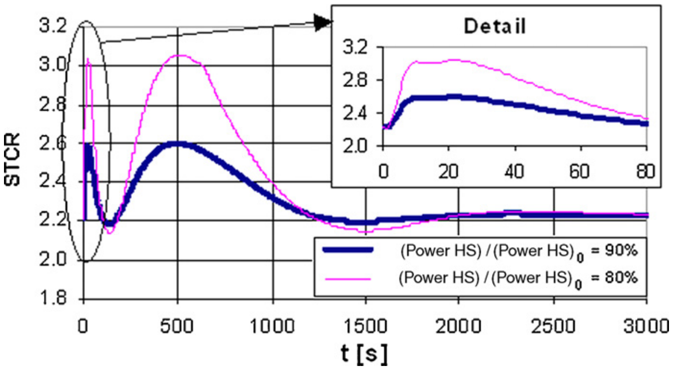

**Fig. 21.** Fuel cell anodic inlet STCR comparison (10% and 20% load step decreases).

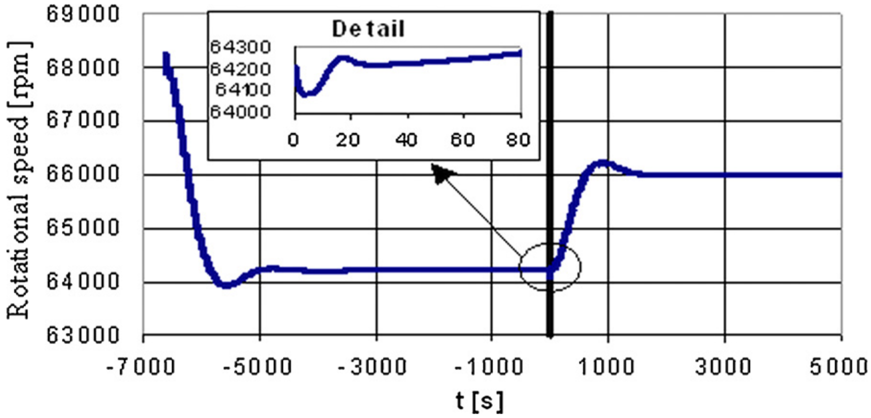

**Fig. 22.** 5% load step increase: mGT rotational speed (the vertical bold line represents the time at which power is increased).

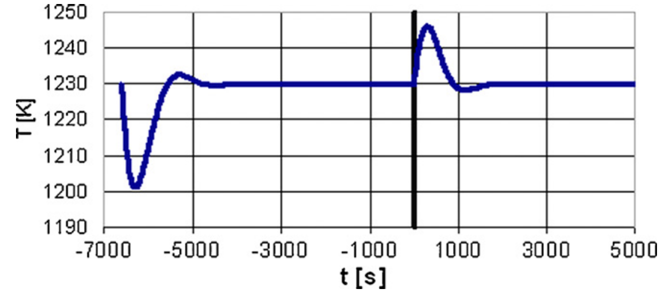

**Fig. 23.** 5% load step increase: average temperature of fuel cell stack (the vertical bold line represents the time at which power is increased).

average temperature (Fig. 20) or the fuel cell STCR (Fig. 21) are always within acceptable ranges, avoiding any dangerous operating regions [36]. In details, Fig. 19 shows that the rotational speed increase due to the 20% load step decrease is well controlled preventing overspeed (the peak value is acceptable according to commercial mGT performance [38]). Furthermore, Fig. 20 shows that, also in this case, the initial value of SOFC average temperature is recovered avoiding excessive thermal stress, and Fig. 21 shows that the STCR is always higher than 1.8 avoiding carbon deposition problems.

Finally, the model was tested with a load step increase of 5%, starting from the final value reached at the end of the 10% load step decrease. A 5% load increase is the maximum allowable step increase that is sustainable with the machine without a non-recoverable deceleration of the rotor. This limitation is basically due to the 5% nominal fractional opening of the bypass valve: higher load fluctuations could be controlled with higher on-design values, but the nominal efficiency would be significantly affected. In Figs. 22 and 23 the abscissa axis zero is set at the beginning of the 5% load step increase, while the negative abscissa part shows the 10% step decrease effect, already presented in the previous pages. Fig. 22 reports the rotational speed variation showing how the control system manages this property to avoid excessive peak values and keeping the average temperature of fuel cell stack constant. Fig. 23 shows that the SOFC temperature increase due to the 5% power step is not excessive for the cell [23]. However, feed-forward control strategies [12] may be considered in future analyses to avoid this temperature increase and to operate with higher load steps.

## 5. Conclusions

This work was carried out at TPG of the University of Genoa, in order to study a new control system for a solid oxide fuel cell hybrid system, based on the coupling of a recuperated micro-gas turbine with a tubular solid oxide fuel cell. The system developed in this study is able to work at stand-alone conditions because it meets the external power demand at any time of operation, performing with good stability and avoiding dangerous conditions. The main conclusions and results presented in this paper are:

- The SOFC hybrid system transient model, already developed with the TRANSEO tool [27] and presented in [36], is used to implement a new control system for the plant.
- The control strategy was completely carried out and the PID parameters were set to prevent unstable behaviour and dangerous operating conditions (the main difficulty, related to the difference between the small mechanical inertia of the microturbine shaft and the very high thermal capacitance of fuel cell stack, was solved by introducing a compressor/turbine bypass valve).
- The design value of the bypass valve FO was set to 0.05 to control the mGT rotational speed during load increases without reducing global plant efficiency too much.
- The results obtained with a 10% load step decrease are presented completely, paying special attention to the most critical variables such as the mGT rotation speed (maximum peak increase under 0.5%), the SOFC average temperature (avoiding stress due to overtemperature conditions), the TIT (the initial peak of about 3 K is not significant for the turbine), the differential pressure between the anodic and the cathodic sides (absolute value always under 20 mbar), the STCR value (always within an acceptable range) and the compressor surge margin value (this margin is increased with this kind of step).
- A comparison of two different load step decreases and a load step increase are studied and presented in this paper to show, especially in the second case, the main control strategy limitation (the 5% load step increase presented here is the maximum allowable step increase for the 5% on-design fractional opening of the bypass valve). For this reason, the load increase phase has to be carried out (starting from the minimum power condition) with load steps smaller than 5% or, better, with small slope ramps.
- The control system layout proposed and simulated here proved to be effective in well regulating the power of the SOFC hybrid system.

The control strategy presented here was also used for IP-SOFC system modelling [39] and for Molten Carbonate Fuel Cell (MCFC) hybrid systems [40].

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