# SYSTEMS ENGINEERING METHODOLOGY ON A MULTI-INTEGRATION TEST ENVIRONMENT FOR FUEL CELL FLIGHT PROPULSION SYSTEMS

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**Abstract**

Achieving the long-term climate goals requires vehicle propulsion systems in all sectors with a CO2 and emissions footprint close to zero. Hydrogen as energy carrier and the corresponding fuel cell propulsion are a promising cornerstone for future ground transportation as well as for the aviation industry. Fuel cell propulsion systems introduce hybrid topologies with very complex operating strategies and many components interacting with each other. The development of safe and robust propulsion systems requires the application of systems engineering methods utilizing state-of-the-art multi-integration test environments. These enable the seamless transition of development activities from virtual design & simulation to the physical testing of actual components as well as the scaling from one system design to a multitude of system variants. This paper describes state-of-the-art development & validation methods from automotive industry and how they can be applied for the development of fuel cell flight propulsion systems.

**Keywords**

Systems engineering; Multi-integration test environment; Fuel cell flight propulsion; BALIS; Simulation

## 1. INTRODUCTION

The aviation industry faces radical changes induced by geopolitical, environmental, and technological challenges. These challenges result in updated development roadmaps/targets for increased energy efficiency, CO2 neutrality, and many more, requiring the adoption of new/alternative technologies.

Beside sustainable aviation fuels (SAF), electrical powertrains have the potential to play an important role in the transition towards a sustainable aviation due to the favorable well-to-tank efficiency of the energy conversion from renewable resources, the absence of CO2 and local pollutant emissions and the reduced noise exposure [1]. In the field of all electric aircraft (AEA) the application of batteries and fuel cells as energy converters are possible [2, 3]. Pure battery electric powertrains offer the advantage of zero emissions during flight and high efficiency. However, due to the low energy density of the current battery technologies the applicability is very limited to small aircrafts and small ranges. High development efforts are required to achieve significant contributions to the decarbonization of the aviation sector with this technology [4]. The application of fuel cells as main energy converters is a promising option for small and medium range aircraft. In several campaigns the feasibility of fuel cell based electric aircraft was demonstrated with small aircrafts [5, 6, 7].

## 2. FUEL CELL BASED MAIN PROPULSION OF REGIONAL AIRCRAFT

Developing a fuel cell based electrical powertrain for short to medium range AEA passenger aircraft new propulsion architectures are required. Main components are the hydrogen storage, the fuel cell system, the electric motor, cooling system, power routing and the control system.

Several hydrogen storage options for aviation are discussed in the literature. However, considering the current state-of the art technologies cryogenic hydrogen is to be preferred for the application in a regional aircraft because of its volumetric and gravimetric energy density and technological maturity [8, 9 ,10]. The design and architectures of such cryogenic hydrogen tanks are still a field of research [9, 11]. Moreover, the investigation of refueling processes, dormancy times and dynamics of gaseous hydrogen supply are crucial to demonstrate the applicability of the technology.

At present, proton exchange membrane fuel cells (PEMFC) appear to be the only fuel cell technology, which is suitable for the named purposes [9]. Other available fuel cell technologies like solid oxide fuel cells (SOFC) do not offer the required power densities and robustness today. New approaches in the field of high temperature PEMFC are of great interest for the aviation sector as the temperature increase in the fuel cell leads to higher efficiencies and less cooling efforts. However, currently they do not offer the technology readiness level, which is needed for the application in demonstrators and a near-term market launch [12]. PEMFC stacks, which are available on the market, offer a maximum gross power of 250 kW [13]. Thus, an upscaling of the fuel cell technology on a component-of-the-shelf basis can only be achieved by a multi-stack or multi-module approach.

Hybridization with a battery is inevitable in many cases and



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at least an option to be considered. The combination of the benefits of the fuel cell system with its high specific energy with the high specific power of a battery system enables optimization of the system efficiency and weight [14, 15]. Moreover, a hybridized approach can offer advantages with respect to redundancy, system stability and dynamic behavior [3, 16, 17]. Li-Ion batteries are currently the preferred technology [18, 19]. However, thanks to intensive research in this field, new cell chemistries like Li-metal and sulfur cathode materials offer great potential for significantly improved energy densities and could supersede Li-Ion cells for this application in the future [3, 20, 21, 22].

Different electric motor configurations are suitable for aircraft applications. Especially, the application of brushless DC (BLDC) motors, permanent magnet synchronous motors (PMSM) and induction motors (IM) are discussed in the literature [23, 24, 25]. In addition, the conceptual design of the power system and new technologies like superconducting approaches are important fields of research enhancing the system weight and reliability [24, 25].

Several studies exist in literature dealing with fuel cell-based powertrain architectures and hybridization approaches [3] for the aeronautical sector. However, to the best of the authors' knowledge no fuel cell-based electrical powertrain for aircrafts in the megawatt range has been demonstrated yet. In this work the development of a test infrastructure is described, which offers the possibility to test the different components and system architectures in the relevant power range experimentally. The paper gives an overview over the possibilities of the test field and focuses on state-of-the art development and validation methods that support activities throughout the development process.

## 3. FLIGHT PROPULSION TOPOLOGY

As a first step on the way to a full electric aircraft, retrofitting of an existing short range regional aircraft is a promising concept [26]. A regional aircraft in the 40 PAX class like the Do 328, ATR-42, Dash-8 might be equipped with two jet engines of 1 to 2MW each. Replacing each of them with a fuel cell drivetrain requires a fuel cell system of comparable power. However, neither PEM fuel cell stacks nor systems in the MW-range are available today. A possible short-term solution is to combine multiple fuel cell modules to a system of sufficient power. Each system might internally host multiple stacks. A typical building block would be a module in the range of 100 to 400kW as they become available in the automotive industry (cf. [27, 28]). This approach requires serial and parallel connection of multiple modules which yields new issues.

A more elaborated solution might involve distributed propulsion which leads to significant increase of total propulsion efficiency [29]. In combination with electric drives distributed propulsion gains more attention because the reduction of size does not affect the efficiency of the electric drive as it is the case in jet engines. Distributed propulsion might be realized using a central fuel cell system e.g., in the fuselage similar to the turboelectric distributed propulsion concept [30]. A high voltage DC bus must be maintained to supply the electric motors. This concept enables a close thermal integration of the hydrogen tank and the fuel cell system, which is advantageous with cryogenic hydrogen storage. Another option is to use distributed fuel cell systems. As even the central fuel cell system must be built from smaller modules, it would also be possible to use a separate system for each electric drive. In that case the fuel cell system and the electric motor might be placed in a nacelle. No central high voltage DC bus is necessary, but hydrogen must be transported from the central tank to the nacelles.

## 4. SYSTEMS ENGINEERING

Beside the technical maturity, fuel cell systems and their application in hybrid propulsion topologies are introducing a new level of complexity not only in the aeronautical sector, but also in many other mobility applications, as examples are shown in Figure 1. The balancing of the individual components like fuel cell stack, balance of plant components, battery, power electronics and e-drive requires a new development approach, which helps to make the right engineering decisions already in an early phase of the development. The automotive industry has been leading the development of hybrid propulsion systems in the last decades and has developed processes, methods, and tools to manage the complexity and launch robust, mass-customized products into their markets [31]. Some of those learnings are also applicable for other mobility sectors.

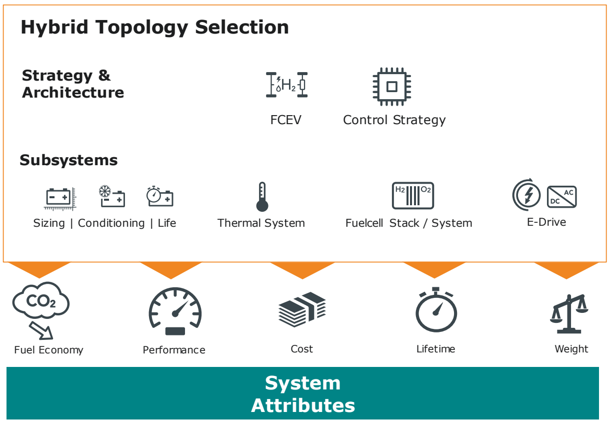


*Figure 1: System attributes for hybrid vehicle powertrain topologies integrating fuel cell systems.*

Systems engineering has proved to be a useful approach within the development of complex systems. The intention of Model Based Systems Engineering (MBSE) is to bundle all the knowledge about the complex correlations and create a generic model that can be used to describe such a complex system on abstract system requirements and architecture level [32]. The model enables the development team to deal with the complexity, the many interfaces and it provides a holistic overview of the system, where no aspect will be overlooked. In a further effect it generates time savings, minimizes errors by the reuse of specifications, simulation results, and validation plans (DVP&R).

### 4.1. Integration, verification, and validation of complex powertrain topologies

When developing complex systems, the integration, verification, and validation at system level is dependent on a multitude of system elements and so the emerging behavior that results from their interactions. Integration faults and system failures typically caused by unintended interactions, missed tolerances, non-fitting or non-functioning interfaces, control deficiencies, insufficient operation strategies, etc., and is revealed due to the integration of the system elements into the complete system. [33]

The successful integration of a complex system depends on the approach of partitioning it in system elements in the early development stages: So, every system element interacts with another in a comprehensible way. The partitioning takes place from system level to subsystem level, component level, etc. – while considering the interface management across all levels. In later stages of the development process, the reversing of the partitioning process becomes the core principle for integrating the whole system step-by-step. Best practices described in literature prefer conservative approaches in terms of system integration. This means, that only a limited number of further system elements is added in each integration step. This is done to proof the expected operational capabilities of the partial system before integrating the next system elements. In general, this eases the tracing of unintended/unforeseen behavior, that may emerge from interacting system elements. [34]

The key for the establishment of such a procedure is the capability to support the system design process as well as the system integration, verification and validation process with an integrated and open development platform covering end-to-end methods and toolchains for physical and virtual development assets: [35]

- For defining the system’s targets, behavior, structure, and composition,
- For designing and safeguarding the function, shape, and topology,
- For sourcing and/or manufacturing the system elements,
- For continuous integration, verification, and validation of physical and/or virtual system elements on all levels [36].

These processes and methods (cf. [37]) are the basis for the state-of-the-art agile (i.e., iterative, incremental) development approach. This requires development organizations to adapt their integration, verification, and validation environments to leverage the full potential of the systems engineering approach. Traditional design validation plans have shown that there is a significant gap between the component validation and the integration testing, which widely is executed in the physical full-scale test carrier or the actual recipient (e.g., prototype, final product). The integration is the first time all individual components are validated together as one system, which is very late in the development process and iterations require much more effort. [38]

### 4.2. Multi-integration test environment

A highly automated multi-integration test environment, where real and emulated components are brought together, is closing the gap, as depicted in Figure 2. As soon as components are available, they can be integrated and validated in a system setup under true load conditions. The automation backbone allows a switching between real and virtual components with the possibility of quick and safe realization of multiple use cases. This enables the physical testing of real components in combination with time-synchronous simulation models on the co-simulation capable execution backbone. The virtual components are represented by simulation models running in (hard) real-time. [35]

Typical elements of such a multi-integration test environment for electrified powertrain systems are dedicated test cells for the units-under-test (UUT), e.g., fuel cell systems, battery systems, and e-motor systems. Furthermore, the capability for routing, patching, switching, and emulating signals and power (e.g., electric, mechanic, hydraulic) between the individual test cells is required to mock the real environment for each UUT as close as required. This may also include the simulation of environmental conditions (e.g., altitude, climate, humidity), the integration of further actuators, but also supply and conditioning systems, e.g., for fuel, coolant, and lubricants. The entire multi-integration test environment is run by the automation backbone, overseeing test run preparation, UUT identification and initialization, test run execution and monitoring, and test run data acquisition for online/offline data analytics. [38]

This results in a testing and validation environment bringing the separate (and often distributed) development teams together in an earlier stage and so, allowing quicker iteration cycles. Integration phenomena can be uncovered early due to the operation under true load conditions. Specifically, in the case of a fuel cell-based hybrid propulsion system the impact of other components (e.g., battery state of health, stack degradation mechanism, high voltage ripple) on the system degradation and long-term performance can be understood. So, countermeasures in the operating strategy can be implemented (e.g., pro-active wear management to prevent battery cell aging).

Further benefits of multi-integration test environments are the reduction of full-scale test carriers, their development, their sourcing, assembling, rigging, etc. and the flexibility in reconfiguring the test environment to changing DVP requirements.

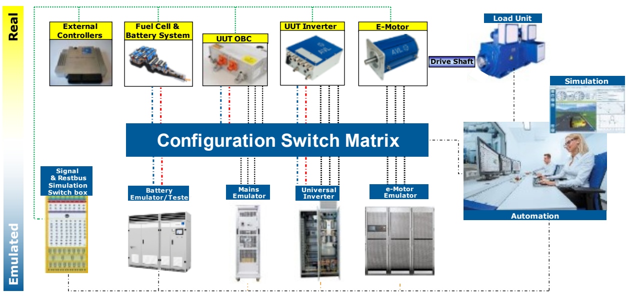


*Figure 2: Example of a multi-integration test environment topology integrating real, emulated, and virtual components.*

## 5. BALIS PROJECT

Within the project BALIS a unique test environment is built up to enable the upscaling of fuel cell-based powertrains to the megawatt range. It consists of several test fields for the different UUTs of the powertrain which are: Liquid hydrogen tank, fuel cell system, battery system and electric motor. The test environment offers the possibility of single component as well as coupling tests by procedural or electrical connection of the test fields following the multi-integration test environment approach as described above. A schematic flow diagram of the configuration of the BALIS test facility is shown in Figure 3.

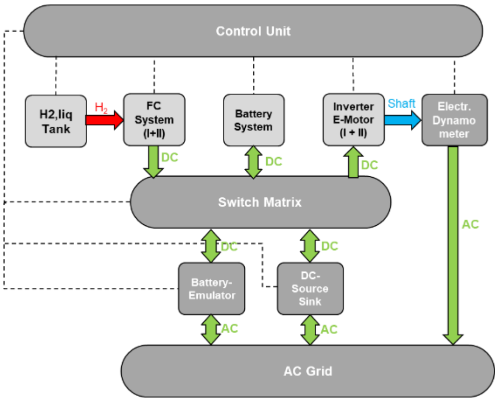


*Figure 3: Schematic flow diagram of the configuration of the test environment BALIS. Light grey: UUTs, dark grey: test field infrastructure, red, green, and blue arrows: material, electrical and kinetic energy flows.*

The switch matrix is the key element to connect the different test fields flexibly. It enables the investigation of different powertrain architectures as well as hybridization concepts and electrical power components. In the following the different test fields of the facility are described and the use cases, which can be realized by coupling together the test fields via switch matrix are explained.

### 5.1. Liquid hydrogen test field

Because of the large quantities of hydrogen needed for applications in the megawatt range the storage of hydrogen in liquid form is at present the method of choice for aircraft applications. Therefore, the test field for hydrogen tank systems (*test tank*) is designed for liquid hydrogen (LH2) applications. A schematic flow diagram of the LH2 infrastructure is shown in Figure 4.

In a storage tank an amount of up to 2.5 t LH2 is held ready for the hydrogen supply. The refueling infrastructure allows the test tank to be filled, whereby the refueling process itself is the subject of investigation regarding the optimization of the process parameters to reduce losses as well as the investigation of components like e.g., the refueling nozzles. The test tank itself can contain up to 200 kg LH2. With respect to the tank architecture different approaches are possible, e.g., internal or external evaporation/heating for the supply of gaseous hydrogen, use of cryogenic pumps. The test field is equipped with an external evaporator, which is integrated in the thermal management of the whole infrastructure. If no measures for hydrogen evaporation and heating are integrated in the test tank this evaporator can link the test tank and the fuel cell system for preconditioned gaseous hydrogen supply. Gas flows of up to 120 kg/h of hydrogen supply for the fuel cells are possible with the infrastructure.

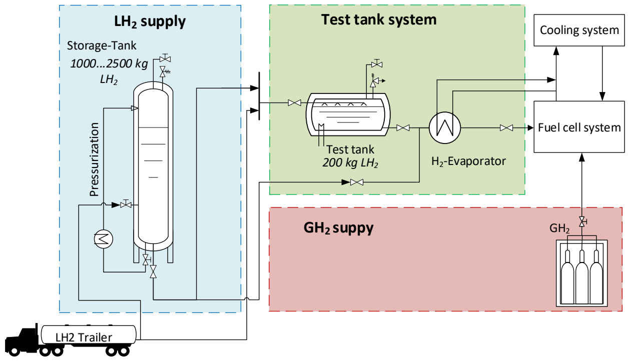


*Figure 4: Schematic flow diagram of the LH2 test field including the LH2 infrastructure and the hydrogen preconditioning system.*

### 5.2. Fuel cell test field

Multi-stack approaches have to be considered for power supply in the megawatt range. Moreover, considering the different possible propulsion topologies the ranges of required power output per fuel cell system are broad. Hence, the fuel cell test field of the BALIS test environment is designed to run fuel cell systems with variable power outputs and interconnection concepts. It offers test places for commercial 100 kW modules as well as the possibility to bring in larger systems of 300 to1500 kW gross power. The test field is accommodated in a test container and coupled to the GH2 supply of the LH2 test field and the thermal management of the facility. For air supply flow rates of up to 6150 $m^3$/h are possible. Product water condensate is separated, and the exhaust gases are safely discharged. The test field is equipped with two galvanic isolated DC powerlines with 1200 V/1250 A each. For sole fuel cell testing relevant loads can be simulated by DC source/sinks.

### 5.3. Electric motor test field

In order to enable e-motor testing with high flexibility the electric motor test field is equipped with two galvanic isolated DC powerlines of 1200 V/1250 A each. One electric inverter/motor unit of variable power can be fed by each powerline. Alternatively, the powerlines can be connected to feed a single inverter/motor unit of 1200 V/2500 A max. In case of two motors, they must be mounted on a single shaft or be coupled by a gearbox. A recuperating dynamometer which is connected to the AC grid is used to emulate a propeller shaft. The dynamometer operates at a continuous maximum power and torque of 1800 kW and 10 kNm, respectively.

### 5.4. Battery test field

To provide the possibility for FC/battery hybrid testing a test field for the implementation of a battery system is considered. It allows the testing of battery systems up to 500 kW power and a capacity of 500 kWh. For single component tests the battery can be connected to the DC source/sinks to simulate the electrical load of a discharging and charging processes. Moreover, the DC source/sinks can also act as an emulator of battery systems with the possibility to simulate battery technologies, which are not available physically.

### 5.5. Switch matrix and DC source/sink

The switch matrix is the central point where the electric power routing of the BALIS test environment is managed. It consists of a total of 15 double pole contactors which allows to freely connect energy sources with consumers. Three bus bars can be used for different potentials in parallel. Each bus bar is connected to a regenerative 2-quadrant source/sink of 825 kW.

### 5.6. Use cases

The switch matrix of the BALIS test environment allows a flexible interconnection of the components on the electrical side. For example, a direct hybridization concept can be tested by connecting battery and fuel cell system and investigating the hybrid behavior under load profiles simulated with the DC source/sinks. In addition, parallel and redundant hybrid topologies with two motors and separate energy supply systems can be realized by a galvanic separation of the two drivetrains. By the integration of power electronics like circuit breakers and DC/DC converters more sophisticated load control concepts can be investigated. Three examples of such interconnection approaches (use cases) are illustrated in Figure 5.

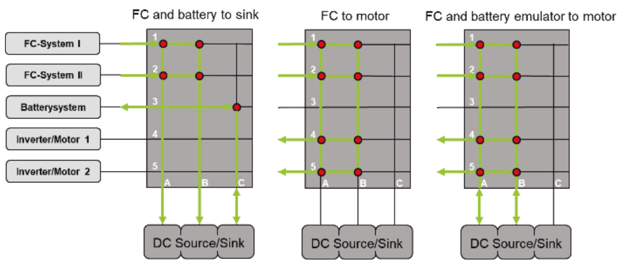


*Figure 5 Simplified single line diagram of the switch matrix. The figure shows three different interconnections (use cases) exemplarily.*

An overview over the overall 16 possible use cases is shown in Table 1. By now, only interconnections with one or two independent electric potentials are defined. However, interconnections with up to three independent potentials are possible.

## 6. NEXT LEVEL SIMULATION

Many industries are undergoing a significant paradigm shift from a hardware centric development approach using simulation and modelling as a support function to a simulation-centric approach, leveraging hardware when available in the development timeline. Virtual prototypes and models are used from the beginning to shorten development times and support an agile simulation approach.

*Table 1 Overview of the 16 use cases defined in the BALIS test field. FC: fuel cell system; BAT: battery system; EM: electric motor; DC: DC source/sink.*

| Source Potential 1 | Source Potential 2 | Sink Potential 1 | Sink Potential 2 |
|---|---|---|---|
| FC1+FC2 | | DC1+DC2 | |
| FC1+FC2 | | EM1+EM2 | |
| FC1+FC2 | DC1 | DC2 | EM1+EM2 |
| FC1 | FC2 | DC1 | DC2 |
| FC1 | FC2 | EM1 | EM2 |
| BAT | | DC1 | |
| BAT | | EM1+EM2 | |
| DC1+DC2 | | EM1+EM2 | |
| DC1 | DC2 | EM1 | EM2 |
| FC1+FC2+BAT | | DC1+DC1 | |
| FC1+FC2+BAT | | EM1+EM2 | |
| FC1+FC2 | BAT | DC1+DC2 | DC3 |
| FC1+FC2 | BAT | EM1 | EM2 |
| FC1+FC2 | DC1 | EM1 | EM2 |
| FC1+FC2+DC3 | | DC1+DC2 | |
| FC1+FC2+DC1+DC2 | | EM1+EM2 | |

The next level extension to the already described testing environment would be the step from a hardware-in-the-loop to a pilot-in-the-loop-setup. The real time connection to a flight simulator would allow to capture the human impact on operating strategies and could reduce airborne flight hours with physical prototypes. This approach has been proven in racing applications before, in order to cover test track miles on a semi virtual test environment. The human factor and its impact on operating strategies can be augmented, which results in much more robust software functions and reliable products.

Furthermore, simulations on all levels and with different fidelities can be coupled the multi-integration test environment, as shown in Figure 6.

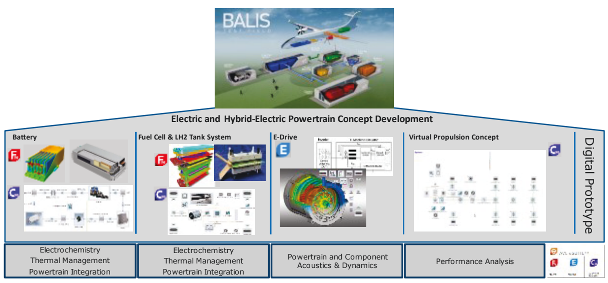


*Figure 6: Simulation-centric development on integrating different model fidelities and all model levels.*

As mentioned before, the time guarantees of each simulation model define, whether the simulation model can be executed in the loop, i.e., complying to (hard) real-time constraints, or offline, e.g., for generating upfront calibration data or utilizing actual test measurement data as simulation input for model validation purposes. This leads to the ability of shifting between testing and simulation seamlessly, i.e., the instantiation of the digital thread [39]. For example, this is essential for developing virtual sensors to replace physical sensors in series powertrain components with the effect of lowering production and operation costs significantly. [40]

## 7. CONCLUSION & OUTLOOK

This paper highlights the abilities of state-of-the-art test facilities based on the BALIS project. Utilizing this multi-integration test environment will support the development of fuel cell powered flight propulsion systems for 40 PAX class aircrafts in the next decade. Besides the physical testing capabilities, virtual testing and therefore model-based development approaches can be integrated seamlessly. So, development activities from different phases in the product lifecycle can take place at the same time in the same place.
This kind of test facility represents the state-of-the-art in automotive industry and is transferred to the aviation industry now. This includes the upscaling from the kilowatt range of ground-based vehicles propulsion systems to the megawatt range of aircrafts for the first time.

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