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HARDWARE-IN-THE-LOOP OPERATIONS WITH AN EMULATOR RIG FOR SOFC HYBRID SYSTEMS

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ABSTRACT

This paper shows the Hardware-In-the-Loop (HIL) technique developed for the complete emulation of Solid Oxide Fuel Cell (SOFC) based hybrid systems. This approach is based on the coupling of an emulator test rig with a real-time software for components which are not included in the plant. The experimental facility is composed of a T100 microturbine (100 kW electrical power size) modified for the connection to an SOFC emulator device. This component is composed of both anodic and cathodic vessels including also the anodic recirculation system which is carried out with a single stage ejector, driven by an air flow in the primary duct. However, no real stack material was installed in the plant. For this reason, a real-time dynamic software was developed in the Matlab-Simulink environment including all the SOFC system components (the fuel cell stack with the calculation of the electrochemical aspects considering also the real losses, the reformer, and a cathodic recirculation based on a blower, etc.). This tool was coupled with the real system utilizing a User Datagram Protocol (UDP) data exchange approach (the model receives flow data from the plant at the inlet duct of the cathodic vessel, while it is able to operate on the turbine changing its set-point of electrical load or turbine outlet temperature). So, the software is operated to control plant properties to generate the effect of a real SOFC in the rig. In stand-alone mode the turbine load is changed with the objective of matching the measured Turbine Outlet Temperature (TOT) value with the calculated one by the model. In grid-connected mode the software/hardware matching is obtained through a direct manipulation of the TOT set-point.

This approach was essential to analyze the matching issues between the SOFC and the micro gas turbine devoting several tests on critical operations, such as start-up, shutdown and load changes. Special attention was focused on tests carried out to solve the control system issues for the entire real hybrid plant emulated with this HIL approach. Hence, the innovative control strategies were developed and successfully tested considering both the Proportional Integral Derivative and advanced approaches. Thanks to the experimental tests carried out with this HIL system, a comparison between different control strategies was performed including a statistic analysis on the results The positive performance obtainable with a Model Predictive Control based technique was shown and discussed. So, the HIL system presented in this paper was essential to perform the experimental tests successfully (for real hybrid system development) without the risks of destroying the stack in case of failures. Mainly surge (especially during transient operations, such as load changes) and other critical conditions (e.g. carbon deposition, high pressure difference between the fuel cell sides, high thermal gradients in the stack, excessive thermal stress in the SOFC system components, etc.) have to be carefully avoided in complete plants.

INTRODUCTION

The development of innovative complex power plants [1,2], such as hybrid systems based on Solid Oxide Fuel Cell (SOFC) technology [3], showed critical issues in performing experimental tests [4]. These are essential activities to complete the system knowledge, to validate the calculation models, to optimize the components and technology aspects, to develop low cost solutions, and to increase the plant reliability [5-8]. Even if the modeling activities can significantly help researchers and engineers, the experimental approach cannot be completely avoided. This is due to the fact that any model has to be validated before accepting the calculated results and several phenomena have to be investigated through experiments before defining apt equations. Moreover, such innovative plants are often including high costs or fragile components. This implies that experimental rigs for preliminary tests could be very expensive and very sensible to wrong operations, especially when control system is at preliminary level (not able to prevent dangerous conditions). So, critical tests for control system design or improving time-dependent operations have to be carried out with apt facilities [9-11]. They, not including expensive or high risk components, have to be capable to produce significant results for the real plant design and operations.

A solution for these issues can be obtained with the emulator test rigs [9-12]. These are experimental plants able to generate the same (or similar) effects of the real systems (in terms of pressures, temperatures, mass flow rates, etc.), without the installation of the expensive or high risk components. The activities on such kinds of test rigs have produced significant results, especially for SOFC based hybrid systems. The most significant achievements related to these innovative plants regarded transient operations and management including control system solutions. The specific topics ranged from start-up, shutdown, load change phases to surge prevention and SOFC degradation aspects.

Different research teams have developed hybrid system emulator rigs: the "Hyper" plant at the National Energy Technology Laboratory (NETL) [13], the test rig installed by the Thermochemical Power Group (TPG) of the University of Genova [14], and the plant by the German Aerospace Centre (DLR) [15]. All of them are based on the coupling between a microturbine and a vessel (for the SOFC emulation). However, each plant has specific aspects. The rig at NETL includes a very high temperature vessel and a completely in-house developed control system [9,13]. The facility at TPG is equipped with an anodic vessel (a recirculation system is also present), a cathodic modular tank and a steam injection system for chemical composition emulation [10,14]. The test rig developed by DLR emulates the fuel cell with a large high temperature vessel where the temperature is controlled by a cooling coil. The wanted flow composition is obtained by the fuel mass flow rate [11].

In the activities related to the emulator test rigs, several authors [16-18] proposed hardware-in-the-loop (or named as software-in-the-loop) configurations to evaluate the behavior of component not physically installed in the facilities using real-time tools. These models (even if developed and validated separately) are connected to the emulator plants. Usually, they are receiving input data from the field and they are able to operate on the test rig control system to generate in the plant the same conditions calculated (as output) by the model. For instance, the test rig by NETL can be operated in conjunction with an SOFC real-time model [9]. The software receives data related to its inlet property values from the plant (mass flow rate, pressure and temperature at the vessel inlet). It operates on the facility fuel valve to generate in the rig a temperature value (at the turbine inlet) equal to the same property calculated by the model.

The TPG used a hardware-in-the-loop (HIL) approach connecting the emulator rig with a real-time model developed in Matlab-Simulink environment [18]. Since in stand-alone mode no Turbine Inlet Temperature (TIT) measurement is possible, the software-hardware matching is obtained for the TOT value. This approach was used for designing and verifying the control system that has to maintain constant SOFC temperature during transient operations, such as load changes. In details, a comparison with different approaches was possible because no stack damage would occur in case of risk conditions (e.g. surge operations) [19-21]. A direct TOT set-point change (available in grid-connected mode) is presented, but not tested yet.

While this paper presents a review of different control approaches developed with the emulator test rig by TPG, a novel result comparison is included. In details, an assessment of the different approaches (supported by a statistic analysis) is presented to show advantages/disadvantages of each solution. An important novel analysis is included to show the constraints related to the maximum acceptable time-dependent temperature gradient for the SOFC. This is an important consideration (usually neglected in previous hybrid systems works) to evaluate the control strategy limitations and to justify the development of advanced and complicated techniques (e.g. Model Predictive Control based approaches).

NOMENCLATURE

Acronyms

AW	Anti-Wind up
B	Blower
C/A	Control/Acquisition system
CI	Confidence Interval
CV	Check Valve
DLR	German Aerospace Centre
E. grid	Electrical grid
Ex	heat Exchanger
FC	Fuel Cell
FF	Feed-Forward
HIL	Hardware In the Loop
LUT	Look-Up Table
M	Motor
MIMO	Multi Input and Multi Output
MPC	Model Predictive Control
mGT	micro Gas Turbine
NETL	National Energy Technology Laboratory
OGB	Off-Gas Burner
PE	Power Electronics
PI	Proportional Integral controller
PID	Proportional Integral Derivative controller
PMC	Power Module Controller
REC	Recuperator
REF	Reformer
Ref.	Reference

S. alone	Stand alone
SOFC	Solid Oxide Fuel Cell
TPG	Thermochemical Power Group
UDP	User Datagram Protocol
VB	bleed valve
VBCC	compressor-combustor bypass valve
VC	recuperator bypass valve
VCC	fuel valves (pilot and main)
VM	cathodic vessel bypass valve
VP	ejector primary duct valve
VO	cathodic vessel outlet valve
VR	cathodic vessel inlet valve
WHEx	Water Heat Exchanger

Variables

e	temperature error [K]
FO	Fractional Opening [%]
I	electrical current [A]
K	PI coefficient [-]
N	rotational speed [rpm]
m	mass flow rate [kg/s]
P	power [W]
p	pressure [Pa]
T	Temperature [K]
TIT	Turbine Inlet Temperature [K]
TOT	Turbine Outlet Temperature [K]
t	time [s]
u	control variable [-]
η	efficiency [-]
τ	integration variable [s]

Subscripts

C	Calculated
PID	Proportional Integral Derivative controller
el	electrical
FC	Fuel Cell
FF	Feed-Forward
i	integral
IN	Inlet
M	Measured
max	maximum
p	proportional
SP	Set-Point

TEST RIG

The test rig (Fig.1) is composed of a T100 recuperated microturbine (performance data at nominal conditions: P_{el}=100 kW; N=70000 rpm; η_{el}=30%) connected with an SOFC emulation system. The device includes a cathodic modular vessel and an anodic recirculation system (with a single stage ejector, a second vessel, and an air compressor). While the modular layout was chosen to emulate different fuel cell sizes, the anodic side emulator (the flow is just air instead of fuel) was designed for the maximum system size only (Fig.2). This emulator system (to perform tests on the SOFC) was designed considering a 450 kW hybrid system operating at 59% electrical efficiency. Its design was developed considering a similitude approach (more details were reported in [10]) with the stack manufactured by Rolls-Royce Fuel Cell Systems [22]. The dimensions of these vessels (3.2 m^3 for the cathodic side and 0.8 m^3 for the anodic one) were calculated considering an SOFC size consistent with the nominal mass flow rate of the microturbine (about 0.8 kg/s) [10,14,18].

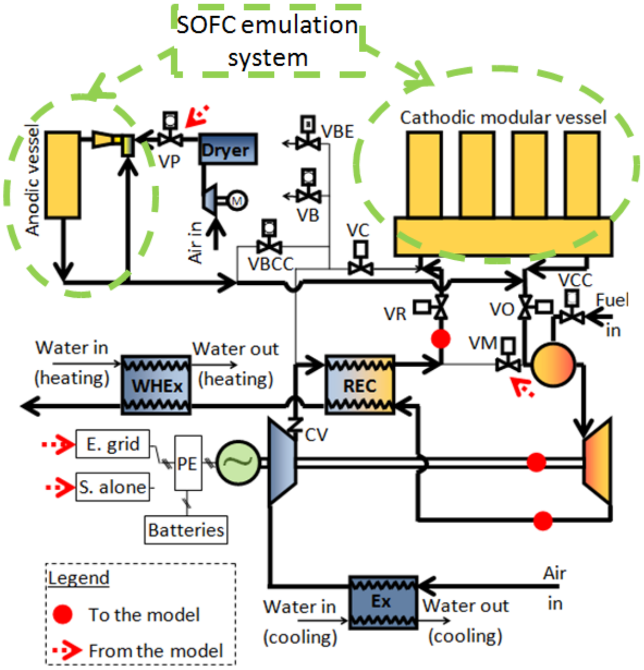

Figure 1. Test rig layout (the bold continuous lines represent the plant layout during hybrid system emulation tests).

The test rig was also equipped with a check valve at the compressor outlet (to reduce risks in case of surge events), a direct connection between the recuperator (cold side) and the combustor (managed by the VM valve), a recuperator bypass line (operated by the VC valve) and a direct connection between the compressor outlet duct and the combustor inlet vane (with the VBCC valve). Bleed lines were included (one of them is managed by a control valve named VB and the second line is an emergency duct operated with the VBE on/off valve) for special operations involving surge risk aspects. A heat exchanger for producing hot water (WHEx) in co-generation mode was installed at the T100 outlet and three air/water heat exchangers (shown in Fig.1, for simplicity, as a single device named "Ex") were included in the air intake ducts for controlling air inlet temperature [10,14,18]. The plant is also equipped with a system to inject superheated steam at the expander inlet, considering a specific heat similitude condition in comparison with the emulated plant [18].

Additional probes were installed and connected with a Field Point system to measure mass flow rate, pressure and temperature values between each component. The related measurements and the valve management can be carried out with a control/acquisition tool developed in LabVIEW environment. Since this instrumentation was presented in several previous works (e.g. [10,14,18]), no further details are shown here. Even if these additional devices are managed in LabVIEW, the original T100 control system was maintained for the microturbine operations. So, the following two options are possible for the microturbine: stand-alone mode with the control system operating at constant rotational speed (in this case batteries are necessary for the start-up phase), and electrical grid-connected mode with the T100 controller operating at constant TOT. While in the T100 commercial version the TOT set-point is fixed at 645°C (918.15 K), a modification was introduced to change this set-point value for such hybrid system emulation activities.

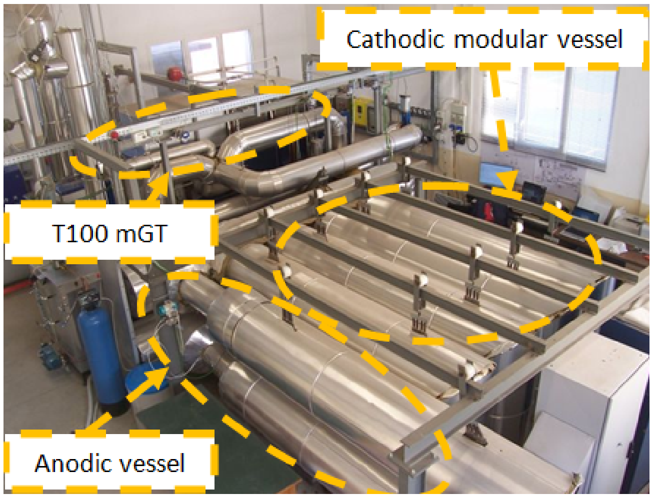

Figure 2. Test rig picture.

Finally, Fig.1 also shows the connection with the real-time model developed for the HIL operations and described in the following section.

REAL-TIME MODEL

The model necessary for the components which are not physically included in the rig was developed to operate in real-time mode. It includes the following components: the SOFC (both the anodic and the cathodic sides), the reformer (REF), the anodic ejector, the off-gas burner (OGB), a blower to generate a cathodic recirculation, and the expander (Fig.3). The novelty aspects of this analysis from the model point of view are shown in the following points:

- The model was developed and validated considering the SOFC manufactured by Rolls-Royce Fuel Cell Systems [22-24]. This choice was necessary for consistency with the installed hardware (mainly the size of the vessels).
- The model allows to perform HIL operations with a commercial machine operating with its standard control system. Since in this case it is not possible to have a direct access to the fuel flow rate (as in [9]), some components are redundant (included in both the plant and the model).

Even if the anodic ejector and the expander are also present in the rig, these components are included in the model too for plant/model matching reasons: the anodic ejector is necessary in the model too to calculate the primary duct mass flow rate. This flow is generated in the rig through the VP valve opening. The turbine model is necessary to evaluate the TOT value. Since no measurement is present in the rig for the TIT, the plant/model thermal matching is carried out obtaining in the rig a measured TOT value (TOT_M) equal to the calculated one (TOT_C). The apt TOT_M value is obtained by changing the TOT set-point in the grid-connected mode or changing the turbine load in the stand-alone operations. Even if it is a more complicated approach in comparison with previous similar works [9,13], it allows HIL tests with a commercial microturbine operating with its standard control system. This is a significant improvement for hybrid systems due to the cost decrease obtainable with commercial machines instead of special design components.

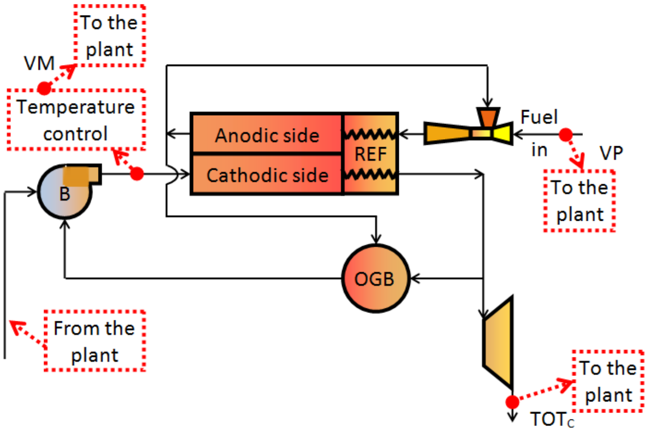

Figure 3. Real-time model layout.

To obtain real-time performance, a 0-D approach was considered for all the components. The SOFC model is fed by the reformed gas (H_2, CH_4, CO, CO_2 and H_2O) [22]. The fuel cell performance was implemented considering: adiabatic stack, uniform cell voltage, reactions at equilibrium and CO electrochemical reaction neglected. More details on this model were shown in [18]. The reformer model (calculating the methane reforming and shifting reactions) was developed including the active surface for heat transfer and catalytic reactions at chemical equilibrium. The off-gas burner was implemented considering the inlet-outlet energy balance equation. The ejector was based on mass flow rate, momentum and energy equations applied between the inlet and the outlet ducts. Finally, the blower model was simply implemented considering the calculation of power consumed by this component to obtain the requested recirculation.

Since the real-time performance is essential, the mass-continuity approach was chosen [18]: components were connected to receive mass flow information from the upstream or downstream device and the pressure information in the opposite direction. Instead of using time constants [23] for the transient phenomena, all the components were based on a physical approach. They were modeled including the following differential equations: mass continuity, momentum, and energy [18]. In details, the energy equation was implemented including the thermal capacitance of the component material, due to its extreme importance in components, such as the stack and the reformer [22].

HARDWARE-IN-THE-LOOP APPROACH

The HIL approach developed for emulation of SOFC based hybrid systems is shown in Fig.4. The signals between the plant control system (in LabVIEW) and the model (in Matlab-Simulink) are exchanged with UDP connections. The input is the fuel cell load that can be set by the operator. This value is used inside the simulation tool (the real-time model discussed in the previous section) to evaluate the performance of such components which are not physically installed in the rig. The tool receives (in real-time mode) the values of the following properties from the plant: mass flow rate, pressure, temperature at the cathodic vessel inlet and T100 rotational speed. The simulation model produces calculated values of TOT (TOT_C in Fig.4) and fuel mass flow rate (or better the VP fractional opening value to obtain the same air mass flow rate in the anodic ejector primary duct in the plant). It calculates also the VM fractional opening value through the fuel cell temperature control system. So, VM operates as a bypass valve, decreasing the air flow in the cathodic vessel (and also in the FC model) at part-load condition, because the stack inlet temperature has to be maintained constant during operations. The testing activities on this SOFC temperature controller are the core of the HIL application to generate a significant improvement in such kind of hybrid systems. The tested different control strategies and the related results are presented in a following devoted section.

All the simulation tool output values are used inside the control/acquisition (C/A) system to manage the plant. While VM fractional opening values are used for controlling SOFC temperature in both stand-alone and grid-connected modes, two different approaches were developed for the two different T100 configurations. Table 1 shows that in both cases the microturbine is controlled by its standard control system implemented in the T100 Power Module Controller (PMC). However, two different approaches are used in the two different cases. In the stand-alone mode it is not possible to directly match measured and calculated TOT values. For this reason, the matching between the model and the plant is carried out by changing the T100 load to obtain the calculated TOT value in the rig (this is carried out with the help of a Proportional Integral (PI) controller implemented inside the LabVIEW software). This is a limitation for the emulation flexibility due to the machine standard control system constraints. However, this is a significant improvement for the hybrid system research because this approach allows the application of commercial machines instead of special design components.

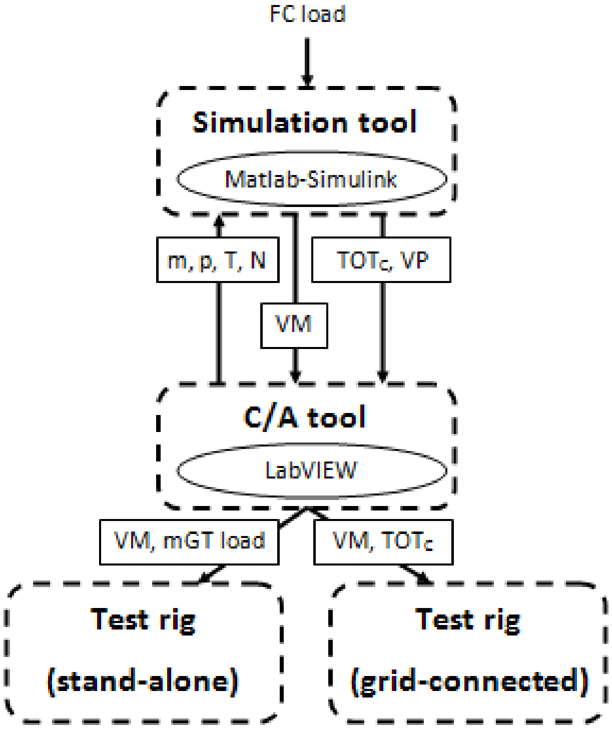

Figure 4. Model/plant interactions.

A simpler approach was developed for the grid-connected mode: thanks to a modification in the T100 control software, the turbine receives the TOT set-point value directly from the model. So, in this case the C/A tool is just an interface to transfer the TOT calculated value to the T100 PMC.

Table 1. Different control approaches for the microturbine.

	C/A tool	T100
Stand-alone	Load calculation and transfer to match TOT_M with TOT_C	Constant N
Grid-connected	TOT set-point transfer	Constant TOT

In both cases, the HIL approach is a good compromise between the costs of a complete prototype and the limitations of a complete model. Even if a validated model is necessary for components not physically present in the rig, the microturbine and the SOFC emulation system can produce experimental results reliable for specific tests. For this reason, this emulation approach is considered essential for tests on the SOFC/mGT matching especially during transient operations and the development of a reliable control system for the real plant.

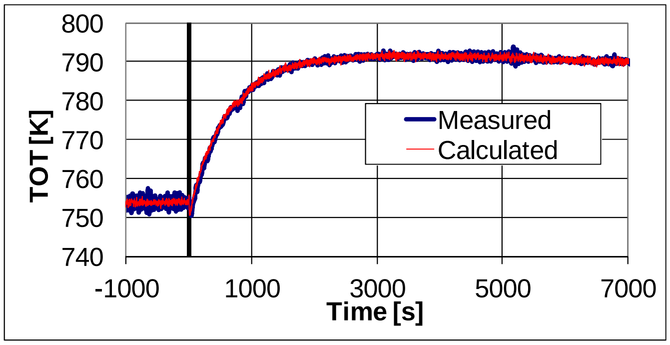

Figure 5. 10% fuel cell power increase: TOT matching between measured and calculated values.

PRELIMINARY RESULTS

Since in the stand-alone mode the model/plant interaction includes an indirect approach to match the TOT_M value with the TOT_C, a preliminary experimental analysis was carried out to define an apt Proportional Integral (PI) control system [24]. In comparison with the plant developed by NETL (where the real-time tool is able to directly operate on the fuel mass flow rate), here it is necessary to consider that the microturbine is managed by its standard control system. Since it operates on the fuel flow to maintain constant the rotational speed, the only reasonable approach to match the model output (calculated TOT) with the plant is linked with mGT load change (TOT increases with load increase). So, this PI is implemented in LabVIEW to evaluate the load value necessary to obtain the calculated TOT value in the plant. Thanks to the Ziegler-Nichols technique [24,25], it was possible to obtain the PI coefficients (considering Eq.1 for the calculation of the control variable u(t), that is the mGT load in this case): K_p=0.0012 for the proportional part and K_i=0.0022 for the coefficient that multiplies the error value upstream of the integration.

$$u(t) = K_p \cdot e(t) + K_i \int_0^t e(\tau) \cdot d\tau \qquad (1)$$

To show the performance obtained with this PI controller (necessary to obtain in the rig the same TOT values calculated by the model), Fig.5 shows the comparison between the TOT calculated and measured values obtained for a fuel cell load step increase (from 80% to 90% of its nominal value). The step was operated at time zero in Fig.5. However, no control system impacts (on the SOFC based plant) are considered here because the topic is discussed in the following section. No SOFC temperature control was included and, for this reason, VM was maintained at constant position during the test. Since VM did not changed the SOFC bypass mass flow rate, the air feeding the SOFC was almost constant. For this reason, a fuel cell load increase (fuel flow rate was also increased in the model) generated the temperature increase that is also visible in the TOT trend (Fig.5). These values show that the control system was able to generate a measured TOT that is matching with good accuracy (except of few peaks with differences close to ±4 K, average errors were in the ±2 K range) the related values calculated by the Matlab-Simulink model.

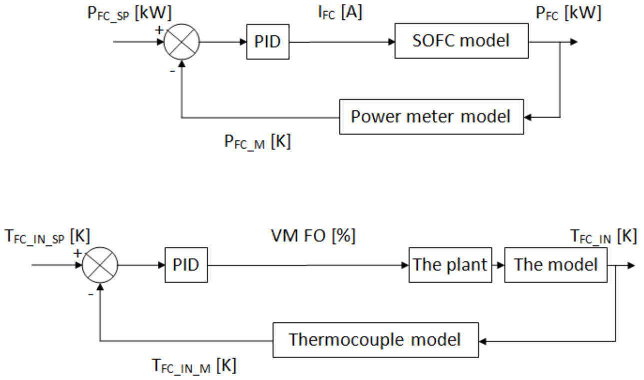

Figure 6. PID controller: SOFC temperature control system and related interactions with the SOFC power controller.

RESULTS ON SOFC TEMPERATURE CONTROL

Since in SOFC hybrid systems it is necessary to maintain constant the fuel cell temperatures during load changes, special attention was devoted on this aspect. Due to the SOFC ceramic material limitations, it is necessary to avoid thermal stress by maintaining constant the temperatures at both steady-state and transient conditions. Even if the maximum acceptable thermal gradient depends on the fuel cell type (design and material), some authors considered the maximum acceptable time-dependent temperature variation of 3 K/min [14,26,27]. The control system performance assessment considering this thermal gradient limitation is an important aspect of such hybrid systems, since several authors working on this topic did not take into account this important constraint [28,29].

As shown in Figs.6-8, the HIL approach was essential to perform experimental tests on such fuel cell temperature control system. In all the tests, the SOFC temperature control was carried out by fixing a set-point value (1024 K) for the cathodic side inlet temperature and maintaining this value through the management of the VM valve. The tests were carried out with the mGT in stand-alone mode to compare the performance of the following three different control approaches:

- Standard PID tool (Fig.6).
- PID controller including an Anti-Wind up (AW) and a Feed-Forward (FF) additional tools (Fig.7).
- Model Predictive Control (MPC) tool (Fig.8).

While using the standard PID tool the SOFC temperature controller was completely separated from the SOFC power control system, in the other cases a significant coupling level was included. In the PID controller including AW and FF tools the connection with the SOFC power control system regarded the fuel cell current. The MPC controller is based on a Multi

Input and Multi Output (MIMO) approach because both control signals were calculated by this MPC tool.

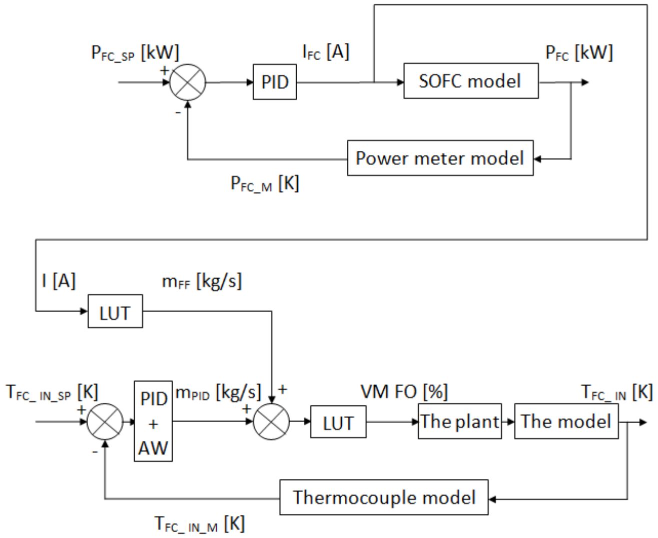

Figure 7. PID controller including Anti-Wind up (AW) and Feed-Forward (FF) tools: SOFC temperature control system and related interactions with the SOFC power controller.

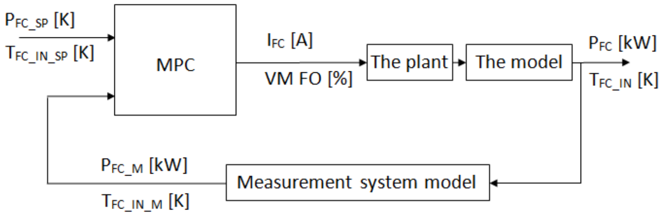

Figure 8. MPC controller.

Before performing each HIL test it is necessary to prepare the plant considering the following procedure:

- Microturbine start-up in stand-alone mode considering the standard recuperated layout (VM fully open and VR, VO, VP, VB, VBE, VBCC fully closed) and load increase up to the maximum.
- Slow connection with the cathodic vessel (VR, VO were slowly opened and VM was slowly closed considering the heating time of the vessel).
- VP opening operation to generate a significant flow in the anodic vessel for heating reasons.
- Waiting time (at least 3 hours) necessary to reach the steady-state condition (this long time is necessary because of the slow vessel thermal response due to its high thermal capacitance).
- Connection establishment between the Matlab-Simulink real-time model and the LabVIEW software (UDP based exchange of data).

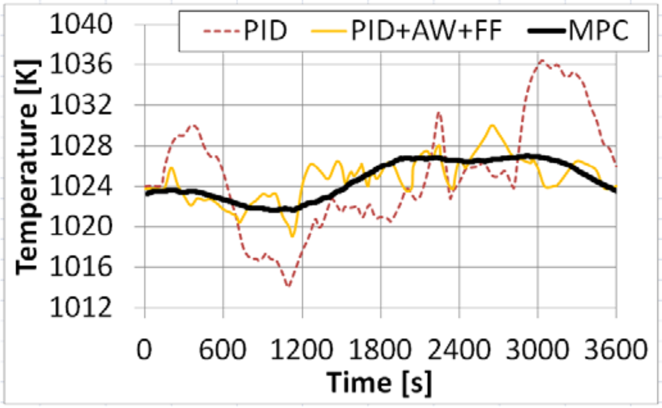

Figure 9. SOFC cathode inlet temperature with the three different controllers during the double ramp test.

Table 2. Performance of the SOFC temperature controllers tested with the HIL configuration.

Controller type	T oscillations	$(\Delta T/\Delta t)_{max}$	Ref.
PID	±12.4 K	6.4 K/min	[30]
PID+AW+FF	±6.0 K	4.8 K/min	[30]
MPC	±3.0 K	1.0 K/min	[31]

At this point it was possible to operate the tests considering a 900 s load ramp (from 100% to 80% of the SOFC load) started after 200 s from the test beginning, followed by a constant load zone at 80% condition for the fuel cell (1000 s). Then, an increase ramp was implemented from 80% to 100% of the stack load (operated in other 900 s) and the tests were concluded maintaining this load at the 100% value (for other 600 s). This input load value was the same for all the three tests operated with three different control systems for the fuel cell temperature.

The main result of these tests is the fuel cell cathodic inlet temperature that is the temperature controlled by the VM FO. Figure 9 shows this temperature values obtained with the three control systems during the tests operated with the same SOFC load ramps. The most significant aspects of these results are shown in Table 2 for temperature maximum oscillation and time-dependent gradient. To complete the result analysis Fig.10 shows the mean values and the 95% Confidence Intervals (CI) related to Fig.9 data (see [32] for 95% CI definition).

The PID controller (tuned with the Ziegler-Nichols technique [33,34]) was able to generate a stable behavior for the cathodic inlet temperature. The related confidence interval that includes the set-point value (1024 K) shows an important positive aspect of this controller: this approach (not including scheduled or predictive aspects) is able to compensate the error also in case of mismatch with the planned conditions (e.g. due to SOFC degradation). However, a high oscillation (±12.4 K) was present, as shown in [30]. This is not acceptable for SOFC ceramic material that is not able to sustain this kind of thermal stress. This aspect was underlined by the 6.4 K/min maximum time dependent gradient that is very high in comparison with the 3 K/min mentioned constraint. The PID control response evaluated with this HIL technique was in agreement with the previous works [26,29] which are stating that simple PID controllers cannot avoid such significant thermal gradients in the stack. This is due to the fact that the necessary decrease in the air mass flow rate is obtained only with excessive temperature errors (behavior due to the SOFC high thermal capacitance [26]).

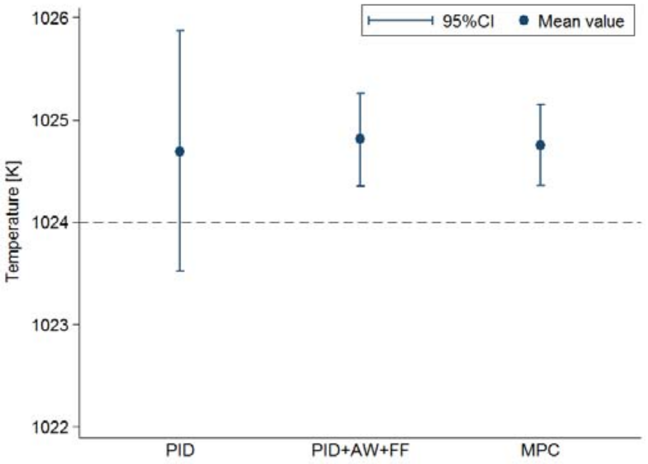

Figure 10. Mean values and 95% confidence intervals for the cathode inlet temperature with the three different controllers during the double ramp test.

The second case (PID+AW+FF controller) was able to improve the time-dependent temperature trend, as calculated with only theoretical approach in [26]. While the experiments showed that oscillations were contained inside the ±6.0 K range [30], the thermal time dependent gradient (4.8 K/min) remained higher than the mentioned constraint. Since this gradient is affecting a very small temperature variation, the control approach can be considered acceptable for this load variation. However, a faster variation in the load input value can be seriously dangerous for the stack. So, it would be essential to have smooth load changes on the fuel cell using an apt electrical device, such as the battery package considered in [26]. Considering the statistic analysis, in this case the set-point value is outside of the confidence interval. This is due the scheduled look-up table implemented to calculate the VM FO values. Since external disturbances are always present, it is possible to have significant mismatches with the scheduled plant behavior. However, in this case, the difference between the CI lower limit and the set-point value is small due to a good LUT development. Possible higher mismatches can be generated in case of component degradation or other important disturbance effects.

The best performance was obtained with the MPC technique [35-37] using the apt Matlab-Simulink toolbox [31]. As shown in Tab.2, the MPC controller was able to maintain the cathode inlet temperature in the ±3.0 K range with a maximum time-dependent gradient of 1.0 K/min. However, since the MPC approach is based on a linear technique and the plant is not linear, it was necessary to use multiple MPC tools (each one obtained with the system linearization operated at a specific load value) [31], with a significant increase in computational effort. Moreover, the tuning of these MPC tools required a complete system model that was linearized in several operative points requiring a significant effort for both model development and calculations. Another drawback is also shown by the 95% CI values (the set-point is not included inside the CI extreme values). Also in this case, due to the predictive approach, it is possible to have significant mismatches between the implemented predictive tool and the real behavior (e.g. for disturbances).

Considering these results obtained with the HIL approach (as shown in [18,30,31]), it is possible to conclude that the second case (PID+AW+FF controller) could be the best compromise between performance and tuning effort. However, this control approach requires additional systems (e.g. battery packages) to smooth large variations in load values. On the other hand, the MPC tool is able to obtain better performance (load changes operations are safe also without smoothing devices), but with a more extensive tuning effort. Due to the possible mismatches between the planned and the real behavior (according with the 95% CI discussion), a possible combination of MPC approach with the PID solution could be evaluated.

EDUCATIONAL OPPORTUNITIES

The unique aspects related to this HIL configuration generate important opportunities also at educational level. As discussed in [38], including a comparison with the "Hyper" facility by the NETL, the flexibility of this test rig is linked with important benefits for students that can be involved in several different activities on hybrid plants: new system configurations, control strategy development, evaluation of critical aspects, etc. In details, it is possible to classify the educational activities with the following points:

- The rig is an important opportunity for undergraduate students to experience real hardware components after the theoretical basic classes. This plant allows the students to be involved in limited scope laboratory projects as requested for short training activities (consistent with the undergraduate level). So, they can receive training about the equipment (e.g. material constraints, correlations, safety aspects, etc).

- The postgraduate students are usually involved in more extensive analyses, such as design of further components, start-up/shutdown phases, load changes, compressor surge, etc.
- Ph.D. students provide substantial research contributions using the entire HIL approach described in this paper. They collaborate with researchers and professors to plan and execute experimental tests on the entire dynamic aspects, the control system development and the implementation of innovative solutions. Significant advancements of the state-of-the-art have been achieved in such kinds of activities related to power generation with SOFC based hybrid systems [18,30,31].

FUTURE WORKS

During the next years, the TPG is planning further activities using this experimental facility in HIL configuration, as in agreement with the newest research issues for hybrid system development (such as SOFC degradation impact, advanced control strategies, surge prevention through measurable precursors, etc.) [39-43]. An initial work will be carried out to assess the SOFC temperature control system considering the grid-connected mode configuration for the T100 turbine. In comparison with the stand-alone approach considered for the previous results [30,31], this operation mode will enable the researchers to control SOFC temperature not only through the air bypass, but also with the turbine speed variation. While the operation on the VM valve could be used for preliminary tests, the SOFC temperature would be controlled by changing the T100 load to have the apt rotational speed change. This is an important additional feature because the rotational speed decrease at part-load condition is able to generate higher efficiency values in comparison with the air bypass approach [26].

The following experimental analyses are planned for this facility in HIL configuration:

- Emulation of ambient temperature change effect [26] and the related issue on control system.
- Emulation of SOFC degradation effect [39] on system performance and control system issues.
- Development of a control system which is able to prevent surge conditions (this would be possible by considering instability precursors [44-46]).
- Analysis of the volume size effect on the entire plant in terms of compressor stability, time-dependent response, etc.
- Experimental analysis of optimized management for hybrid systems in smart polygeneration grids [47].

For all these planned future activities, the student involvement (especially for Ph.D. courses [38]) will be essential to maximize the benefits for both learning experience and research opportunities. Student and personnel exchange programs could be important for international collaborations devoted to the hybrid system development targets.

CONCLUSIONS

The Thermochemical Power Group of the University of Genova has developed a HIL technique to perform experimental analyses on SOFC based hybrid systems. This is an important approach based on an experimental plant including a recuperated microturbine connected with a system able to emulate the SOFC stack. A real-time model is coupled with the experimental facility to simulate the components which are not physically included in the plant, such as the SOFC, the reformer, etc. This tool is able to calculate the performance necessary to generate real operative conditions of the hybrid system in the test rig. The main results presented in this work are summarized in the following points:

- The software/hardware coupling is carried out through the load change in stand-alone mode (to obtain a TOT_M value equal to the calculated one). In grid-connected operations, the direct TOT set-point change is presented, but not tested yet (at the moment).
- This HIL technique is essential for studying the SOFC/mGT matching especially for the control system point of view.
- The simple PID controlling approach is not able to safely control the fuel cell temperature due to high oscillation (±12.4 K in the ramp SOFC load variation shown in this work) and unacceptable time dependent gradient (up to 6.4 K/min) related to this property. However, it this approach is able to compensate disturbances or other mismatches between the planned and the real plant behavior.
- The PID+AW+FF controller could be the best compromise between performance (oscillations contained inside the ±6.0 K range and time dependent maximum gradient equal to 4.8 K/min) and tuning effort. However, this control approach requires additional systems (e.g. battery packages) to smoothen large variations in load values to obtain acceptable gradient values (lower than 3 K/min). Another significant drawback (shown by the statistic analysis) is related to the difficulties to compensate disturbances and component modifications (e.g. for degradation).
- MPC tool is able to obtain better performance (oscillations in the ±3.0 K range with a maximum time dependent gradient of 1.0 K/min), but with a more extensive tuning effort and poor performance in terms of disturbance compensation.
- This HIL configuration is a significant opportunity for both students and researchers to

be involved in several different activities on such hybrid plants.

Thanks to the plant high flexibility, several research activities are planned to study important hybrid system issues, such as ambient temperature effect, surge prevention and optimization of generation operations, etc.

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