GIANTLEAP

DELIVERABLE D3.4

PUBLIC

Validation of the control system in laboratory and demonstration

Michael Deibler (BEG)/ Ulrich Seufert (BEG)

Quality Assurance: Ivar J. Halvorsen (SINTEF)

Project acronym: GIANTLEAP

Project title: Giantleap Improves Automation of Non-polluting Transportation with Lifetime Extension of Automotive PEM fuel cells

Project number: 700101

Document date: January 07, 2020

Due date: October 31, 2019

Keywords: control, laboratory, demonstration.

Abstract: This report describes the validation of the control system in laboratory and the demonstration phase. There is a close interaction of the work package Results from demonstration of the range extender (WP6.3). The tests with the laboratory system are finished and the tests on the demonstrator are ongoing.

Revision History

Date	Description	Author
October 09, 2019	First draft	Deibler (BEG)
October 17, 2019	Chapter System Operation	Seufert (BEG)
January 7, 2020	Layout adjustments	Zenith (SINTEF)

Table of Contents

1 Fuel Cell System Overview

The Giantleap project develops a fuel cell system that is placed in a trailer and acts as a range extender for an electric bus. The bus batteries can then be continuously charged by the fuel cell during driving, and the bus becomes thereby independent of charging stations during operation.

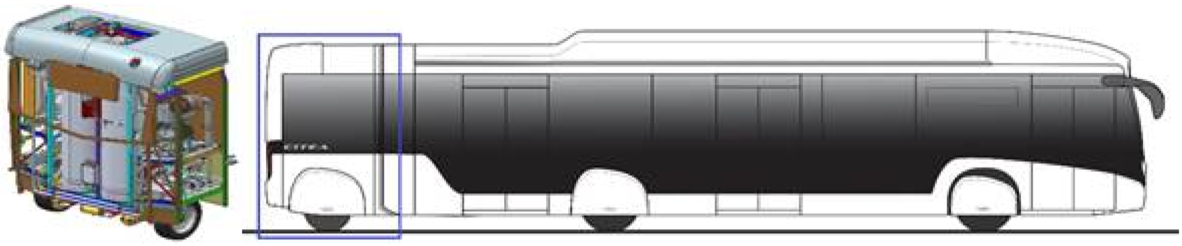

Figure 1: Electric bus with the Giantleap Fuel Cell system in the trailer (indicated with the blue rectangle).

The overview of the fuel cell system topology is shown in Figure 2. The electrical interface, as seen from the bus, shall be the same as for any ordinary charging station. The main components of the fuel cell system are fuel cell stacks, hydrogen storage, DC/DC converters, air compressor, humidifier, cooling system, and the Fuel Cell Control Unit (FCCU) with necessary sensors, actuators and control software to realise the desired operating conditions and interfaces to the bus system.

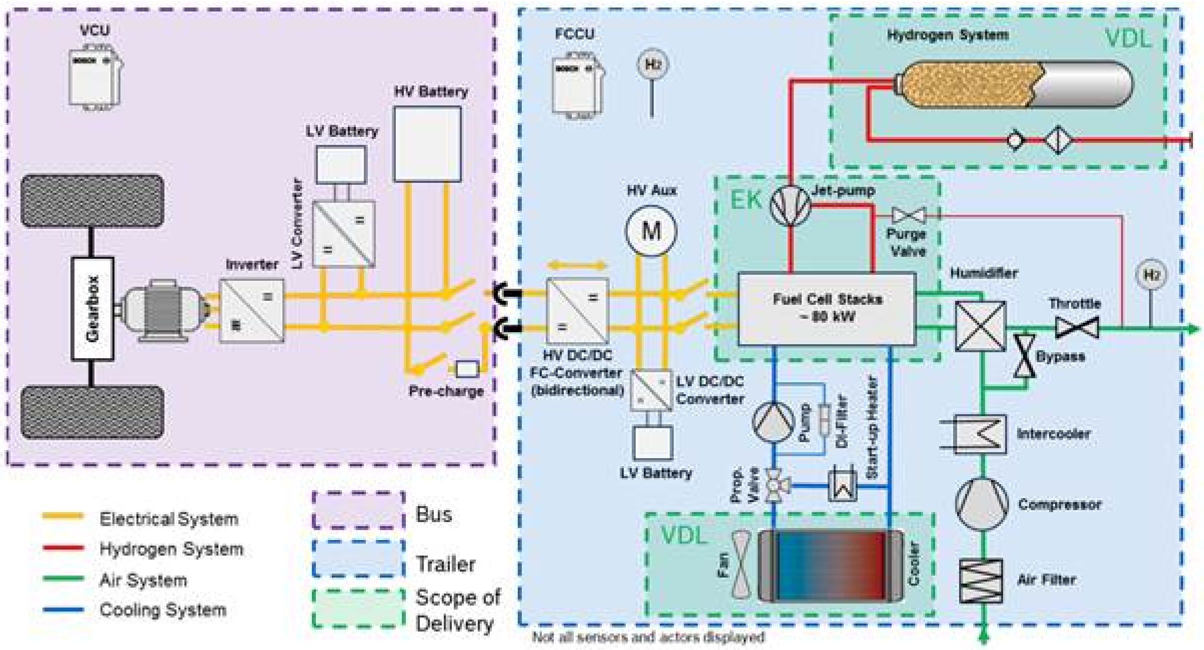

Figure 2: Topology of the Giantleap Fuel Cell System.

The main purpose of the basic control system is to ensure that the demanded power output is delivered by regulating compressor speed, pumps and throttle valves in order to maintain pressure and temperatures at the optimal values for system operation at each load level. In addition, it must be ensured that operating constraints are fulfilled, and in case of exceeding limit values, it is necessary to restrict the power production or even shut down the system immediately.

The FCCU provides all sensor data that also can be utilised by Prognostic and Health Management (PHM) functions.

2 Technical-Economic Considerations

The main economic impact of measures that can increase the technical lifetime or Remaining Useful Life (RUL) of equipment is reduction of the cash flow related to purchase and replacement. In a modular system, this may be used separately for the main components or the system as a whole.

During operation of the fuel cell in the bus, the power demand can be regarded as given by the bus requirement. The energy efficiency is defined as the actual hydrogen consumption per electric energy unit delivered to the bus.

The degree of freedom in operation is related to how the fuel cell operating conditions are selected and how the charging protocol is implemented. The average required power production is determined by the bus consumption, but how this average is achieved is subject to optimisation.

There is a trade-off between the momentary optimisation of efficiency and the impact on the degradation and thereby the RUL. The sensitivity from a change in the operating point to the degradation rate is complex as there are several degradation mechanisms.

Hydrogen consumption can be calculated via the measurements of tank pressure and temperature. Correlations for hydrogen compressibility as function of pressure and temperature are available, and from that the mass of consumed hydrogen during operation can be calculated if the total volume is known. The accumulated power delivered from the stack can be calculated from current and voltage measurements. Similarly, the net power delivered from the FC system to the bus can also be retrieved. This allows for monitoring of both stack and system efficiencies.

Charging the bus at ordinary charging stations is normally cheaper than using the fuel cell system, so a cost-saving option is to charge the bus fully from the grid at the depot during the night and plan arrival at the depot the next evening with almost empty batteries; this will replace one full charging cycle with hydrogen with usual electricity supply[1]. However, the main advantage of the fuel cell range extender is just what the name suggests: to have the bus operational all day without charging breaks plus the ability for usage in regions with limited charging possibilities, e.g. for regional bus lines.

[1] This should however be weighed against the reduction in lifetime of the battery pack due to operation at very high or very low states of charge, even if battery prognostics is outside of the scope of Giantleap.

3 Implemented Functions

The following main levels are defined for the control and monitoring functions of the fuel cell system.

1. Electrical system
2. Air system
3. Hydrogen system
4. Thermal system
5. Prediction functions

The following sections give a brief description of each level.

3.1 Regulatory Control

The Fuel Cell Control Unit (FCCU) handles all **measurements and actuating devices** for the complete fuel cell system including the stacks, hydrogen storage, all necessary balance-of-plant (BoP) components, external communication with the bus system and operator interaction. The FCCU hardware unit and on-board control software is delivered by BEG in work package 5 in Giantleap; the unit is a proven automotive component, and has been selected for having capabilities suitable for the requirements of the fuel cell system. Its basic functions are:

- Process interface, sequencing and basic control functions;
- Process measurements and manipulative outputs, system communication and remote access;
- Establishment and maintenance of operating conditions and handling of transients in presence of real-world disturbances and uncertainties;
- Process monitoring, constraint handling and emergency handling:
  - E.g.: Limit power production if cooling capacity reaches its maximum;
  - Initiate shutdown sequence if any critical limits are exceeded;
- Sequencing and operational mode management:
  - Start-up and shutdown sequences;
  - Transitions between different operating modes, including special PHM ones;
- Charging protocol:
  - The fuel cell system shall deliver power to the bus according to the bus' power demand, as if the FCS were an ordinary charging station;
  - The charging power can be relatively freely chosen when bus batteries are charged above a certain minimum (or below a certain maximum); charging may be implemented in different ways, as long as the average power is sufficient;
- Optimised scheduling based on FC performance test data:
  - Air pressure setpoint as function of delivered power;
  - Air flow rate setpoint as function of delivered power;
  - Coolant inlet and delta temperature setpoints as function of delivered power;
  - Feedback control loops adjusting compressor speed, coolant flow rate and temperature, to reach the specified setpoints;
  - Operating constraints may limit available power;
  - Avoidance of operating regions known to be damaging to the cell;
- Data logging of time series data to storage unit for off-line analysis.

In addition to these basic functions, additional PHM functions can be added via software.

3.2 Electrical system

In the electrical system control the desired power from the bus is send via CAN to the FCCU (Fuel Cell Control Unit). This power request is the net power request that the bus wants to receive. On this request, the power loss of the system is added and this is the requested power from the FC system. Due to an failure or in special conditions (cold coolant temperature) this power request can be limited.

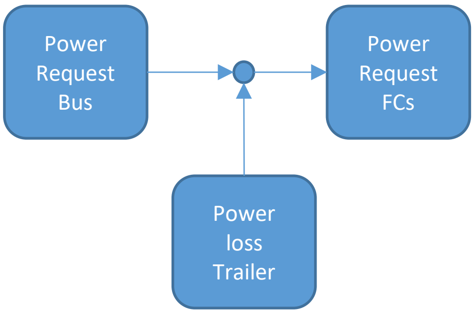

Figure 3: basic power request of the FC system

3.3 Air system

The Air system delivers the required air mass depending on the power requested by the FCs, and controls the cathode pressure. An increase of this mass flow or pressure leads to an increase of the needed power of the air system. This power loss is added to the trailer power loss and increases the power requested from the FCs.

With the measured air mass the system calculate the available power which is set as a request to the DC-DC converter. The actual loss of the DC-DC is also calculated and will be added to the trailer power loss.

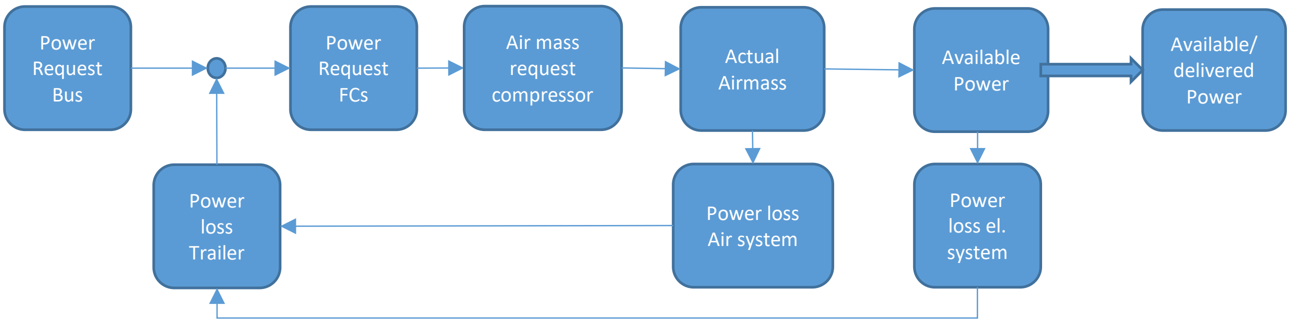

Figure 4: Power request and losses of the FC system

3.4 Hydrogen system

The hydrogen system delivers the needed hydrogen depending on the actual state of the fuel cell. This system maintains the pressure difference between anode and cathode and is responsible for the gas exchange in the anode (purge). In addition to this it also calculates the produced water in the anode loop and initiates its drainage.

3.5 Thermal system

The thermal system tries to bring the system as fast as possible to its set temperature and maintain it in a defined range. These losses will also be added to the loss of the trailer and increase the power requested from FCs.

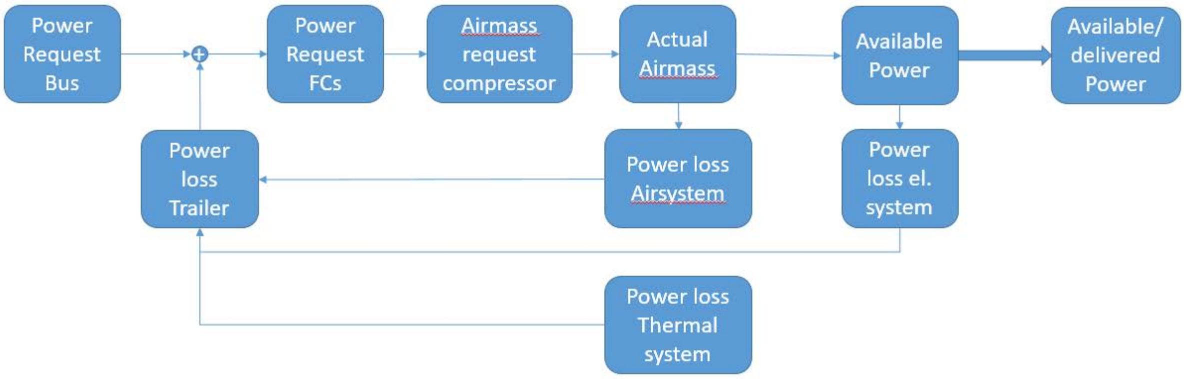

Figure 5: complete power loop of the FC system

4 FC System Operation in Demonstration Phase

The level of maturity of system calibration is shortly after the initial stage, where commissioning has been finished and the calibration and improvement phase has just started. There is still some improvement needed.

4.1 FC System Startup

After T15 On and receiving the VehFCOn command and power request via CAN from the Vehicle Control Unit (VCU), the fuel cell state machine is preparing the start up of the fuel cell system by starting up the subsystems electrical system, air system, thermal system and hydrogen system.

After this preparation the system is starting with a limited power demand. This demand will be ramped up coolant temparture based to the desired value. The machine is then in state "Running" (Figure 6).

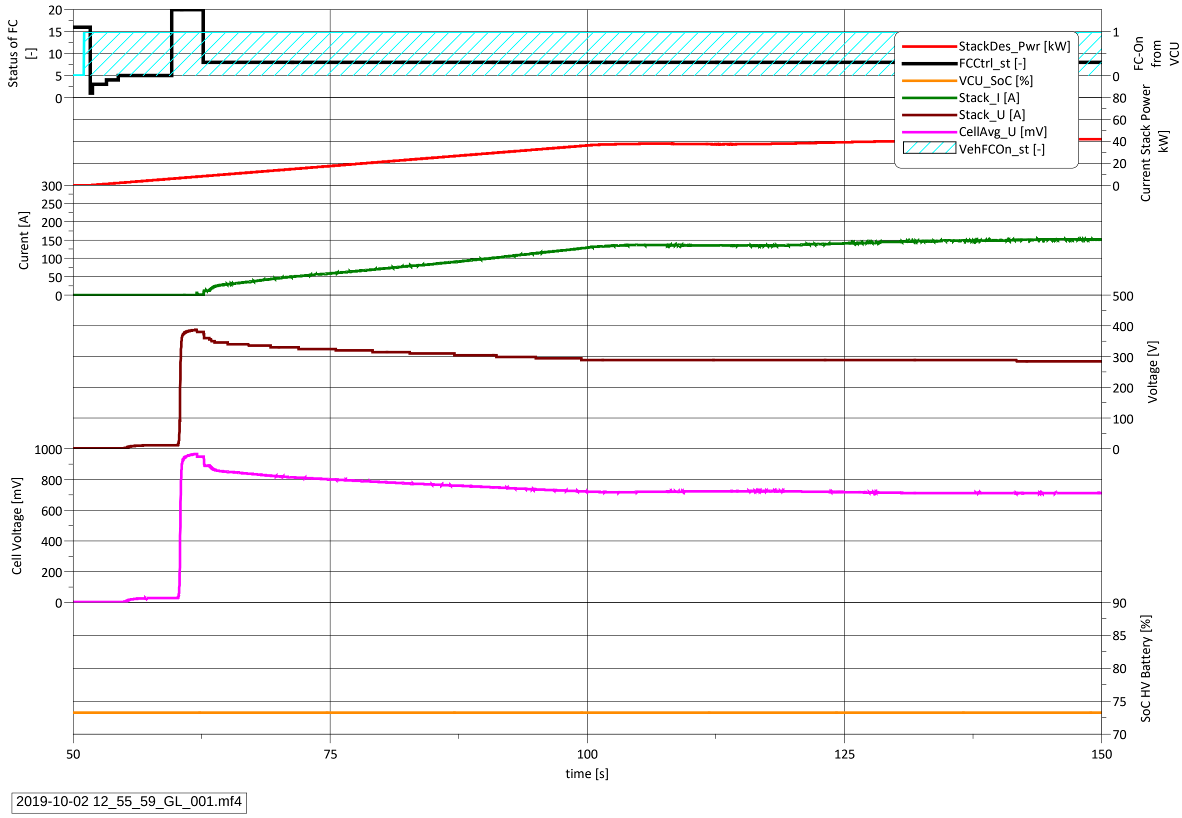

Figure 6: Startup phase of FC System.

4.2 FC System Shut-Down

When receiving the signal from the VCU, that the system should shut down (VehFCOn_st=false), the FC state machine changes from state “Running” to the next states that will prepare the system shut down to leave the system in a defined and uncritical status (Figure 7), dry and with low voltage.

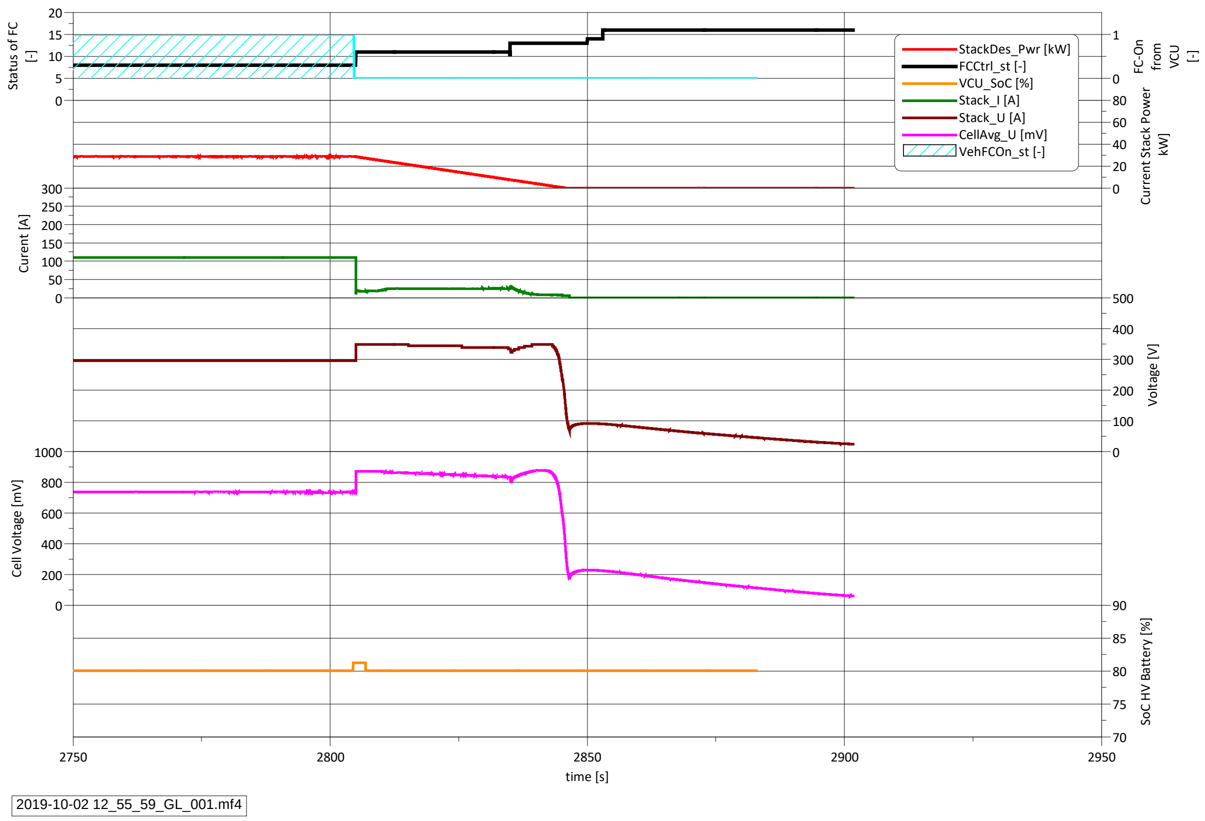

Figure 7: Shut-down phase.

4.3 FC System in "Running" Mode

The main operation point of the system is the state "Running", when the Fuel Cell is charging the HV-Batteries of the Bus.

Figures 8 to 11 are showing a complete sequence of the system including startup, running and shut down phase.

After the power ramp up the system runs on desired power of 60kW as long as the VCU is demanding high power. When the SoC of the HV-Battery reaches 75%, the power demand from VCU will be decreased to 25kW. After reaching a SoC of 80%, the VCU requests a shut down of the FC system.

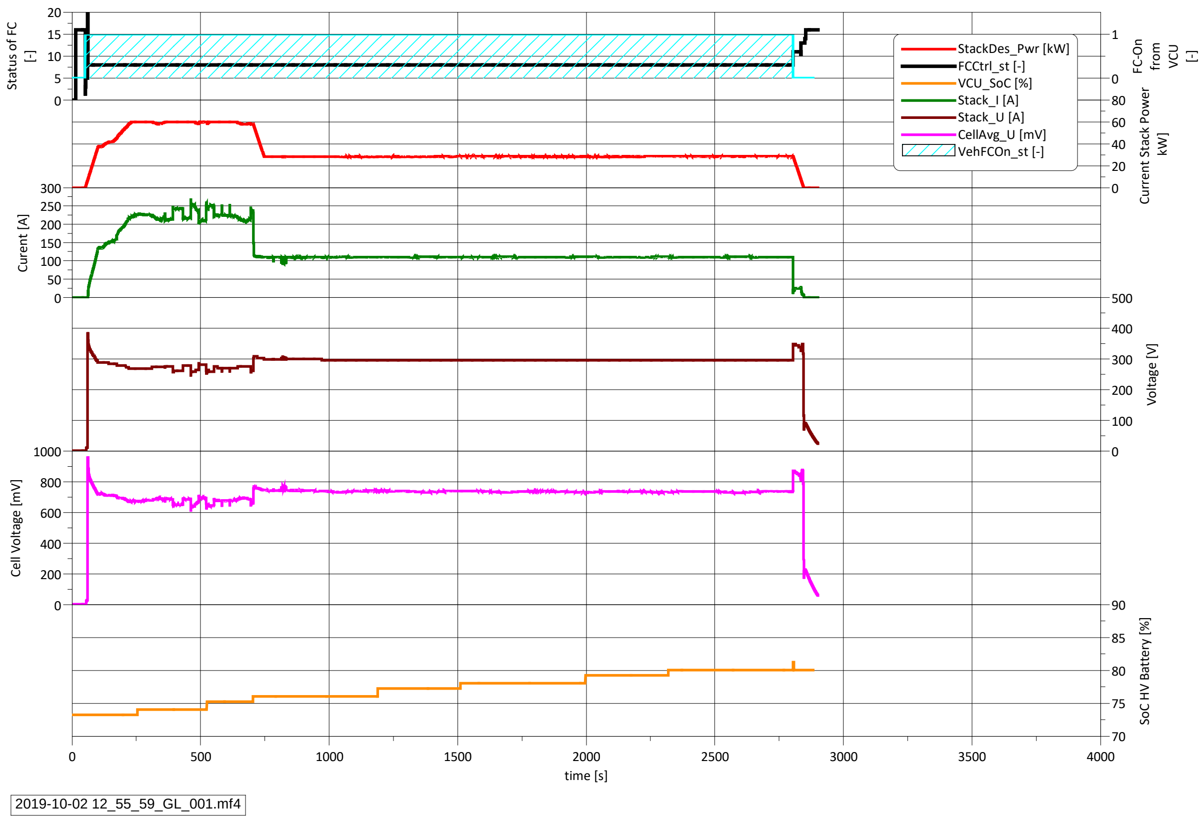

Figure 8: Complete sequence electrical system.

In Figure 8 are also shown the parameters of the electrical system: stack current, stack voltage and average cell voltage. In addition, the SoC of the HV battery is shown on the bottom diagram.

The "noise" on the stack current and voltage during the 60 kW phase is caused by the power derating function based on the coolant temperature.

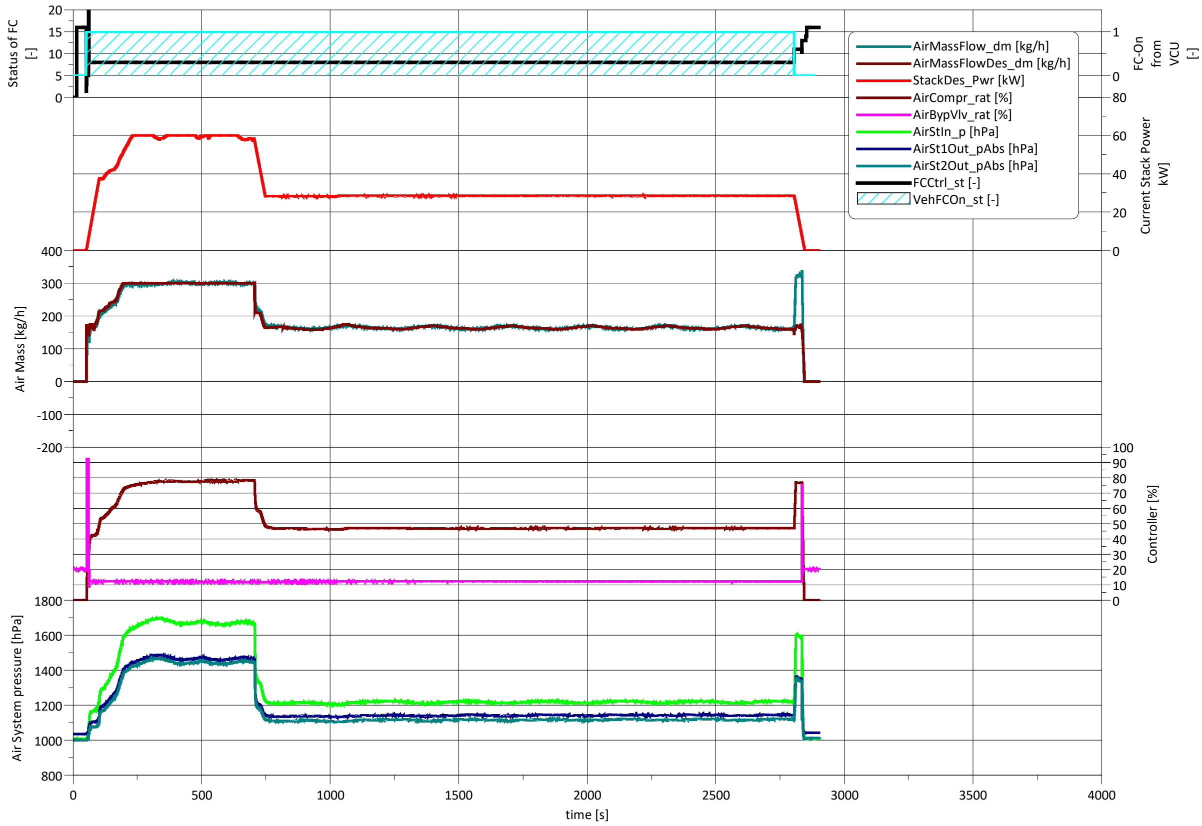

Figure 9: Complete sequence air system.

Figure 9 focuses on the air system. Here the paramteres desired and real air mass, air system pressure, air compressor and bypass flap ratio are shown. The peaks of the bypass valve in the beginning and the end are caused by the startup and shut down phase.

The hydrogen system parameters hydrogen stack inlet pressure, H_2 regulator valve ratio, purge and drain valve ratio as well as the H_2 concentration in the housing and the exhaust are represented in Figure 10.

The H_2 concetration in the exhaust is during the whole runtime below the 4 % borderline, but shows some potential for improvement. The H_2 concentration in the housing is 0 %, so there is no leakage in the housing.

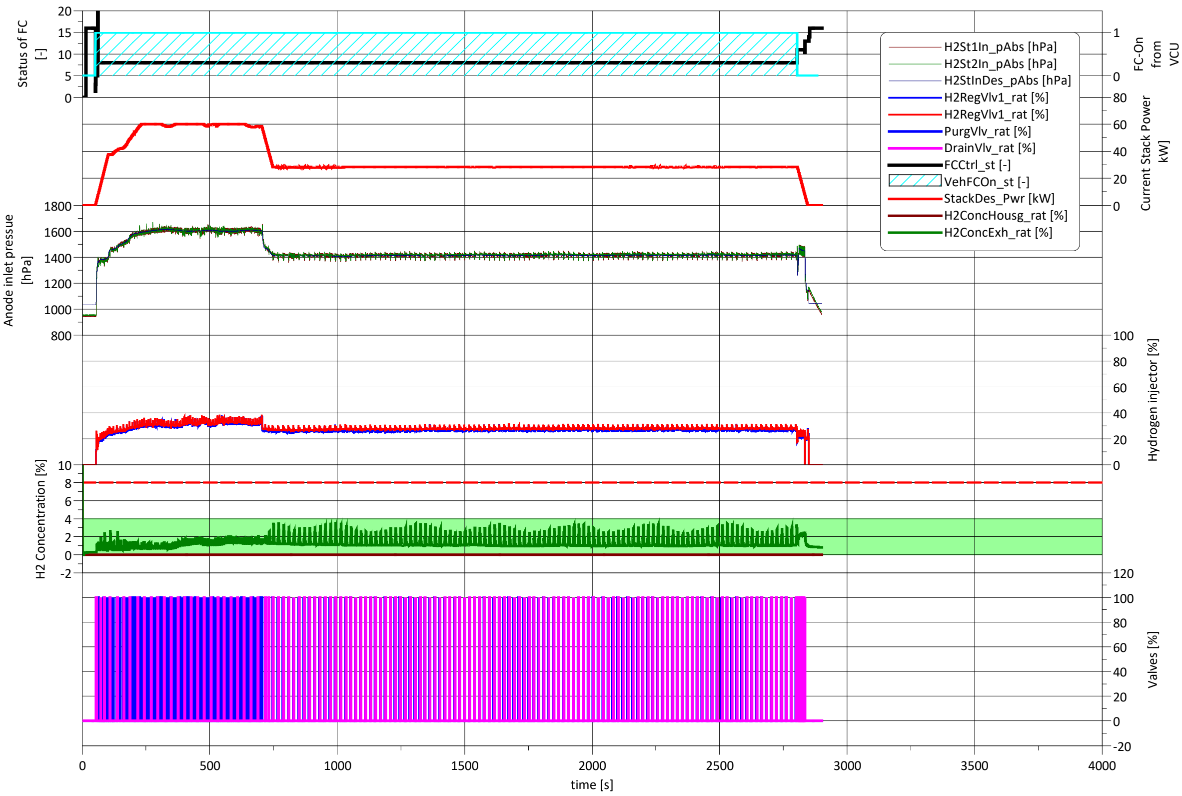

Figure 10: Complete sequence hydrogen system.

The thermal system is shown in Figure 11. There are the parameters coolant pump and Fan ratio, coolant temperature into the stacks, air temperature 1 and 2 downstream of the stacks and the coolant pressure.

Since the 3/2-way valve in the system has been broken, the system is always running with a 50 % radiator and short cooling circuit.

Due to that and due to a long distance between stacks and radiator and therefore a very slow response time the coolant fan is running like in a 2 point control mode.

The coolant pump ratio is based on the temperature difference between coolant temperature upstream stack and air temperature downstream stack.

Due to the broken valve and the long response time the dynamics of the temperatures is to high and the coolant pump control has to react a lot.

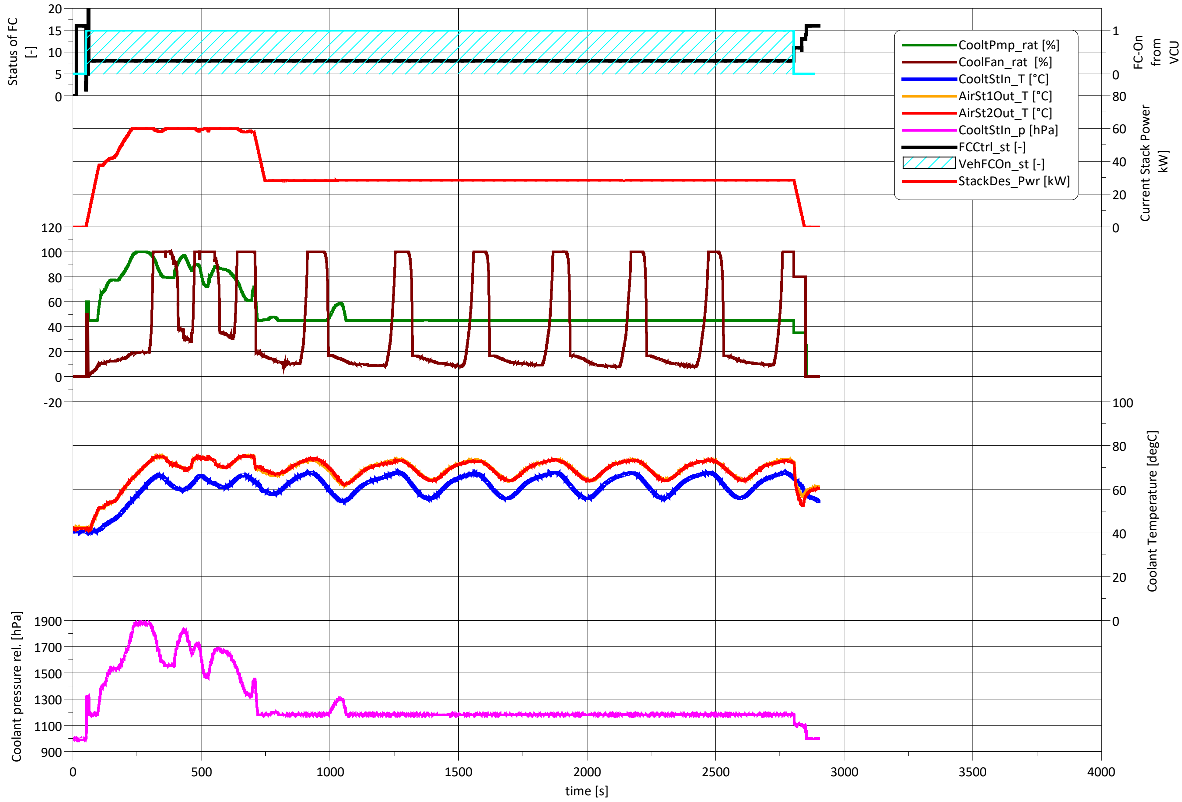

Figure 11: Complete sequence thermal system.

4.4 Resumee commissioning / calibration in demonstration phase

With the measurement used in the figures 6 – 11 it has been proved that the fuel cell system is built up and running in the trailer with interaction between Bus and FC system. The system can also run at different load points up to 60 kW.

Due to some technical issues (broken parts etc.) the current system calibration level of maturity is only short after the initial stage. There are still some points to be improved like e.g. the thermal system hardware and calibration, the purge and drain strategy.

5 References

Ivan Pivac, Gojmir Radica, Frano Barbir, Djedjiga Benouioua, Fabien Harel, Denis Candusso: *Diagnostic methods for automotive fuel-cell systems*, deliverable D1.4 in Giantleap, 2017, http://giantleap.eu/?p=175.

Ivar J. Halvorsen, Federico Zenith: *Control system specification and algorithms*, deliverable D3.2 in Giantleap, 2017, http://giantleap.eu/?attachment_id=238