Grant No.: 641073

Bio-HyPP

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<td>Hybrid system emulation results</td>
<td>30.11.2017</td>
<td>WP 3 / UNIGE</td>
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Short Summary

This document describes the deliverable D3.2 “Hybrid system emulation results” (Report).

In WP3 the existing hybrid power plant test rigs at DLR, NETL and UNIGE have been adapted and optimized for further experiments to provide results for the optimization of gas turbine components, operation and control strategies for the real demonstrator in WP4. In addition, the results are used in WP1 for model validation.

- At DLR, it was planned to use the hybrid power plant test rig based on the Turbec T100PH MGT for the investigation of different air inlet temperatures, biogas mixtures and for the comparison of different emergency procedures. Due to various issues with the test rig, it was decided to be more beneficial to re-allocate the work from WP3 to WP4. In WP4, a hybrid power plant test rig based on the MTT EnerTwin 3kW MGT is set-up and used for experiments.

- UNIGE used the hybrid power plant test rig based on the Turbec T100 to perform tests with different volume sizes at transient conditions. In detail, experimental results were carried out considering the transient response due to an on/off bleed valve operation. So, the main differences between system parameters obtained for a bleed line closing operation were compared considering three different volume sizes. Moreover, special attention was devoted on surge tests. It was possible to compare the effect of different volume sizes on main properties of the system using a modular vessel. Particular focus was devoted to the operational curve plotted on the compressor map. The system was equipped with different dynamic probes to measure the vibrations during normal and surge operations. Possible surge precursor indicators were obtained for the detection of risky machine operations.

- Third party NETL used the Hybrid Performance (HyPer) emulator facility, based on the 120 kW Garrett micro gas turbine coupled to a fuel cell emulator to analyse the manoeuvres start-up and emergency shutdown. The hardware components of the fuel cell emulator were connected to a numerical model of a solid oxide fuel cell (SOFC) and post-combustor. The real-time, distributed model was modified to include local information on fuel cell degradation. Thereby investigations have been carried out on the impact that fuel cell degradation has on the whole system performance and controllability.
**Dissemination Level**

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<th>Description</th>
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<tbody>
<tr>
<td>BA</td>
<td>Bleed Air</td>
</tr>
<tr>
<td>bpf</td>
<td>Blade Pass Frequency</td>
</tr>
<tr>
<td>CA</td>
<td>Cold Air</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
</tr>
<tr>
<td>CHP</td>
<td>Combined Heat and Power</td>
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<tr>
<td>ESD</td>
<td>Emergency shutdown</td>
</tr>
<tr>
<td>FLOX®</td>
<td>Flameless oxidation; registered trademark of WS Wärmprozessstechnik GmbH</td>
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<tr>
<td>FT</td>
<td>Mass Flow Rate Sensor</td>
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<td>N</td>
<td>Shaft Speed</td>
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<td>PT</td>
<td>Power Transducer</td>
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<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>SOFC</td>
<td>Solid Oxide Fuel Cell</td>
</tr>
<tr>
<td>T</td>
<td>Temperature</td>
</tr>
<tr>
<td>TE</td>
<td>Thermocouples</td>
</tr>
<tr>
<td>TOT</td>
<td>Turbine Outlet Temperature</td>
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1 Introduction

Bio-HyPP is a four-year Horizon 2020 EU funded project started on 1st June 2015. The project aims to develop a full-scale technology demonstrator of a hybrid power plant using biogas as main fuel, in order to reach the goals of improving efficiency of CHP systems while simultaneously widening the biomass feedstock base as well as increasing operational flexibility.

The objective of WP3 is a comprehensive experimental assessment of the integrated system, based on hybrid system emulation, to provide the necessary knowledge and practical skills to mitigate remaining integration risks and to guide the full plant demonstration of WP4.

As part of WP3 “Subsystem Testing and Subsystem Emulation”, the existing hybrid power plant test facilities with SOFC emulation of DLR, UNIGE and NETL have been upgraded for the project scope, including supply of different fuel types as biogas. A detailed report of the upgrades is given in Deliverable D3.1 “Upgraded hybrid system emulation rigs”. The different features of the three rigs were exploited in a complementary way to cover all operating conditions of the demonstration plant, thus investigating, already at experimental level and without the risk of damaging the fuel cell stack, the full operational envelope of the hybrid system. The experimental results form the basis to further optimise the components of the micro gas turbine subsystem under coupled condition, as well as the operation and control strategies of the hybrid power plant demonstrator built up in WP4. Furthermore, the results will be used in WP1 for validation of the detailed static and dynamic thermodynamic models of the system.

This report constitutes Deliverable D3.2 “Hybrid system emulation results” for the Bio-HyPP project, and concerns the investigations performed at the different existing and upgraded hybrid power plant test rigs.

The following chapters show the aims and the results of the different investigations.

Chapter 2 lists the tasks and objectives of the investigations as part of WP3.

In Chapter 3 a brief description of each test rig is given.

Chapter 4 describes the investigations and the results at the different test rigs in detail.

Finally, conclusions are drawn in Chapter 5.
2 Tasks and objectives

Based on the upgraded hybrid system emulation test rigs of DLR, UNIGE and NETL, the following investigations were performed:

- UNIGE worked on tests with the T100 machine connected to different additional volume sizes (4.1, 2.3 and 0.3 m$^3$). The following tests were carried out and analysed: (i) bleed valve (VBE) closing step with three different volume sizes, (ii) T100 surge event, and (iii) definition of possible surge precursors.

- NETL analysed the ancillary manoeuvres start-up and emergency shutdown. Furthermore, NETL performed theoretical and experimental analyses on the impact that fuel cell degradation has on the whole system performance and controllability. The general target is to draw lessons and guidelines on how the control system should best cope with fuel cell degradation along the plant life.

- At DLR, it was planned to use the hybrid power plant test rig based on the Turbec T100PH MGT for the investigation of different air inlet temperatures, for the analysis of the impact of biogas mixtures on the operational stability and for the comparison of different emergency procedures. Due to various issues with the test rig, it was decided to re-allocate the work from WP3 to WP4. In WP4, a hybrid power plant test rig based on the MTT EnerTwin 3kW MGT is set-up for experiments. In Chapter 4, the changes are marked.
3 Test rig description

3.1 DLR emulation facility

The test rig is shown in Figure 1 and described in detail in [1,2]. It is based on the commercially available grid connected Turbec T100PH series 3 MGT with an electrical power output of 100 kW at full load with 30% electrical efficiency. It is composed of radial turbo-components mounted on one single-shaft with a maximum shaft speed of 70000 rpm at a pressure ratio of 4.5:1. For the investigations, an adapted version of the control system is used. The modified control system allows either to set an electrical power output limit or a turbine speed limit at different Turbine Outlet Temperatures (TOTs) and to adapt the maps for the Pilot stage of the combustor. In this configuration, the operational area is between 78% (54600 rpm) and 100% (70000 rpm) turbine speed. For WP3 the test rig was equipped with an air conditioning system to control the inlet temperature to the compressor. It allows to cool or to heat the incoming air. The fuel supply and fuel valves were adapted for the preparation and use of different biogas and natural gas mixtures and a new combustor was implemented. An emulator replaces the real SOFC. It consists of two pressure vessels. The first pressure vessel represents the cathode volume and includes installations to adapt the residence time and pressure loss. The installations direct the flow through the pressure vessel. The size is originally based on an estimated volume of a Siemens fuel cell system in tubular design with 1152 cells. The second pressure vessel has been equipped with a gas preheater. It emulates the varying SOFC temperature and is composed of a natural gas combustor. This two-stage combustor allows a wide range of different preheating temperatures. With this emulator set-up, the thermodynamic and fluid dynamic properties of a SOFC cathode side can be emulated.
3.2 UNIGE emulation facility

The experimental test rig is based on a modified commercial recuperated microturbine (Turbec T100) connected to external vessels located between the recuperator outlet and the combustor inlet (Figure 2) [3-5].

For emulations of fuel cell based hybrid systems, a modular vessel was installed to represent the cathodic side of a fuel cell and a second vessel was included for the anodic side (with a recirculation system based on a single stage ejector). The modular vessel is based on two collectors connected to four module pipes. These collectors and modules are 0.35 m diameter pipes for a total length of 34 m approximately. The second vessel (the anodic one in the "fuel cell emulator") is a fifth pipe of 0.35 m diameter. The rig is equipped with connection pipes including control valves for flow management. The total volume related to the vessels and these connection pipes (additional to the standard T100 layout) is about 4.1 m³. The test rig is also equipped with a check valve downstream of the compressor outlet and with the following main control valves:

- VM, and VO, to manage the connection with the modular vessel and
- VBE, an on/off emergency valve, to discharge a part of the air flow through bleed operations.

The simplified plant layout is shown in Figure 3.

Figure 2: Picture of the facility before the upgrade
The test rig [3-5] is operated through a data acquisition and control system developed in LabVIEW™ environment. It includes the data operations on all the probes installed to measure mass flow rate, pressure and temperature in the ducts. During load changes, it operates on the fuel flow to maintain the Turbine Outlet Temperature (TOT) constant, to a value of 918.15 K. The control software developed in LabVIEW™ was also equipped with an interface to obtain all the values measured by the turbine system for performance evaluation. Since the ambient temperature is very significant for gas turbine operations, an additional system was installed to control the compressor inlet temperature (TC1). It is composed of three air/water heat exchangers located in the compressor intake ducts (“Ex”) used for TC1 control operations through water flow operated in open circuit or cooled by an absorption chiller. The turbine is able to produce 100 kW electrical power (in grid-connected operations) in nominal conditions with 30% (±1%) electrical efficiency (nominal rotational speed is 70000 rpm). Due to the microturbine modifications and the volume temperature and pressure losses, the maximum load operating conditions are different from the T100 nominal values. So, the system is able to operate at 73.5 kW maximum net power at 300 K compressor inlet temperature with 68300 rpm rotational speed (Turbine Outlet Temperature: 918.15 K). Figure 4 also shows how the three module pipes can be disconnected (the large arrows on the part a) of the figure) to reduce the volume size connected to the microturbine.
Vibration and acoustic measurements were conducted using a Siemens SCADA mobile data acquisition system, which allows to acquire 8 different channels with frequencies up to 204.8 kHz sampling rate per channel, at the same time. Structural measurements were performed using mono and tri-axial accelerometers located on the compressor side of the microturbine on the electric generator case. Sensor dynamic characteristics allowed investigating the frequency signals up to 10 kHz. Two micro accelerometers were used in order to extend vibration investigation to the higher frequencies, in the range of blade pass frequency (bpf) phenomena. The first, placed in radial position has a resonance frequency higher than 55 kHz, the second, axially oriented has frequency of 80 kHz. Acoustic measurements were carried out with a pre-polarized Gras microphone with range between 2 and 50 kHz of dynamic response.
3.3 NETL emulation facility

The HyPer facility, shown in Figure 5, is described in details elsewhere [11]. This facility represents the coupling between a cyber-physical SOFC and a recuperated gas turbine. The gas turbine is a 120 kW Garrett Series 85 auxiliary power unit designed to deliver approximately 2 kg/s of air at a pressure ratio of 4 and a nominal rotational speed of 40,500 rpm. Two parallel heat exchangers are used for exhausts heat recovery. Turbomachinery and recuperators are directly coupled with the physical components of the cyber-physical SOFC, which consist of: a pressurized vessel to emulate the volume of the cathode and air manifold, including pressure dynamics and residence time; a natural gas combustor to emulate the thermal power coming out of a real SOFC; and a second pressurized vessel that represents the volume of the post-combustor in an SOFC stack. Multiple mass flow rate sensors (FT in Figure 5), thermocouples (TE), and pressure transducers (PT) are located in the facility. Airflow, temperature, and pressure measurements at the inlet of the cathode volume are used as inputs for the real-time, distributed SOFC model that simulates the performance of a 200-600 kW planar SOFC and drives the fuel valve in the natural gas combustor with a feedforward controller. Measurement are acquired and sent to the model every 80 milliseconds.

Figure 5: Diagram of the HyPer facility including sensors and connections
4 Results

4.1 Analysis of hybrid system stability at different operational conditions

4.1.1 Impact of different ambient temperatures
The tests were planned within DLR measurement campaign and were reallocated to WP4. The results will be reported in D4.2 “Characteristics of the hybrid power plant with emulated SOFC”.

4.1.2 Impact of different biogas mixtures
The tests were planned within DLR measurement campaign and were reallocated to WP4. The results will be reported in D4.2 “Characteristics of the hybrid power plant with emulated SOFC”.

4.1.3 Influence on surge margin

4.1.3.1 Influence of Bleed air blow-off on surge margin
Tests were carried out to show the different transient responses due to the T100 coupled with different additional volume sizes. All the three tests started from steady-state condition with the microturbine producing 40 kW electrical load and 0.06 kg/s discharged mass flow rate through the bleed valve (VBE).
This initial condition was selected considering the following purposes: significant off-design condition (usually these advanced systems need to be very flexible in terms of part-load operations), initial condition with a large margin from surge, avoidance of too low load values where the machine control system reduces the Turbine Outlet Temperature (TOT) set-point to decrease surge risk, and an initial condition feasible with the plant equipment (e.g. the VBE size).

4.1.3.2 Influence of different volume size on surge margin
The values of the main properties related to these initial steady-state conditions ("ic") are reported in the following table (Table 1) for three different volume sizes.
At time zero the VBE was closed with a step (it is an on/off valve). This operation was able to generate a pressure peak in the recuperator inlet pressure (PRC1) showing the transient response of the system. This VBE closing step was selected (instead of a load step) to analyse the machine different transient responses with the different volume sizes. The steady-state pressure values obtained before the VBE closing steps are: 3.40 bar, 3.42 bar, 3.27 bar with 4.1 m$^3$, 2.3 m$^3$, 0.3 m$^3$, respectively. No significant difference is obtained between the 4.1 m$^3$ and the 2.3 m$^3$ cases, because the removal of the three module pipes is not generating a significant increase of pressure loss (2 mbar over 178 mbar). However, for the 0.3 m$^3$ test, Table 1 above shows a lower PRC1 value at the initial steady-state condition. This effect is due to the decrease in rotational speed (to obtain the same generated power) that is mainly related to the decrease in pressure loss (significant removal of the vessel additional pipes).

**Table 1: Initial condition values (subscript "ic") for the VBE step test**

<table>
<thead>
<tr>
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<th>2.3 m$^3$</th>
<th>0.3 m$^3$</th>
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<tr>
<td>PRC1 [bar]</td>
<td>3.40</td>
<td>3.42</td>
<td>3.27</td>
</tr>
<tr>
<td>N [rpm]</td>
<td>62805</td>
<td>62926</td>
<td>61637</td>
</tr>
<tr>
<td>Air mass flow rate [kg/s]</td>
<td>0.593</td>
<td>0.594</td>
<td>0.534</td>
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<tr>
<td>Pressure loss [mbar]</td>
<td>178</td>
<td>180</td>
<td>116</td>
</tr>
<tr>
<td>TOT [K]</td>
<td>918.15</td>
<td>918.15</td>
<td>918.15</td>
</tr>
<tr>
<td>Net power [kW]</td>
<td>40.0</td>
<td>40.0</td>
<td>40.0</td>
</tr>
<tr>
<td>Kp [-]</td>
<td>1.19</td>
<td>1.18</td>
<td>1.11</td>
</tr>
</tbody>
</table>
Moving from the maximum to the minimum additional volume size, Figure 6 shows different peak time values: 10.1 s for 4.1 m³, 7.8 s for 2.3 m³ and 2.3 s for 0.3 m³. While the PRC1 transient trends are significantly driven by the rotational speed trends (Figure 6 - part B), the volume size effect is shown by the pressure peak delays (about 7 s, 2 s and 0.7 s for 4.1 m³, 2.3 m³, 0.3 m³, respectively) from the related rotational speed peak.
Figure 7: VBE closing step (combustor inlet mass flow rate (A) and pressure losses between the recuperator and the combustor inlet ducts (B))

Figure 7 shows the direct consequence of the rotational speed: the air mass flow rate (measured with two different probes due to two different layouts) and the global pressure drop between the recuperator outlet and the combustor inlet. Both operational parameters are mainly following the rotational speed trend, even if few differences in the peak time locations are present, due to the pressure-rotational speed link in compressor performance maps. The delay effect related to the volume size is also shown by the TOT value that is maintained constant by the turbine controller. However, limited oscillations are present, showing significant delay increase (Figure 8 - part A) in correspondence of the volume increase. This effect is also significant in the trend of the net electrical power (Figure 8 - part B) produced by the microturbine.
While the controller was able to recover the 40 kW condition, a significant oscillation was generated in all cases. After the bleed valve closing step and about 1 s dead time, the power increased due to the suddenly mass flow rate increase. Then, an oscillation was generated due the control system response that managed the fuel valves. These tests are also represented on the compressor map (Figure 9).

Figure 8: VBE closing step (TOT (A) and net electrical power (B))

Figure 9: VBE closing step (transient operation on the compressor map (each compressor curve is plotted for the same N/N₀ value))
While the trend is almost linear for the 0.3 m³ test, the volume increase generates a sort of “hook” path that is more evident with the largest volume size. So, a significant surge margin decrease during this transient operation is shown in Figure 9 and Figure 10.

![Figure 10: VBE closing step: surge margin](image)

This effect is significantly amplified by the volume size (the highest surge margin decrease during the transient operation is related to the 4.1 m³ case). In detail, Figure 10 shows that large volume layouts, even operating with high surge margin condition in steady-state mode, could be critical in case of more intensive similar operations. This aspect needs to be carefully taken into account by the control system for the real reference plant.

4.1.3.3 Influence of TOT reduction on surge margin and comparison with bleed-air blow off

The tests with TOT reduction were planned within DLR measurement campaign and were reallocated to WP4. The results will be reported in D4.2 “Characteristics of the hybrid power plant with emulated SOFC”.
4.2 Analysis of hybrid system stability with different cathode volumes

4.2.1 Surge margin
The results reported here are related to a second series of tests carried out with different volume sizes. Also in this case, the microturbine was operated in grid-connected mode with the variable speed control system (the TOT value is maintained constant at its set-point (918.15 K) up to the surge events changing the fuel mass flow rate). These tests were carried out to generate surge conditions closing a valve located in the air path (between the recuperator outlet and the combustor inlet). This operation generated a significant increase in pressure loss and, as a consequence, in PRC1, leading the turbine to the surge zone.

4.2.2 System behaviour with 3 different volumes
The values of the main properties related to the surge limit (last stable measured points) are reported in Table 2 for the different volume sizes (“ref” subscript).

Table 2: Last stable measured values (subscript "ref") for the main line valve closing test

<table>
<thead>
<tr>
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<th>4.1 m³</th>
<th>2.3 m³</th>
<th>0.3 m³</th>
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<tr>
<td>Pressure loss [mbar]</td>
<td>611</td>
<td>520</td>
<td>457</td>
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<tr>
<td>N [rpm]</td>
<td>62021</td>
<td>64426</td>
<td>63681</td>
</tr>
<tr>
<td>Net power [kW]</td>
<td>20.0</td>
<td>35.2</td>
<td>39.1</td>
</tr>
<tr>
<td>Air mass flow rate [kg/s]</td>
<td>0.517</td>
<td>0.547</td>
<td>0.533</td>
</tr>
<tr>
<td>PRC1 [bar]</td>
<td>3.50</td>
<td>3.73</td>
<td>3.66</td>
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<td>TOT [K]</td>
<td>918.15</td>
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<tr>
<td>Kp [-]</td>
<td>1.00</td>
<td>1.00</td>
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Figure 11: Main line valve closing: pressure losses between recuperator and combustor inlet ducts (A), surge approaching on the compressor map (each compressor curve is plotted for the same $N/N_0$ value) (B) and rotational speed (C).

Figure 11 (part A) shows the pressure loss (between recuperator and combustor chamber inlet ducts) that was increased by the main valve gradual closing operation. Then, the effect of the surge events (happening at time zero for all cases) is shown by the pressure drop oscillations. Table 2 shows a significant difference between the pressure loss values necessary to reach the surge line. This is due to the different paths (shown on the compressor map by Figure 11 - part B) that were followed by the operating points to reach surge conditions.

To discuss this aspect more in detail, Figure 11 (part B) shows a comparison between the different volume cases. Even if the 4.1 m$^3$ and the 2.3 m$^3$ cases were very similar at steady-state conditions, the differences related to transient operations were responsible of significant modifications for the last stable point values: while in the 4.1 m$^3$ test a 611 mbar pressure...
dropped was necessary to reach the surge line because the rotational speed was decreasing (Figure 11 - part C), in the 2.3 m$^3$ test the rotational speed increase moved the system directly to surge with a direct path. For this reason, the pressure loss necessary to reach the last stable point was significantly lower (520 mbar). The path corresponding to the 0.3 m$^3$ case was an intermediate behaviour between the other volume size tests (the rotational speed was almost constant approaching the surge line). So, no high increase in pressure drop was necessary: the last stable value was 457 mbar. In comparison with the 2.3 m$^3$ test case, this pressure drop is lower for a lower value of the rotational speed.

To complete the presentation of the input condition, Figure 12 presents the net electrical power produced by the turbine (negative values represent electrical power absorbed by the grid for the auxiliary components). Due to critical thresholds in the electrical power conditioning system (constraints on the direct current bar voltage implemented in the Turbec standard control system), it was not possible to maintain the 40 kW load in all cases. Especially during the 4.1 m$^3$ test, the VO valve closing produced a significant power decay down to 20 kW. Even if all the three tests were started with the microturbine load set-point at 40 kW, it was not possible to produce the three surge events (with the three different volume sizes) at the same initial condition. However, the experimental results presented in this section are significant to show the volume size effect during transient operations and to find surge precursors for control system application (in agreement with the purpose of this work).

![Figure 12: Main line valve closing: net electrical power](image)

From the transient point of view, Figure 12 is able to show oscillations due to surge event in case of low frequency phenomena (constraint of the electrical power sensor installed in the commercial T100 turbine). For this reason, while in the 4.1 m$^3$ and in the 2.3 m$^3$ cases power oscillations are visible, the oscillations related to the 0.3 m$^3$ test are completely smoothed. The transient effects of surge events can be better discussed considering the combustor inlet mass flow rate (Figure 13 - part A) and the recuperator inlet pressure (PRC1) at the cold side inlet (Figure 13 - part B). These values are able to highlight the volume effect in terms of...
oscillation frequency (from 0.4 Hz with 4.1 m\(^3\) additional volume to 1.3 Hz for the 0.3 m\(^3\) case). Due to the high rotational speed and large volume values, in this case, it is not possible to calculate these frequency values with the Helmholtz equation [6]. Since a comparison with the theoretical frequency values is not possible, the experimental measurements have a further relevant significance.

Moreover, the effect of the additional volume size is also visible in the PRC1 values after the oscillations due to surge conditions. With higher volume sizes, pressure tends to remain higher for longer time.

![Graph A](image1)

**Figure 13**: Main line valve closing (combustor inlet mass flow rate (A) and recuperator inlet pressure (B))

![Graph B](image2)

**Figure 14**: Main line valve closing: TOT
Figure 14 shows the TOT values during these surge events. The mass flow rate behaviour (it is reduced to zero for fractions of seconds during surge) generated a significant (and dangerous) TOT peak. For this reason, the T100 control system operated the machine shutdown, as shown by the fast rotational speed decrease happening 6-9 s after the surge events. A smoothed delay effect due to the volume size is also visible in the TOT curves (Figure 14).

![Graph showing TOT values during surge events](image)

Figure 15: Main line valve closing (surge events on the compressor map (each compressor curve is plotted for the same N/N₀ value))

The representation of these surge events is integrated by the operating lines plotted on the compressor map in Figure 15 (measured by the T100 manufacturer). No negative mass flow values are present due to the check valve installed downstream of the compressor. The most significant results shown by Figure 15 are the starting points of the surge events. These are the last stable operating points before the surge events, obtained by closing the valve in the air main line. They tend to be on the surge limit curve for all the cases without any specific volume size effect.

![Graph showing surge margin](image)

Figure 16: Main line valve closing: surge margin
Since in Figure 15 the paths are not completely clear because the curves are superimposed or crossed for several times, Figure 16 completes the description of the surge events showing the compressor surge margin.

4.2.3 Initial acoustic and vibrational analysis
Tests were carried out to evaluate how vibration structural response and acoustic aspects (operating noise radiated by the machinery) could be used to detect the inception of the surge. The results shown here will be essential for control system development including improvements on surge prevention. For this purpose, trends and spectra of the accelerometer signals were analysed, during this transient operation.
During the tests, the compressor operating condition was changed from a stable working point to the surge during the main line closing tests. During the transient operation of surge approaching, the machinery changed its rotational speed keeping it in the range between 62000 rpm and 65000 rpm. Speed value determines the lower sampling rate limit of the signals, because previous studies revealed the importance of the entire sub-synchronous frequency range in order to detect the inception of the surge event.
A sampling rate of 8196 Hz was chosen for the acquisitions because of its capacity to contain all significant frequencies. Only for the micro-accelerometer signal, a different sampling rate up to 200 kHz was adopted to examine the range around the bpf.
Vibration analyses were executed in the three different plant conditions characterized by different volumes: 4.1 m³, 2.3 m³ and 0.3 m³. These different analyses were conducted on acquired signals to find a signal transformation or elaboration with a high sensitivity to the approaching surge. Initially, the frequency analysis was conducted to evaluate the change of the signal frequency spectrum while the surge condition was progressively approaching. The time-frequency analysis underlines that sub-synchronous content seems to be more significant for the identification of the surge incipit.
Figure 17 shows the time-frequency analysis through zoomed colour-map representation of axial vibration component (in the case of 4.1 m³), measured on the compressor by the tri-axial accelerometer. This analysis allows to determine which frequency components show an important modification and a possible energy increase before the surge condition (it was reached on the top of Figure 17).

From the colour-map analysis, it is possible to highlight the presence of some frequency components, which show a significant modification and intensity variation (with continuity) during the progressive transient operation toward the surge condition. It is possible to assume that each of them is linked to a physical phenomenon that creates vibrations with a specific frequency. This frequency changes during the transient event with a high rotational speed sensitivity. Once the frequency components, that seem to be the most significant ones, were revealed, this information was used to filter the acquired signals and then calculate their Root Mean Square (RMS) values. Bands ranges, used to filter the data, were chosen in order to consider just the above mentioned frequency variations. Frequency contents of accelerometer signals in the three directions are not necessarily the same. Moreover, some frequency contents, with a significant amplitude for more axes, do not have the same intensity and a relevant increase in energy content in all axes close to the surge condition. The X axial direction presented higher interest in comparison with the other axis because it includes more frequency contents, which increase their energy (RMS) before the surge event.

Figure 18 shows the RMS value trends for the vibration of the X component during the transitory: for the unfiltered signal (over-all signal named Line A), the only sub-synchronous content (Line B) and a specific sub-synchronous band between 550 Hz and the 650 Hz (Line C).
The filtered signals show an evident increment of the RMS value approaching the surge condition, while the over-all signal seems to have less sensitivity with an opposite trend in comparison with the previous ones. From this analysis, it is possible to state that filtered values are more interesting than the entire frequency field because they present a significant increase before the surge, while the overall value has a different behaviour which also changes varying volume size configurations. To generalize the surge identification, it seems preferable to use the entire sub-synchronous content than a specific band content, which could significantly change depending on the type of plant characteristics. Some specific band contents, increasing before the surge with a volume size, are less sensitive in the others cases. The RMS sub-synchronous rate is analysed for the different plant configurations, changing the additional volume size for the same kind of transient event with 4.1 m$^3$, 2.3 m$^3$ and 0.3 m$^3$ respectively.
Figure 19: Main line valve closing (sub-synchronous signal trends of the axial accelerometer component for different values of the additional volume)

Figure 19 shows that this RMS sub-synchronous rate is increasing in all the three instances, but the intermediate case (2.3 m³ additional volume) seems to show the highest sensitivity, since its values close to the surge are 30% higher than in the other cases. This could be due to the plant characteristics that mainly amplify the surge approaching phenomenon response in particular conditions.

![Image of Figure 19](image19)

Figure 20: Main line valve closing (40 kHz signal trends of the high frequency radial (Z), axial (X) accelerometers and 54 kHz signal trend of the microphone)

During the transient to the incipient surge, for the 2.3 m³ volume configuration, acoustic and vibration responses were investigated in correspondence of frequency bands containing bpf superior orders. However, no significant volume size effect seemed to be present at so high frequency values. In Figure 20 energy trends of accelerometer signals, acquired using sensor with appropriate dynamic characteristic, are reported. In detail, the figure refers to accelerometers positioned in radial and axial direction and the frequency band shown is the third order of the bpf. In the same figure the forth order of the bpf trend from the microphone is presented. These trends are characterized by a good sensitivity as they increase near the incipient surge. This behaviour may be related to the flow alteration in the blade channel, which influences high frequency vibration response.

In a second phase, a further analysis was carried out to evaluate if the system vibration response diverged from a stationary condition when it progressively approaches to the beginning of the surge event. For this purpose, sets of a significant number of spectra (21) were calculated temporally far (700 s) and close (1 s) to the surge event. Each spectrum was evaluated from a consecutive extract of the signal corresponding to an interval of time of 0.5 s. These limited intervals of time are still useful to generate a frequency spectrum of sufficient resolution. Each of the series of spectra may be considered important to characterize the
compressor operational vibration response during its total observation time of 10 s. Starting from the obtained spectra, initial attention was focused on the average spectrum to have an average energy indication of the vibration level for the whole observation time (where the entire singular spectrum was calculated). Then, envelope spectrum was calculated: it allows to highlight the maximum values for each frequency component among the entire spectra set. The difference between these two curves may be considered significant to detect the loss of stationary response for compressor vibrations.

Figure 21: Main line valve closing (sub-synchronous, average and envelope vibrational spectrum far from the surge (A) and few instants before reaching surge (B) in axial direction for a configuration with an additional volume equal to 2.3 m$^3$ (1X indicates the synchronous frequency in both cases))

This behaviour appears in the results reported in Figure 21 related to the test carried out with an additional volume value of 2.3 m$^3$. Similar results were also obtained in other configurations. In Figure 21, the singular spectra are compared with the average and envelope spectra. The upper and lower graphs refer to a compressor stable condition far (688 s) from surge operations and another condition 4 s before reaching the surge event, respectively. In these two conditions, the envelope functions appear different in amplitude for the considered frequency interval corresponding to the whole sub-synchronous field. In detail, the envelope spectrum, calculated using the data acquired close to the surge condition, presents higher marked amplitudes. This result could be justified by considering that as compressor operation condition get closer to an incipient surge state, significant random and non-deterministic components appear in the vibration response. This result justifies the marked increase of the envelope spectrum in comparison with the average spectrum. Probably, this effect could be related to a non-negligible dispersion in the singular spectra.

To evaluate this behaviour when system volume varies, two quantifiers were introduced: the envelope spectrum and the variance spectrum RMS values (both of them were calculated from the same spectra set). Table 3 shows the quantifier values of three different system configurations in case of compressor operating conditions gradually closer to the surge event.
Table 3: Main line valve closing (envelope and variance sub-synchronous spectra RMS values with different additional volume sizes (time distances from surge events: "Far" means 700 s, "Intermediate" is 300 s, "Near" is 100 s, and "Nearest" is for 1 s time distance))

<table>
<thead>
<tr>
<th></th>
<th>RMS env. 4.1 m³</th>
<th>RMS σ 4.1 m³</th>
<th>RMS env. 2.3 m³</th>
<th>RMS σ 2.3 m³</th>
<th>RMS env. 0.3 m³</th>
<th>RMS σ 0.3 m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Far</td>
<td>0.160</td>
<td>0.044</td>
<td>0.155</td>
<td>0.042</td>
<td>0.166</td>
<td>0.046</td>
</tr>
<tr>
<td>Intermediate</td>
<td>0.183</td>
<td>0.051</td>
<td>0.153</td>
<td>0.044</td>
<td>0.157</td>
<td>0.044</td>
</tr>
<tr>
<td>Near</td>
<td>0.196</td>
<td>0.057</td>
<td>0.192</td>
<td>0.052</td>
<td>0.195</td>
<td>0.052</td>
</tr>
<tr>
<td>Nearest</td>
<td>0.246</td>
<td>0.061</td>
<td>0.428</td>
<td>0.119</td>
<td>0.216</td>
<td>0.060</td>
</tr>
</tbody>
</table>

Table 3 shows that, in all the considered conditions, these quantifiers (env. and σ) seem suited to identify the approach to the surge condition because, near to this condition, their values rise significantly. Both the envelope and the variance RMS values seem to be more sensitive for system configuration characterized by 2.3 m³ additional volume. This aspect further confirms the existence of specific volume values able to amplify the vibration response.

Accelerometer and microphone signals frequency content were used synergistically through the calculation of cross-power spectrum. It contains only the common frequency contents of accelerometer and microphone signal. So, the obtained spectrum provides the information contained in a signal (for example the microphone) filtered by the frequency content of the second signal (axial accelerometer). This approach allows to underline the common frequency components between the two signals. The same quantifiers previously used on accelerometer spectra, were applied on cross-spectra between the microphone and accelerometer signal. Results reported in Table 4, referred to the analysis on cross spectra, show a better predictive performance of quantifiers.

Table 4: Main line valve closing (envelope and variance sub-synchronous cross spectra RMS values at different volume values (time distances from surge events: "Far" means 700 s, "Intermediate" is 200 s, "Near" is 100 s, and "Nearest" is for 1 s time distance))

<table>
<thead>
<tr>
<th></th>
<th>RMS env. 4.1 m³</th>
<th>RMS σ 4.1 m³</th>
<th>RMS env. 2.3 m³</th>
<th>RMS σ 2.3 m³</th>
<th>RMS env. 0.3 m³</th>
<th>RMS σ 0.3 m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Far</td>
<td>0.489</td>
<td>0.235</td>
<td>0.540</td>
<td>0.258</td>
<td>0.543</td>
<td>0.261</td>
</tr>
<tr>
<td>Intermediate</td>
<td>0.525</td>
<td>0.250</td>
<td>0.609</td>
<td>0.293</td>
<td>0.545</td>
<td>0.262</td>
</tr>
<tr>
<td>Near</td>
<td>0.601</td>
<td>0.293</td>
<td>0.673</td>
<td>0.330</td>
<td>0.638</td>
<td>0.312</td>
</tr>
<tr>
<td>Nearest</td>
<td>0.636</td>
<td>0.312</td>
<td>1.101</td>
<td>0.530</td>
<td>0.750</td>
<td>0.355</td>
</tr>
</tbody>
</table>
A further analysis was carried out considering the application of chaos theory [7,8] on acquired signals to evaluate the possibility of early detection of surge incipient condition. It is assumed that phenomena related to the condition of incipient surge generate a system response with non-linear contributions. For this reason, it seems coherent to apply chaos quantifiers to diagnose the occurrence of the phenomenon. Initially, phase plane was reconstructed starting from the acquired experimental signals. Two criteria were followed. The first one is more exact and provides a single and double integration on the accelerometer signals that allows to reconstruct the attractor in the displacement-speed plane. The second one, through the definition of a proper delay, provides a pseudo phase plane, which also contains information related to the presence of non-linearity in the observed system. The advantage of the second method is the direct use of the raw signal, thus avoiding the integration procedure that may affect the final results [9,10].

System non-linearity presence and the related amount may be quantified by evaluating the attractor fractal dimension. Chaos analysis was carried out using only the experimental data of sub-synchronous components: as from the previous analysis, they seem to be the most significant in terms of contributions related to the incipient detection surge phenomenon. Figure 22 shows the phase plane evaluated in stable condition of the compressor (700 s from surge event) and in the near surge zone (1 s from the surge event).
It is clear (from Figure 22) that, for all the volume cases, in the zone near to surge events (parts B) the attractors present a greater complexity probably related to the system cyclical and deterministic nature reduction. This phenomenon is likely due to the occurrence of random vibratory components which lead to non-linearity in the system. The increase of the phase plane complexity from a stable condition (parts A) to an incipient surge condition (parts B) was evaluated. While this phenomenon is significant in all volume cases, it is possible to show a sort of amplification of surge associated phenomena for the 2.3 m³ size. This effect was also quantified by evaluating the information dimension. It is a chaos indicator that quantifies the system chaotic behaviour through the calculation of the fractal dimension of the attractor, which in this case is the phase plane. This method provides information through a time domain analysis as it considers the phase plane reconstructed using acquired time
histories without using FFT algorithms, and so, it seems to give additional information with respect the previous methods. Figure 23 shows the trend of this indicator for the different additional volume configurations during the transient operations for several different instants, expressed in seconds before reaching the surge events.

![Figure 23: Main line valve closing (information dimension trend varying the distance in seconds from the surge (from the pseudo phase planes))](image)

With this final analysis, it is possible to highlight that this indicator is very sensitive to the detection of the unstable surge condition (rising behaviour). While in the 2.3 m$^3$ the parameter increase is shown by a monotonous trend, also in the other cases the values close to the surge events (1 s before instability) are significantly higher than the values obtained in the other instants. Information dimension, which is calculated considering the phase plane through acquired signal time domain analysis, is useful for the development of a diagnostic system together with the previous indicators.
4.3 Impact of fuel cell degradation on system performance

The impact of fuel cell degradation on the performance of the hybrid system was evaluated using the 1D distributed SOFC degradation model previously implemented as described in deliverable D3.1 “Upgraded hybrid system emulation rigs”. Different operating strategies were analyzed and compared: constant fuel cell power, constant fuel cell current and constant fuel cell voltage. Additionally, two operating strategies for the gas turbine were considered: oversized turbine working in off-design conditions and perfectly sized turbine at constant load. Fuel cell lifetime and system efficiency were compared with the same initial conditions and degradation model to determine the optimal operating strategy.

Figure 24 and Figure 25 show the fuel cell power over time in the four cases. In Figure 24a, the blue line depicts the case at constant current, in which cell voltage (and consequently power) decreases linearly as the cell degrades. Total system power is kept constant in this case shifting the load to the gas turbine, which is significantly oversized and operates in off-design for most part of the lifetime, as shown in Figure 24b with the blue line. The case at constant voltage is illustrated by the black curve in Figure 24. To maintain constant voltage, the current is decreased to reduce the degradation over time. Fuel cell lifetime is substantially extended, because the fuel cell degrades much more gradually. For this reason, the turbine size could be smaller if a constant total power strategy is considered. These two operating modes are compared in Figure 24a with the case of a standalone SOFC operating at constant power, represented by the red line. The benefit of hybridizing fuel cell and gas turbine is evident in the lifetime increment. As such, to operate at constant power, current must be increased in the standalone fuel cell to offset voltage degradation, and this operating condition accelerates degradation.

![Figure 24: Fuel cell power (a) and turbine power (b) with different operating strategies as the fuel cell degrades](image-url)
A final case considered was to operate the fuel cell at constant voltage allowing the total system power to decrease. In this scenario, the gas turbine is matched with the SOFC at the beginning of life and the load on the turbine is held constant. Thus, the turbine size is approximately a third of the previous case and the machine always works in design condition. Fuel cell power follows the system power trend, shown in Figure 25. The lifetime (determined as the total system power reached 50% of nominal power) is very similar to the previous case, at constant cell voltage and constant system power.

![Figure 25: Hybrid system power at constant fuel cell voltage and constant turbine load as the fuel cell degrades](image)

The system efficiency in the four cases is illustrated in Figure 26. Constant voltage operations showed the highest efficiency either with oversized turbine (Figure 26a) and constant power turbine (Figure 26b).

![Figure 26: System efficiency over time as the fuel cell degrades with different operating strategies](image)
4.4 Ancillary manoeuvres

4.4.1 Start-up
During the start-up of a direct-fired SOFC/GT hybrid system, the fuel cell stack must be gradually brought up to temperature over a period of hours to avoid thermal stresses and damage of the stack. On the contrary, the turbine ramp-up to nominal speed is done in few minutes. Four important requirements must be considered during system start-up:

- Maintaining sufficient surge margin to avoid compressor stall/surge;
- Minimizing the temperature gradients and heat rate in the fuel cell stack;
- Limiting turbine exhaust gas temperature below the maximum allowable temperature in the exhaust gas recuperator;
- Ensuring a sufficient equivalence ratio in the combustor to avoid flame-out.

Several test campaigns were conducted on the HyPer facility at NETL to evaluate these four key aspects and optimize start-up operation in a hybrid system [12]. Turbine speed ramp-up rate, bleed air valve position, and fuel cell bypass flow were manipulated to achieve the goals mentioned above.

It was demonstrated that a higher turbine speed ramp rate increased the surge margin during start-up. The use of bleed air valve was effective in increasing the surge margin but had a negative impact on turbine exhaust gas temperature and cathode inlet temperature. In order to ensure a gradual warm up of the fuel cell, it was chosen to keep the bleed air (BA) valve only 10% open during start-up.

Fuel cell cathode airflow was regulated by manipulating two bypass valves, cold air (CA) and hot air (HA) valves, whose location is described in deliverable D3.1. The aim of cathode airflow modulation was to minimize the heat rate and temperature gradients in the SOFC stack while maintaining a sufficient fuel to airflow ratio in the combustor. In the HyPer system, the combustor used for start-up is the one that emulates the SOFC thermal output during hardware-based simulations, as described in deliverable D3.1; the considerations made here hold however in a real hybrid system where the fuel cell post-combustor is employed for start-up with injection of auxiliary fuel.

Minimizing cathode airflow through bypass valves regulation ensured a gradual fuel cell warm up. Figure 27 shows cathode airflow during start-up in four conditions: BA 10% open and CA fully closed (blue line), BA 10% open and CA 40% open (red line), and constant equivalence ratio control at 0.5 and 0.6 (green and purple lines, respectively). In these latter cases, BA was maintained at 10% open, and a minimum opening position of 40% was applied for the CA valve to guarantee sufficient surge margin.
Figure 27: Cathode airflow trend during different start-up strategies

Figure 28 and Figure 29 show the comparison between start-up with BA only, constant CA bypass, and equivalence ratio control via bypass valves manipulation. The reduction in cathode airflow in case of equivalence ratio control guaranteed a gradual fuel cell stack warm up, maintaining temperature gradient and heat rate below the safety limits.

Figure 28: Fuel cell temperature gradient during start-up with constant BA only (a), constant BA and CA (b), and cathode airflow regulation (c)
In conclusion, the start-up strategy identified at NETL includes:

- Maximizing the turbine speed ramp rate to increase the surge margin during start-up;
- The use of bypass valve to regulate cathode airflow, minimize temperature gradients and heat rate in the stack, and ensuring sufficient fuel equivalence ratio in the start-up combustor;
- The use of bleed air valve at 10% open to maintain sufficient surge margin while avoiding excessive temperature at the exhausts recuperator.

### 4.4.2 Emergency shutdown

The goal of an emergency shutdown (ESD) strategy is to avoid any equipment failure and risk to the personnel in emergency situations. In a standard APU, an ON/OFF emergency fuel and load control is commonly used, where fuel and electric load are immediately cut off by the ESD strategy. Failure analyses at NETL proved this strategy to be detrimental in an SOFC gas turbine hybrid system, leading the compressor to surge condition [13]. As such, when a...
sudden loss of energy to the turbine occurred, a surge event was observed with 4 surge cycles in 5 seconds, as shown in Figure 30a. This phenomenon occurred because of the SOFC system volume, which is two orders of magnitude larger of a standard compressor plenum volume; the pressure inertia in the volume caused the pressure ratio to decrease more gradually than the compressor inlet mass flow, which led to a reduction in surge margin (Figure 30b). A compressor surge must be avoided during ESD because it would not only damage the turbomachinery, but it would also be catastrophic for the fuel cell stack.

![Figure 30: Surge cycles during ESD with sudden fuel cut (a) and turbine parameters trends after a sudden step down in fuel valve (b)](image)

A fuel valve ramp-down strategy based on a non-linear function, using a feed-forward approach, was proposed and implemented to decrease the fuel to the combustor gradually. The same non-linear ramp was implemented for the electric load, delayed by 5 seconds with respect to the fuel ramp-down. The effect of bleed air and cold air valve positions during ESD was also studied. A safe BA position was determined at 10% open, which allows sufficient surge margin without excessively incrementing the load on the turbine shaft. Opening the CA valve was observed to be very beneficial to increase surge margin. The final ESD strategy thus includes an immediate 30% increment in CA valve opening (from the nominal position, which is 40%, to 70% open), which contributes to increase the surge margin in the first few seconds of the transient.

The overall shutdown strategy is presented in Figure 31, where the actuators commands are illustrated by red lines. FV-170 represents the CA valve, FV-432 is the fuel valve, and E-105 is the turbine electric load. The fuel is decreased gradually following the non-linear feed-forward approach, and at the same time, the cold air by-pass is opened up to 70%, a 30% variation from the nominal condition. The compressor impact is reduced because the surge margin is increased during the transient path of cold air valve opening. Lastly, the load is decreased gradually with the same non-linear ramp, but delayed by 5 seconds. The fuel valve was completely closed to the minimum position in approximately 7 seconds. This ESD strategy
represents the quickest path on the safe side of the surge line, as illustrated in Figure 32, where ESD is shown starting from different initial conditions.

**Figure 31**: ESD strategy implemented at NETL with fuel valve ramp-down (FV-432), cold air valve opening (FV-170), and electric load ramp-down (E-105)

**Figure 32**: ESD strategy from different initial conditions represented on the compressor map
5 Conclusion

The activities carried out by UNIGE show an experimental campaign to analyse the effect of different volume sizes connected to a gas turbine (between the recuperator outlet and the turbine inlet, as in fuel cell based hybrid plants). The tests were carried out with the experimental facility including a T100 microturbine connected to a modular vessel (to change the volume size) between the recuperator outlet duct and the combustor inlet line. The main results obtained with these tests are summarized in the following points.

- The tests on the bleed valve were necessary to evaluate the pressure time-response increase with the volume increase. The different peak time values were: 10.1 s for 4.1 m$^3$, 7.8 s for 2.3 m$^3$ and 2.3 s for 0.3 m$^3$.
- The tests related to surge conditions showed the volume effect in terms of oscillation frequency for the recuperator inlet pressure on the cold side (from about 0.4 Hz with 4.1 m$^3$ additional volume to 1.3 Hz for the 0.3 m$^3$ case).
- The surge condition tests also showed that the surge zone was the same for all cases without any significant volume size effect.
- Diagnostics, acoustic and vibration investigations seem to show an interesting solution to predict the incipient surge condition using suitable quantifier calculated both in the time and in the frequency domain from accelerometer and microphone signals. This analysis, preliminarily conducted here, is considered essential to develop an advanced control system able to prevent surge conditions on the basis of such precursors.
- Spectrum energy level seems useful as a quantifier for the surge prediction. Higher sensitivity may be obtained by analysing the energetic level of specific frequency bands (which, in the study of this specific case, was between 40-60% of rotational frequency) internal to the sub-synchronous spectrum. However, to generalize the quantifier efficacy to different machinery and plant configuration, it seems more convenient to employ the energetic level of the entire sub-synchronous band.
- Promising prediction and diagnostic results were obtained through analysing and quantifying the stationarity lack of vibrational and acoustic signals through the definition of envelope and variance function. This function was calculated from a number of spectral sets acquired from equal and consecutive time intervals.
- In addition, the work considered the possibility to define an indicator using the chaos theory, which analysed the experimentally acquired signals exclusively in the time domain. Also in this case, it could be observed that the fractal dimension can be suitable for diagnostic purpose.

Experimental tests at the HyPer emulator facility proved that emergency shutdown operations can mitigate compressor surge and stall events by opening the cold-air bypass valve and optimizing the ramp rate of the post-combustor fuel valve and gas turbine electric load.
An equivalence ratio controller that aimed to minimize the fuel cell gradients during start-up operation by opening cold-air and hot-air bypass valves was successfully tested at the HyPer. The main objective of this controller was to saturate the cold-air and hot-air bypass valve at 100% open position to minimize the cathode airflow through the fuel cell. Four cases were evaluated during these experimental tests:

1) bleed-air 10% open, cold-air and hot-air bypass valve closed,
2) bleed-air 10% open, cold-air 40% open, and hot-air bypass valve closed,
3) Equivalence ratio 0.5, bleed-air 10%, and cold-air/hot-air bypass saturated at 100% in automated mode,
4) Equivalence ratio 0.6, bleed-air 10%, and cold-air/hot-air bypass saturated at 100% in automated mode.

Experimental results showed that from case 1) to case 4) the maximum ceramic solid temperature of the fuel cell was reduced from 480 K to 368 K, the fuel cell temperature gradients from 1.35K/mm to 1.19K/mm, and the fuel cell temperature heat rate from 1.13K/sec. to 0.66K/sec.

An innovative control strategy to extend the fuel cell life as the fuel cell degrades was designed and validated at the HyPer facility. During this experimental test, the fuel cell voltage was kept constant by decreasing the fuel cell current while a degradation rate was reduced over time, the differential temperature from the inlet and the outlet of the fuel cell was kept constant as well by increasing the airflow through the cathode, and the turbine speed was maintained at nominal condition by changing turbine electric load. Compared to the fuel cell stand-alone configuration the life of the fuel cell in a hybrid system was increased by 10 times.

The experimental tests planned at the DLR Turbec based hybrid power plant test rig were re-allocated to WP4 due to various issues with the test rig.
References


