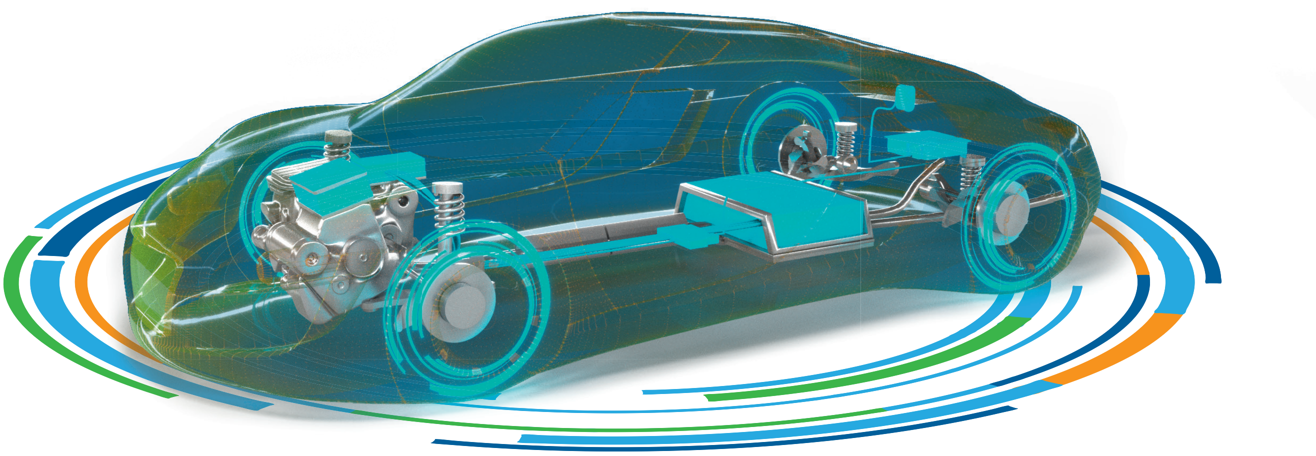

INTERNATIONAL SYMPOSIUM ON DEVELOPMENT METHODOLOGY

Methods to develop PEM fuel cell-based powertrains for regional aircraft – a multiple scales approach

Dr. Dominik Murschenhofer, Dr. Cornelie Bänsch –
Institute of Engineering Thermodynamics, German Aerospace Center (DLR)

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Summary

In this paper, four different test environments operated by the DLR Institute of Engineering Thermodynamics are presented. These test environments are designed for the development and optimization of fuel cell systems and fuel cell-based powertrains for aircraft applications and the development of application-specific operating strategies. To this end, the research is conducted on different scales, ranging from the investigation of short-stack fuel cell systems with a few kW power under high-altitude conditions to the analysis of the coupling behavior of the different subsystems of a fuel cell-based electrical powertrain in the MW range. Selected results of experimental investigations are discussed. On the one hand, these results highlight the large optimization potential through altitude-adaptive fuel cell system control. On the other hand, the successful proof of performance of a multi-stack fuel cell system and an e-drive system in the MW range conducted on a novel large-scale research facility is shown.

1 Introduction

The development of powertrains for regional aircraft based on polymer electrolyte membrane fuel cells (PEMFCs) is a promising approach to contribute to the decarbonization of the aviation sector [1-3]. However, the complex interplay between the multiple powertrain subsystems such as electric motor, power electronics, hydrogen storage system and the fuel cell system poses significant challenges [4]. Moreover, despite the fuel cell (FC) system's high efficiency at ground level, it suffers from severe power losses when it is operated under high-altitude conditions [5], i.e. low ambient pressure and temperature. To address these issues, a development approach on different scales is proposed, ranging from investigations on short stack level with only a few kW power output up to the analysis of powertrain systems in the MW range.

In this paper, the various small-scale and large-scale testing environments of the DLR Institute of Engineering Thermodynamics are presented, including the discussion of optimization methods and experimental results. Covering the testing needs on all relevant scales allows to efficiently pursue the path towards climate neutral future aviation.

2 Development and Testing Environments

For the experimental investigation of fundamental research questions adherent to a high risk of failure, such as the performance analysis of novel PEMFC technologies under extreme operating conditions, small-scale testbeds providing high flexibility and low financial risks are well suited (see Section 2.1). On the other hand, larger test environments, capable of testing fuel cell stacks and systems in an application-relevant scale of several hundred kW power output, are required to develop and optimize operation strategies and system setups with more mature and market-ready components (see Sections 2.2 and 2.3). Eventually, the analysis and improvement of the electrical as well as the procedural coupling behavior between the multiple subsystems of a fuel cell-based aircraft powertrain is performed on a large-scale MW research facility (see Section 2.4), representing the preliminary testing stage before the integration into an iron bird testbed.

2.1 ATLAS: Short Stack Testing inside an Altitude Chamber

The "Altitude Test Chamber for Low-Pressure Analysis of FC Systems" (ATLAS, see Figure 1a), enables the operation of short-stack fuel cell systems up to 15 kW inside a high-altitude environment (see Figure 1b) simulating conditions of up to 35000 ft (10688 m), i.e. a pressure of 238 mbar(a) and a temperature of -54.5 °C. Therefore, the exhaust of the low-pressure chamber is connected to a vacuum pump and the inlet air temperature is controlled via a pocess thermostat. The test environment is used for fundamental research about the behavior and optimal operation of different fuel cell stacks and balance-of-plant (BoP) components under aviation relevant high-altitude conditions. The test setup and the corresponding controls can be flexibly adapted according to various research questions. A more detailed description of the testbed is given in Refs. [6], [7].

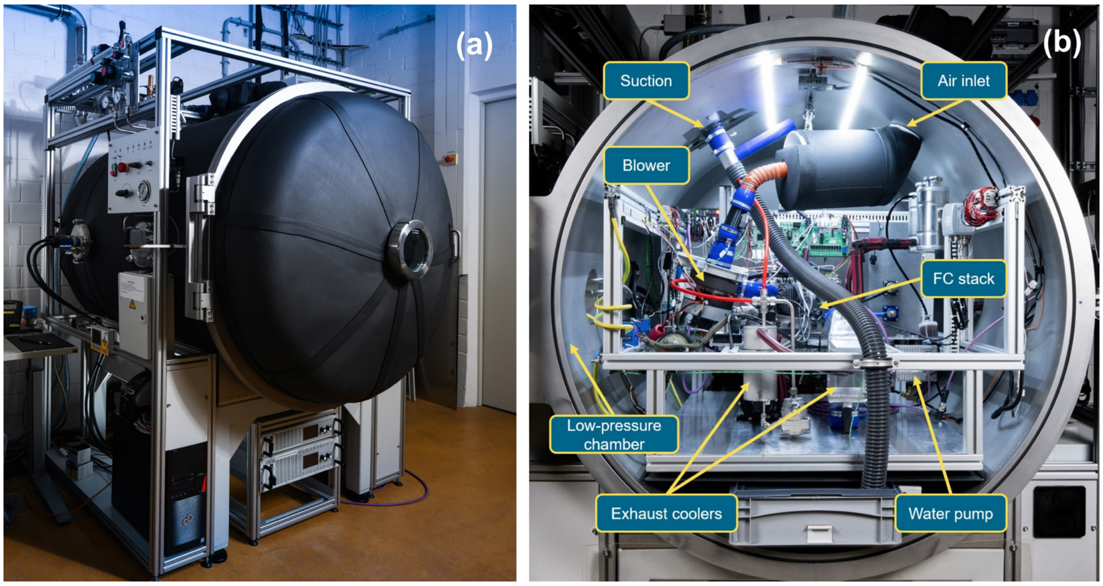

Figure 1: ATLAS test chamber (a) and the test setup inside the chamber (b).

2.2 EO²S: Modular FC Stack and BoP Testbed

The 150 kW fuel cell stack testbed EO²S (Experimentally Optimized Operating Strategies) is designed to flexibly exchange various fuel cell stacks and BoP components to evaluate different system configurations in an application relevant power class. The testbed is highly instrumented with multiple mass flow meters, temperature and pressure probes to determine all relevant mass and energy fluxes in order to conduct detailed component and system characterizations, see Figure 2. The research scope of this testbed is the development of advanced operating strategies aiming e.g. for the maximization of hydrogen utilization with different system setups according to the individual application purpose.

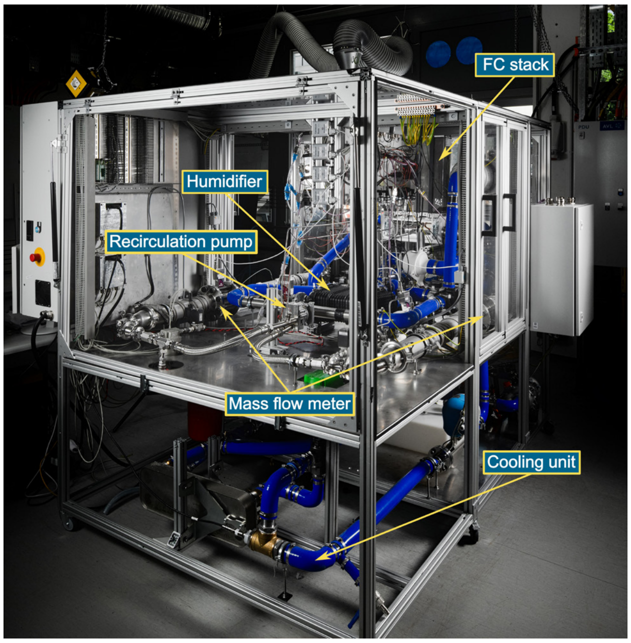

Figure 2: EO²S fuel cell stack testbed.

2.3 AERIS: Testing of FC Systems up to 275 kW under Altitude Conditions

The AERIS (Altitude Environment for Research of Integrated FC Systems) testbed enables the analysis of fuel cell systems up to 275 kW under aviation-relevant conditions, i.e. pressures between 1013 and 340 mbar(a) and temperatures between 50 and -40 °C. To simulate realistic aircraft mission profiles, the test facility is capable to realize highly dynamic operation with pressure and temperature gradients of up to ±120 mbar/min and ±6.5 °C/min, respectively. To this end, the FC intake air and exhaust are evacuated via a vacuum pump, while the intake air is simultaneously dehumidified and cooled by an advanced air conditioning system containing an air dryer and a chiller unit, see Figure 3. This simulates altitude conditions up to 27000 ft (8230 m), supporting the development and optimization of aircraft propulsion strategies based on commercial and custom-made fuel cell systems.

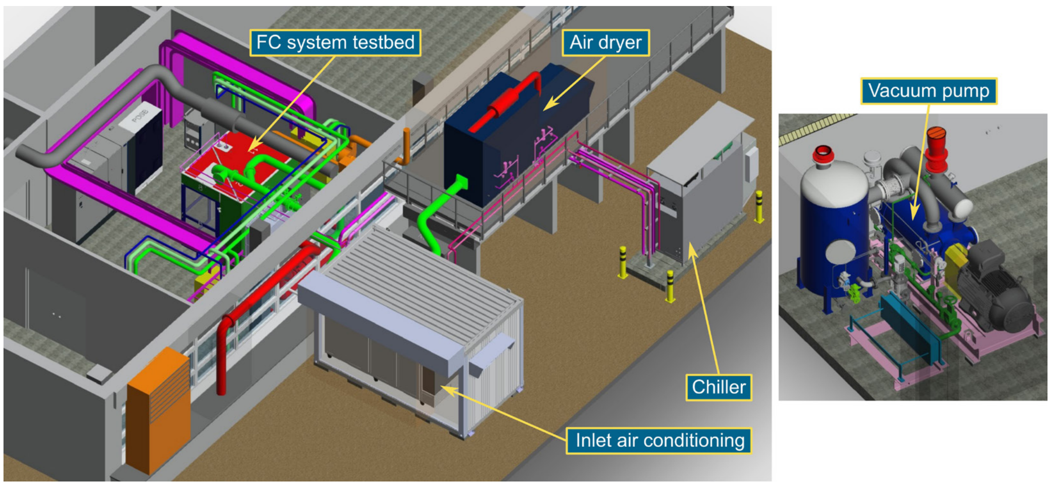

Figure 3: Components of the AERIS testbed. The vacuum pump is located in a separate room in the basement.

2.4 BALIS: Test Environment for FC-Based Powertrains up to 1.5 MW

The BALIS (Brennstoffzellenbasierter Antriebsstrang für Luftfahrzeuge 1.5+ MW, i.e. german for "fuel cell-based powertrain for aircraft 1.5+ MW") large-scale research facility is a modular test infrastructure for the investigation of FC-based powertrains in the MW range. The test environment is divided into different test fields, which enable the experimental investigation of the powertrain subsystems e-motor, fuel cell system, battery and liquid hydrogen (LH2) tank system, see Figure 4. The test fields can be operated separately or combined in various coupling modes ("use cases") via the so-called switch matrix. The focus is on functionality tests with the flexibility to integrate different components and test systems (units under test, UUT) and to examine them in combination. A detailed explanation of the methodological approach and an overview of the different use cases are given in Refs. [8], [9].

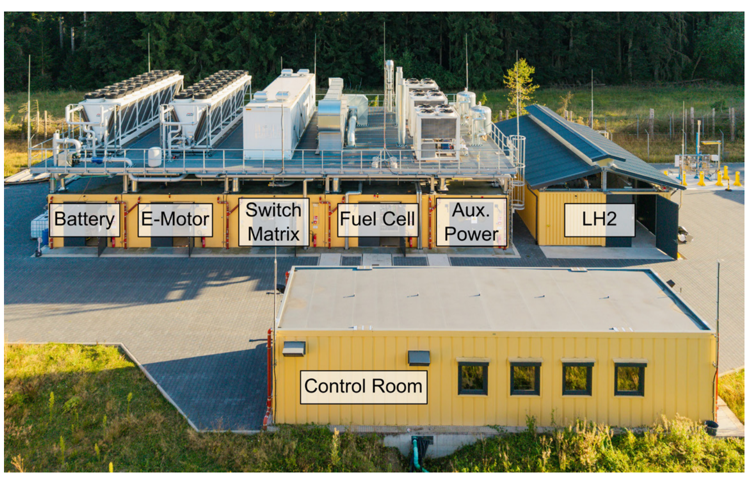

Figure 4: BALIS test facility with indication of the battery, e-motor, fuel cell and LH2 test fields, as well as the containers for the switch matrix, auxilliary power and the control room.

2.4.1 BALIS Fuel Cell Test Field

The BALIS Fuel Cell Test Field provides the possibility to operate FC systems with a total power of 1.5 MW. The large power can either be realized by one large FC system or by connecting multiple smaller FC systems to a large multi stack fuel cell system (MFCS). For the latter, various configurations of serial and parallel connection between the small FC systems can be investigated within the maximum voltage of 1200 V and the maximum current of 1250 A. The currently installed MFCS test setup consists of 12 commercial FC modules (PowerCell PS-100, P_{gross} = 120 kW, P_{net} = 100 kW, I_{max} = 420 A) in a configuration with pairs of FC modules in series ("fuel cell string") and six fuel cell strings connected in parallel, see Figure 5.

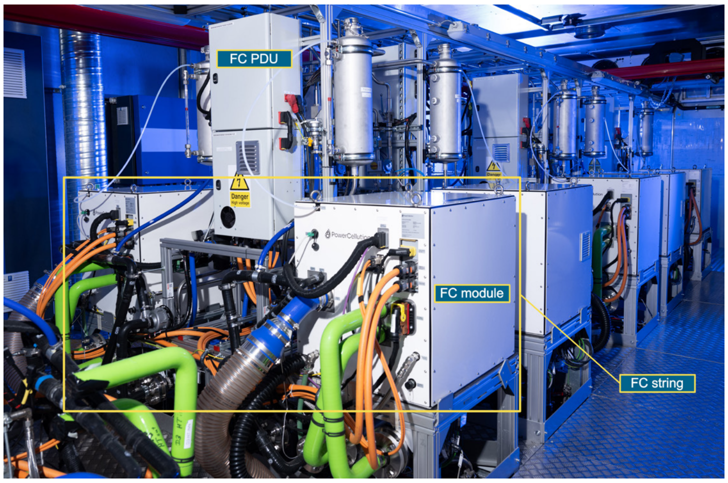

Figure 5: Inside view of the BALIS Fuel Cell Test Field. The pair of FC modules of one FC string are connected via a fuel cell power distribution unit (FC PDU).

2.4.2 BALIS E-Motor Test Field

The BALIS E-Motor Test Field is equipped with two galvanically isolated DC power lines of 750 kW (max. 1200 V/1250 A) each, to power either a single or two electric motors as UUT. In case of two motors, they are either mounted to a single shaft or connected via a gear box. The propeller shaft of an aircraft is emulated by an electrical generator, which is connected to the AC grid. The currently installed e-drive test setup consists of two permanent magnet synchronous machines with inverter (Compact Dynamics, 600 kW_{max}/500 $kW_{continuous}$ at 17000 rpm), which are connected mechanically in a parallel configuration via a summation gear (Chemnitzer Zahnradfabrik, > 98 % efficiency), see Figure 6.

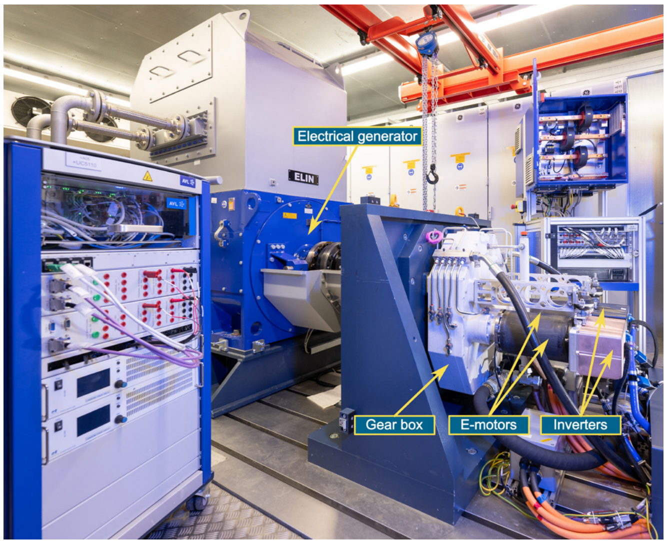

Figure 6: Inside view of the BALIS E-Motor Test Field showing the two UUT connected to the shaft of the electrical generator via a gear box.

2.4.3 BALIS Liquid Hydrogen Tank Test Field

The large amount of hydrogen needed to power a regional aircraft for several hundred km requires the use of liquid hydrogen (LH2) at cryogenic temperatures between 21 and 29 K. The BALIS Liquid Hydrogen Test Field is designed to investigate different test tanks, e.g. with regard to the dynamic behavior during filling and withdrawal of LH2, pressure build-up inside the tank, or boil-off reduction. Therefore, the test tank, which is located in the LH2 test field container (cf. Figure 4), is connected to the FC test field as well as to a large LH2 storage tank with a capacity of about 4 tons LH2 and a maximum flow rate of about 1000 kg/h. While the storage tank is currently under development, the first-generation test tank, i.e. an Air Liquide Advanced Technologies (ALAT) tank with a capacity of 200 kg LH2 and a maximum flow rate of 120 kg/h, is coupled with a liquid heated evaporator unit and already integrated into to the BALIS test environment, see Figure 7.

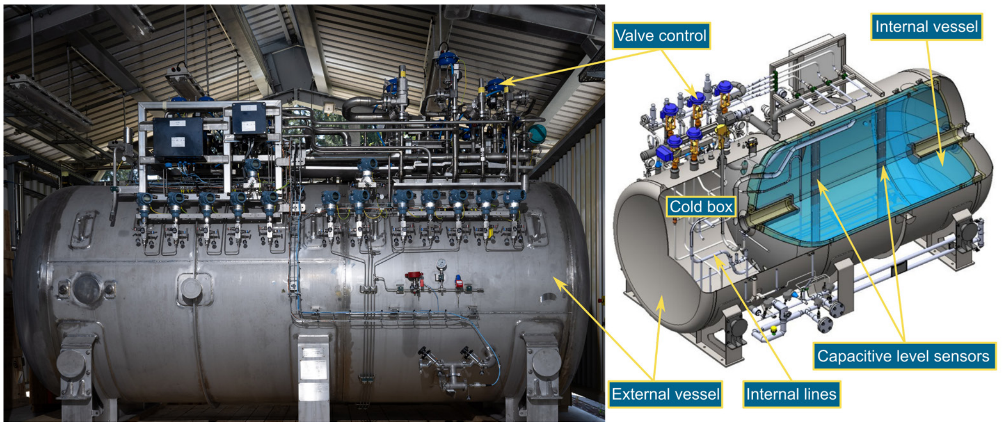

Figure 7: Inside view of the BALIS LH2 Test Field with the ALAT test tank (left). Sectional view of the ALAT test tank with indication of the vacuum insulated cold box (right).

2.4.4 BALIS Battery Test Field

The BALIS Battery Test Field is currently under development in order to test batteries up to 750 kW with a maximum capacity of about 500 kWh inside a temperature-controlled (between 90 and -40 °C) safety chamber. In addition, a battery emulator is already available to implement various battery models and investigate the coupling behavior and stability of the electrical high-voltage system in combination with other test fields as well as different hybridization strategies.

3 Discussion of Selected Results

3.1 Development of Operating Strategies for FCs under High-Altitude Conditions

Aiming at the aviation application of PEMFC systems, the effect of low ambient pressure on a Hydrogenics HD10 system, i.e. a self-humidifying, non-pressurized 120 cells PEMFC stack with a nominal power of 12 kW, anode recirculation and a cathode blower, is operated inside the ATLAS altitude chamber, cf. Section 2.1. Polarization curve measurements are performed at pressure levels between 980 and 491 mbar(a), which corresponds to an altitude of up to 5712 m. During these measurements, the stack temperature and cathode stoichiometry are set according to the default values given by the manufacturer. Figure 8a shows the resulting polarization curves, where a strong effect due to the environmental pressure is visible. The performance losses are partly attributed to the reduced oxygen partial pressure, which leads to less reactants available for the electrochemical reaction, cf. [10]. In Figure 8b large net power losses are observed at low-pressure operation. To some extent, these losses result from an increased air blower power as the decreasing air density at low pressures requires a higher blower speed and consequently a higher power to maintain a certain stoichiometry. At a pressure of 491 mbar(a) the maximum net power output is 59 % lower with respect to the maximum net power at 980 mbar(a).

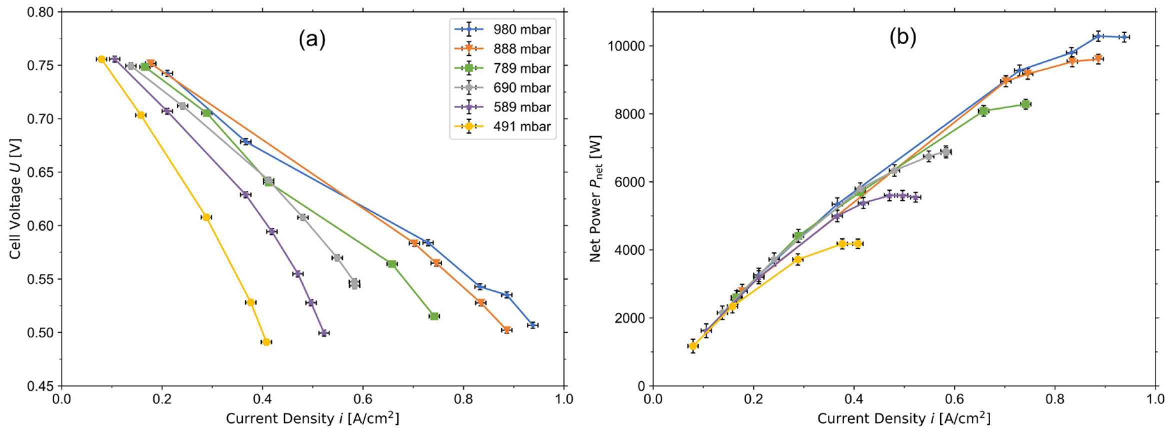

Figure 8: Polarization curves (a) and net power (b) versus current density at different ambient pressure levels by using the default parameters for stack temperature and cathode stoichiometry control.

To reduce the power losses under high-altitude operation to a minimum, a comprehensive parameter study is performed to identify the optimal operating strategy, i.e. the optimal combination of the stack temperature and the cathode stoichiometry for a given altitude, in terms of net power. Figure 9 shows the maximum net power output under altitude conditions (chamber pressure p and FC inlet temperature Tin are set according to the ICAO International Standard Atmosphere (ISA) [11]) with default (dashed line) and optimized (solid line) parameters for stack temperature and cathode stoichiometry control. While the optimization yields a moderate performance improvement of 11 % at an altitude of 111 m (p = 1000 mbar(a), T_{in} = 14 °C), a net power increase of 42 % can be observed at the highest investigated altitude of 5574 m (p = 500 mbar(a), T_{in} = -21 °C).

More details about the development of optimal operating strategies for low-pressure and high-altitude operation are given in Refs. [7], [12].

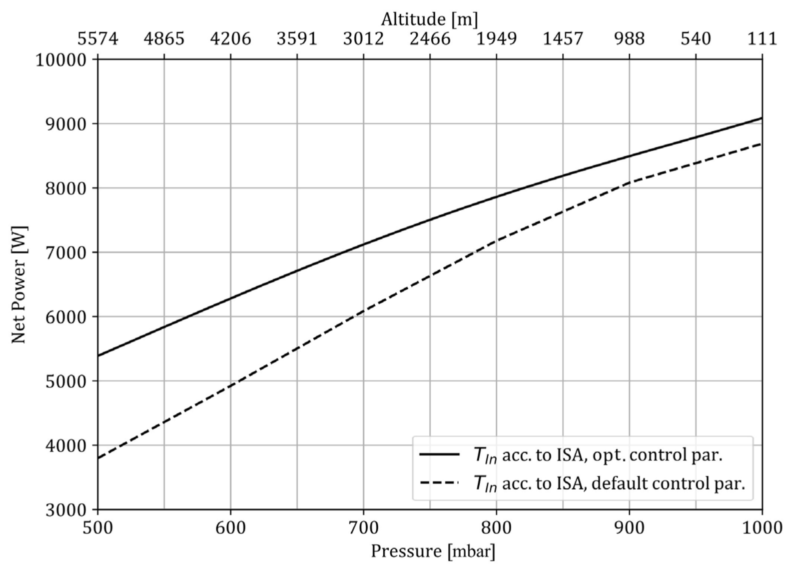

Figure 9: Maximum net power obtained with default and optimized parameters for stack temperature and cathode stoichiometry control at changing altitude conditions.

3.2 Megawatt Proof of Performance of the First-Generation BALIS Fuel Cell and E-Drive Test Systems

After the commissioning phase of the BALIS research facility, the first tests at the BALIS Fuel Cell and E-Motor Test Fields aim for a megawatt proof of performance with the correspondingly installed first-generation test systems, cf. Sections 2.4.1 and 2.4.2.

In the BALIS Fuel Cell Test Field the test campaign is conducted with 10 PowerCell PS 100 FC modules. A "full parallel" configuration with five parallel FC strings results in a maximum power of 926 kW, which is only 86 % of the theoretical maximum power of 1069 kW at 400 A, i.e. the limiting current of one FC string. This deviation results from the direct parallel connection of the strings via one bus bar, which forces all strings to be operated at the same bus voltage. As soon as the best performing string reaches the current limit of 400 A, the overall power output cannot be increased further and the voltage of all strings is determined by the voltage level of the best performing string at its current limit.

To increase the maximum power output, the implementation of two DC/DC converters is emulated in a "partly parallel" configuration by a parallel connection of three and two FC strings to one DC sink line each. The measuring results of this test run are shown in Figure 10. At a system current of 1719 A, the respective best performing string of each part of the system reached the string current limit of 400 A. A power output of 966 kW (i.e. 90 % of the theoretical maximum) is obtained, which is 40 kW higher with respect to the full parallel configuration. Further, by stepwise increasing the current up to 420 A, the MW proof of performance is achieved at a power output of 1020 kW. However, stationary conditions could not be reached at a power above 1 MW and the system had to be shut down after 120 s to prevent from overheating.

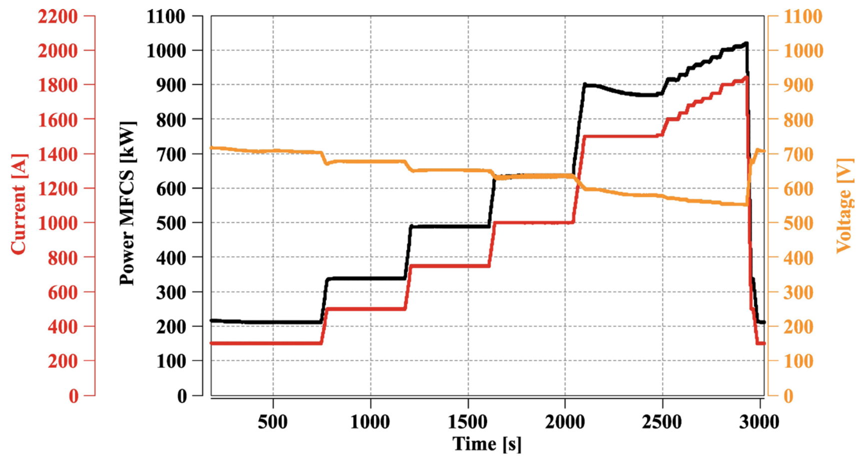

Figure 10: Current and voltage over time and corresponding calculated power output of the MFCS in „partly parallel" configuration.

In the BALIS E-Motor Test Field the two installed Compact Dynamics e-drives are initially characterized in single-mode operation. The measuring results of the tests in dual-mode operation at a total input current between 1040 and 1360 A are shown in Figure 11. At the operational limit of 600 kW electrical power at each inverter input and 1200 kW in total, a maximum mechanical power output of 1140 kW at the dynamometer shaft and a system efficiency of 95 % is obtained at a rotational speed of 15000 rpm. Hence, the MW proof of performance of the UUT is achieved.

More details about the test campaign to reach the MW proof of performance of the BALIS Fuel Cell and E-Motor Test Fields are given in Ref. [13].

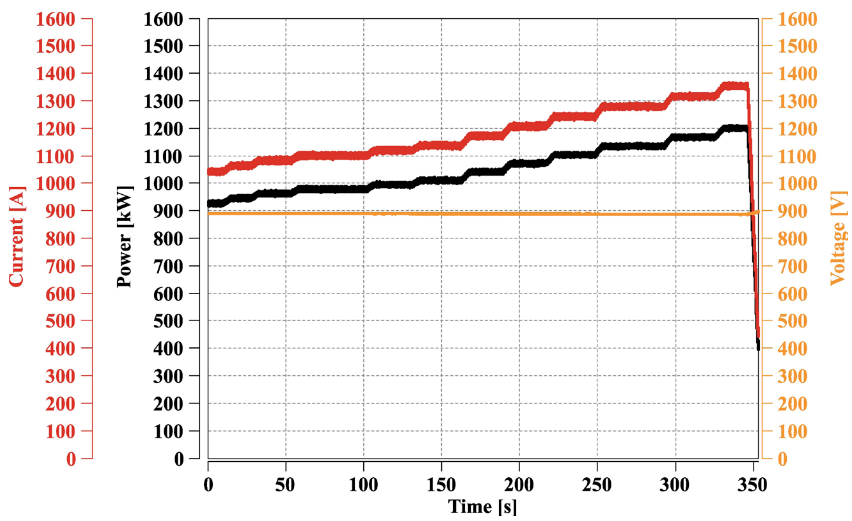

Figure 11: Current and voltage measured over time and corresponding calculated power input of the e-drive system in the dual-mode operation during the test run at 15000 rpm.

4 Conclusions

Various test facilities of the DLR Institute of Engineering Thermodynamics have been presented, each serving a different purpose in course of developing fuel cell-based powertrains for aircraft applications. The small-scale fuel cell testbed ATLAS is used to investigate PEMFC short-stacks and BoP components under extreme environmental conditions inside an altitude chamber. Operation of the system with the default parameters for stack temperature and cathode stoichiometry control showed 59 % maximum net power loss at a chamber pressure of 491 mbar(a) compared to 980 mbar(a). An optimized operating strategy for high-altitude operation is developed based on a widespread parameter study. Application of the optimal parameters showed an increase of the maximum net power of up to 42 % compared to the use of the default parameters when the system is operated under ambient conditions corresponding to an altitude of 5574 m (p = 500 mbar(a), T_{in} = -21 °C). These results highlight the large optimization potential due to altitude-adaptive control.

The large-scale research facility BALIS provides the possibility to investigate the different subsystems of a fuel cell-based electrical powertrain for aircraft. Therefore, each subsystem can be operated alone or combined to analyze the coupling behavior and develop operating strategies for a stable MW operation. During the initial test campaigns with the first-generation BALIS test systems, the MW proof of performance could be demonstrated by the FC system as well as the e-drive system. However, for a stable continuous MW operation of both systems, further research is necessary.

Acknowledgements

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