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Dynamic investigation of PEFC stacks in interaction with the air supply system

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Abstract

This paper explores the behaviour of a dynamically operated fuel cell system regarding to an automotive application, examining the air supply and their interaction with the fuel cell stacks. The dynamic limits of stack operation are also discussed. Finally, the paper provides a description of the test facility used in these investigations.

The research of dynamically operated fuel cell stacks shows that in order to achieve high energy efficiency, a power-dependent modulation of the pressure and flow rate of the air supply is necessary.

A test facility designed for energy management and power train research (up to 42 kW) was used for the experiment. A number of 11.5 kW fuel cell stacks was examined experimentally with respect to performance in interaction with the air supply in stationary and dynamic operation. The stacks were tested individually and in parallel. All of them were operated "dead-end" on the hydrogen side. Experimental results varying the parameters and load curves applied to the air supply system are given in the paper. The results show different dynamic behaviours between the stacks and a substantial difference in efficiency and dynamic response of the fuel cell system operated with different strategies. The results of different operating strategies for fuel cell systems, with respect to the interaction between the fuel cell stack and the air supply and in their dependency on air mass flow and pressure level are presented. The examinations were done with the test facility using real current demand profile of the experimental car HyLite® from zero to full load and the New European Drive Cycle (NEDC).

Keywords: PEFC; PEMFC; Fuel cell; Power train; Dynamic operation; Air supply

1. Introduction

The work of the Institute of Vehicle Concepts (FK) of the German Aerospace Center (DLR) is focused on advanced power trains, mainly in dynamic operation. DLR-FK has assembled a number of test benches and created software tools for developing and testing hybrid and electric drive concepts, components, and energy management strategies. Within the scope of the HyLite Project FK developed and operates the fuel cell vehicle HyLite® [1] as a testing and development platform [2] and a fuel cell power train test bench HyLite® 20 for testing components and operation strategies. A major advantage of the test bench is its control flexibility, regarding, e.g. changes of operating strategies or simulation models. With its short evaluation time, the test bench provides quick verification of simulation models, as well as testing of operation and system regulation strategies under dynamic automotive conditions including various drive cycles.

In this network project automotive part suppliers are working in co-operation with the DLR to develop an energy supply system for a fuel cell hybrid vehicle. The system integration is carried out by the DLR. This project offers a platform for the automotive companies to create and develop new components specifically designed for fuel cell hybrid vehicles. The development of an optimised strategy for the fuel cell system operating in the fuel cell car regarding operation stability, water neutrality and the maximum power dynamics of the system, and a high energy efficiency forms especially the necessity to characterise the fuel cell stack and system behaviour in interaction with the air supply sub system [3]. The exact knowledge of these characteristics is important to design an efficient and well operating control for a PEFC system.

2. Experimental setup

2.1. Test bench

The energy management facility is a flexible system consisting of a dynamically operable modular fuel cell system

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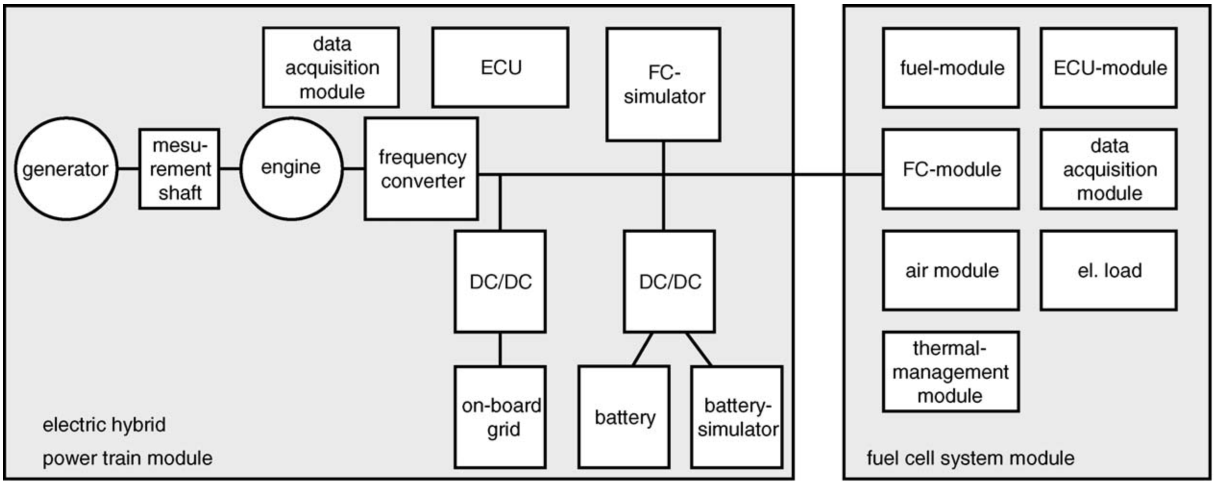

Fig. 1. Energy management test facility with the power train and the fuel cell modules, including their sub modules.

connected to an electric hybrid power train (Fig. 1). The electric power from the PEFC system is delivered to the power train module or to an electronic load.

This design encourages investigation of the interactions between different subsystems, depending on the system concept and operating strategy. Different operating strategies influence energy consumption, water neutrality, power output, and dynamics, among other considerations in a different way. The investigation and examination of individual subsystems, as well as of new types of components developed specifically for fuel cell systems in vehicles, are also aims of the test bench.

The power train module of the test facility includes a 100 kW electric machine as a load for the electric drive engine (THIEN, 12/36 $\text{kW}_{\text{el.}}$), a power converter (MES-DEA), a dc/dc-converter (FhG, 10 kW@50 V and 18 kW@90 V), a battery set (Hawker, Pb 48 V/Varta, NiMH 90 V), a battery simulator (Regatron and Höcherl&Hackl GmbH), a simulator for the on-board power supply system, and a fuel cell simulator (Regatron, TopCon Quadro) capable of operating the power train module.

The fuel cell test bench (Fig. 2 and fuel cell system module in Fig. 1) is a dynamically operable PEFC system regarding to its highly dynamic operable media supply up to a power output of to 42 kW. The modular construction of the test bench allows a high degree of flexibility in operation and testing of components and sub modules. Sub modules may be operated singly or in combined operation. It is easy to customise and exchange parts or sub modules.

It includes the following sub modules:

- fuel cell module;
- fuel (hydrogen) supply module;
- air supply module;
- water and heat management module;
- control unit;
- data acquisition system.

The fuel cell module consists of two fuel cell stacks (NUVERA) with 120 cells each. The electrical power of the each stack is 11.5 kW at 140 A and nominal operating conditions ($T = 75\,^{\circ}\text{C}$; $\lambda_{\text{air}} = 2$; $p_{\text{air}} = 2.2\,\text{bar}_{\text{a}}$). The stacks are of the type direct water injection (DWI) operating without external humidification. The humidification occurs by internal mix of the air and the deionised-water. The two stacks are operated electrically in series and regarding the fuel, water, and air supply in parallel. Both stacks are integrated in an explosion proof stack chamber [4] and equipped with single cell voltage monitoring system (CVM). The CVM is installed for measuring the 240 (maximum 600) single cell voltages of the stacks (accuracy 0.1%, time < 1 ms cell^{-1}, and isolation 1 kV).

The fuel supply module feeds the stacks with hydrogen from a bundle of gas bottles at a pressure up to 200 bar. The storage pressure is reduced to a constant level of 6 bar by using a reduction valve. The operation stack pressure is adjusted continuously by a pressure regulation valve software-controlled with a PI-simulation model implemented in the electronic control unit ECU (see Fig. 2). The hydrogen pressure follows the air pressure with a pressure difference of +0.2 bar. Hydrogen-wise the fuel cell stacks are operated in dead-end mode. For removing the water and traces of the accumulated gases, a solenoid purging valve is opened periodically for short time in the path of hydrogen outlet as long as a pressure drop of 0.2 bar is reached. During this short purge time period, the pressure control on the inlet side is abandoned. These cleaning sequences are of high importance for a stable operation of the stacks.

The air supply module features two options of the stack air feeding:

- The air supply is provided by compressor plant with pressure storage. In this case the air is taken from a pressure tank and the mass flow is adjusted by a valve.
- The air supply is provided by a claw compressor (Zephyr DLR60, manufactured by Rietschle Thomas) from the environment. This option is comparable with the HyLite® vehicle fuel cell system and forms the basis for these dynamic investigations. In this case the mass flow is adjusted by the number of revolutions of the compressor applying the pressure mass flow characteristics [5]. In order to achieve a higher system dynamic and to avoid mutual influences between the mass

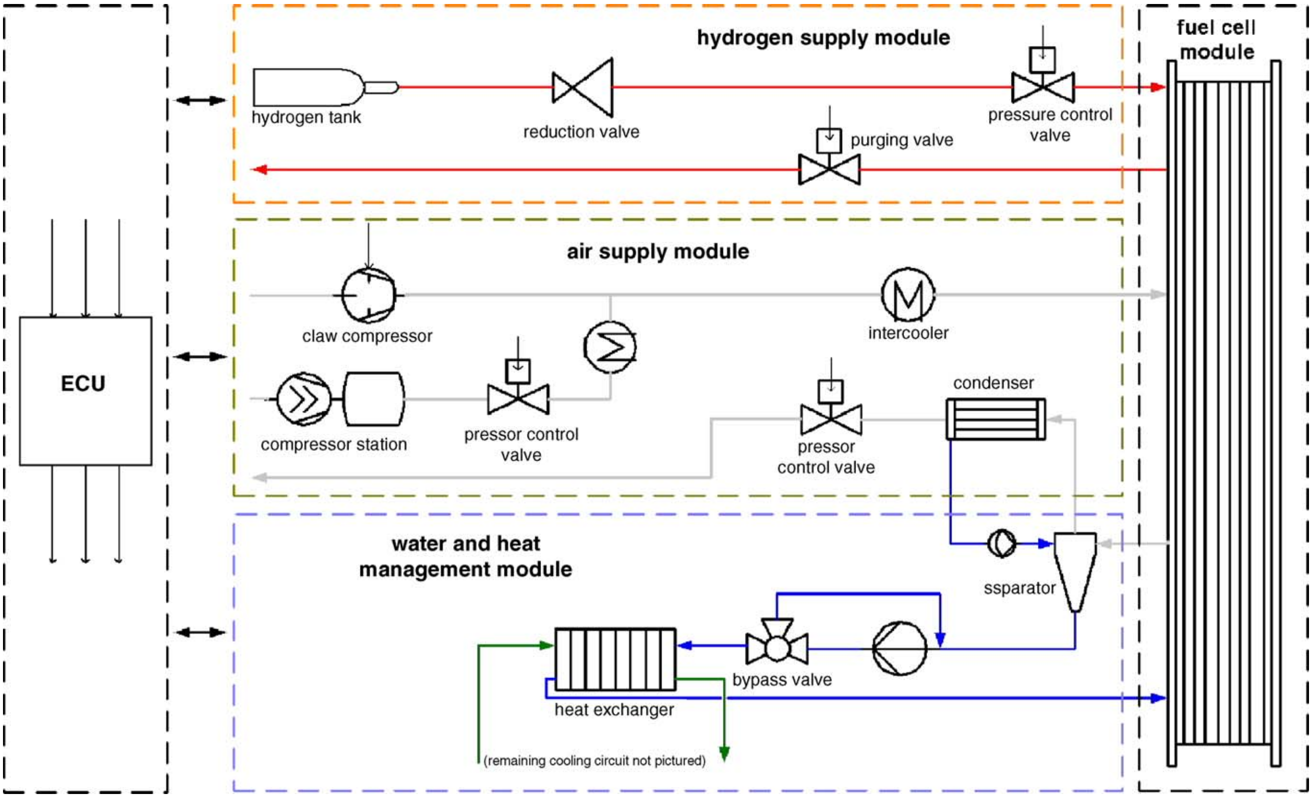

Fig. 2. Scheme of the fuel cell system test bench, including the modules: air supply, hydrogen supply, water and heat management fuel cell, control, and data acquisition.

flow and pressure the concept of revolution adjustment and parallel continuous pressure control was selected [6].

Before feeding the stacks, the air is conditioned by an intercooler to provide a constant inlet temperature. To achieve water neutrality, an air cooled condensor, allows water recovery back in to the deionised-water circuit. This water recovery system is installed after the common stack outlet.

The water and heat management sub module consists of two circuits, a stack-internal one, operating with deionised-water and an external one working with a water–glycol mixture. The internal circuit flows through the PEFC stacks and combines the functions of cooling and humidification of the membranes. Internal and external circuit are coupled by a heat exchanger. The external circuit delivers the thermal energy to an especially developed car cooler installed outside the building and transfers it to ambient air. The temperature of the stacks is adjusted by the mass flow of the deionised circuit.

The electronic control unit (ECU) of the test bench, based on a PC104, is managed by a xPC-controlled operating system, enabling full automatic and dynamic experimental operation. The control system is easily programmable using the tool chain: Stateflow, Dymola-MODELICA, or C-code to build the operation strategies and Matlab–Simulink (RTW) for creating control code running on the xPC-target (Fig. 3). The programmability of the control system permits flexible adaptation for different tests as well as dynamic operation of the test bench using existing simulation libraries covering electrical storage, power electronics, fuel cells, and control systems. The sensors and actuators are connected via CAN bus communication. The real-time function is realised for a time base faster than 10 ms.

Additionally the PEFC fuel cell test bench is equipped with a distributed, modular expandable measurement system (Delphin TopMessage). The data acquisition system contains 100 high-performance measurement circuits (accuracy 0.01%, electric isolation of 750 V, 100 Hz channel^{-1}, and 24 bit resolution). The test bench is equipped with six Coriolis flow sensors (accuracy 0.1%), eight pressure difference sensors (accuracy 0.065%), temperature sensors (class A, accuracy 0.15 °C), and other sensors for measurement of pressure, voltage, current, humidity, etc. An interactive human machine interface (HMI) based on xPC LabDesk is also integrated to interact with the control unit. The

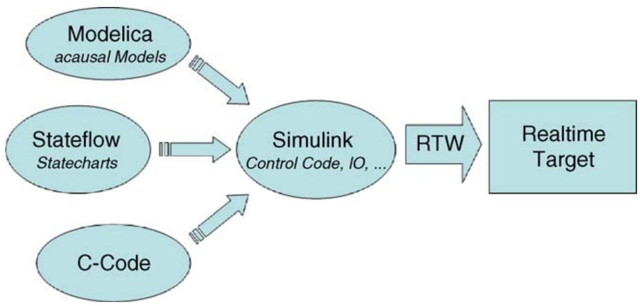

Fig. 3. Tool chain for code generation.

HMI enables modification of the operating parameters and data logging during operation. The process management operates in automatic or manual mode.

2.2. Test procedure

For the test performance, the test facility described above was used for the stationary and as well as for dynamic examinations. The fuel cell stacks were investigated individually and in parallel. For the system performance examination the fuel cell stacks were operated in parallel mode. Dead-end hydrogen operation was applied. The air supply for all examinations was performed with the DLR60 compressor. For the dynamic investigation a maximum acceleration profile described below and the New European Drive Cycle (NEDC) as a standard load profile were applied.

For different operating strategies [7], the ECU of the test bench allows the fuel cell system to be operated using simulated drive cycles. In case of the dynamic operation, the ECU was aimed to operate the fuel cell system with two different options for the air supply to examine the operation strategies regarding the air supply for maximum energy efficiency, given the dynamic power demand of a car, and to support the highest possible dynamic response. Therefore, however, at first, a separate characterisation of system components, such as a PEFC stack and air supply was necessary. Various load curves, such as cathodic air pressure and air ratio as a function of current were, therefore, recorded (see paragraph 3).

The following two operation strategies for the air supply were investigated:

- *Operation strategy 1:* The operating pressure and air mass flow rate of the fluid is adjusted in accordance to the required current. The pressure on the cathode would increase with the current continuously, from a value of 1.2 bar_a at 40 A to a value of 2 bar at a current of 120 A. The air mass flow increases in such a way that always $\lambda = 2$ (λ is a defined as the ratio of the input oxygen to the oxygen required for the reaction) is achieved. Below 40 A, the mass flow rate is kept constantly. The manufacturer recommends, to have a minimum mass flow rate corresponding to the values $p_\text{air} = 1.2\,\text{bar}_\text{a}$, $\lambda = 2$ at $I = 40\,\text{A}$.
- *Operation strategy 2:* Constant operating pressure and adjustment of air mass flow according to the required current. The pressure on the cathodic side is maintained at a pressure level of 2.0 bar_a. The air mass flow is adjusted such that always $\lambda = 2$ is achieved. Below a current value of $I = 40\,\text{A}$, the air mass flow stays constant (refer to the strategy 1),

For both operating strategies, the following two forms of current–time characteristics (A and B) were performed:

(A) "*The maximum speed up-examination*"*:* This load profile represents the current demand of the HyLite® vehicle for a full acceleration. Therefore, the current of the fuel cell system has to rise from 0 to 120 A with in a time period of 3 s.

(B) "*NEDC-examination*"*:* This standard load profile was used as a basis for the dynamic and energy efficiency investigations of the fuel cell system with respect to the current demand of the HyLite® fuel cell vehicle for driving the NEDC.

For the experiments following boundary conditions were applied as recommended by the stack manufacturer:

- the maximum temperature of the stacks (air outlet) was set not to exceed 80 °C;
- the operation temperature (air outlet) was adjusted to 75 °C;
- for experiment performing, the stacks were conditioned before, i.e. a warm up of the stacks was preceded till the operating temperature of the fuel cell stack air outlet was at minimum 55 °C;
- the difference of pressure between anode and cathode was fixed to 0.2 bar;
- the minimum single cell voltage was adjusted to 0.4 V.

3. Results and discussion

3.1. Investigations on fuel cell stack and system efficiency in interaction with the air supply

At first, the interrelationship between gross stack power and the quality of air supply regarding pressure and mass flow, respectively, air ratio was examined for different current values. Fig. 4 shows the results of a full set of experiments. The diagram includes the dependency of stack voltage (corresponding to stack gross power) on air mass flow for defined currents and pressure levels at an operating temperature of 70 °C.

The investigation was done within the current limits of 40–140 A, in six steps with a step size of 20 A. For each current value, mass flow was varied regarding stoichiometric ratio (ratio between air oxygen needs for the applied current a delivered) from 1.5 to 3 in three different pressure levels (except for the 40 A current) in 0.2 bar steps. This investigation results in 17

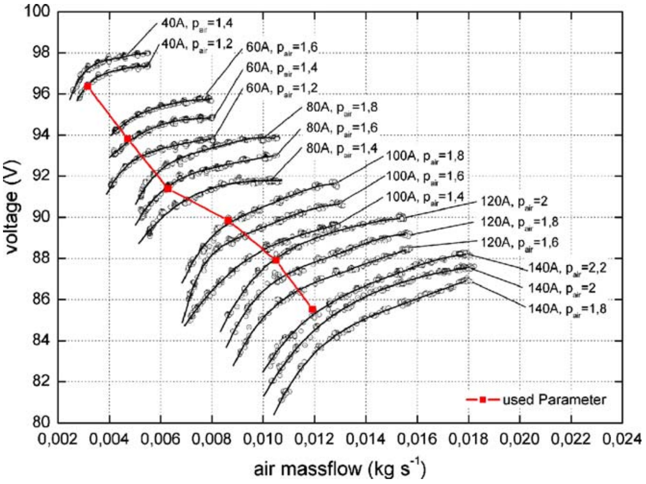

Fig. 4. Investigations of the fuel cell stack operation parameters, consisting for different flows, air pressures, and currents.

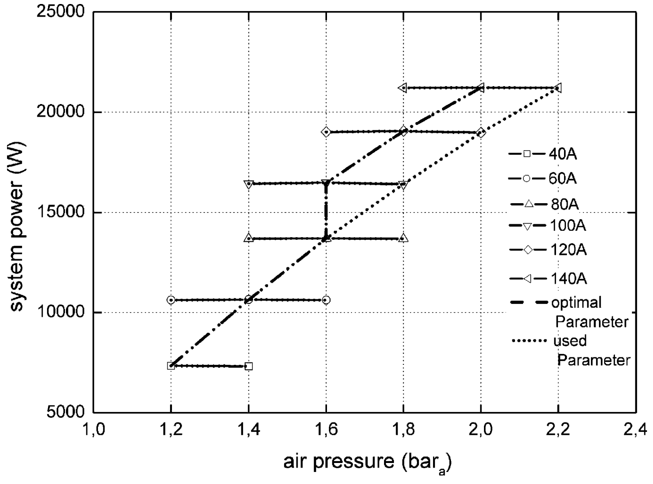

Fig. 5. Characterisation of the fuel cell system power, dependent on compressor power and fuel cell stack power for different pressures, and currents.

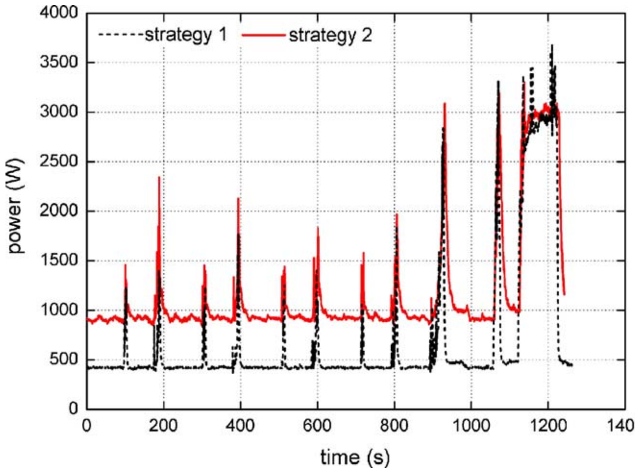

Fig. 6. Energy demand of the air compressor for a NEDC-load profile for the operation strategies 1 and 2.

separate experiments. They were performed for current and air pressure as static values. Voltage was measured and power was calculated as the results.

The maximum energy output of the fuel cell system in interaction with the air supply (covering the power consumption of the compressor) leads to optimal working points regarding the air parameters [5] for each current value in Fig. 5. The dashed curve "optimal parameters" in Fig. 5 represents the best energy working points for a fuel cell stack–air supply system. Due to the insignificant effects regarding the influence of the system power and the simplification of the control parameters, working points as represented by the dotted curve in Fig. 5, were realised in the control strategy regarding all the following examinations with operation strategy 1.

The deviation of the system power output from the stack power output is mainly caused by the energy consumption of the compressor itself which strongly depends on the delivered mass flow at a given pressure level. Working in operation strategy 1 (adjusting the air mass flow as well as the pressure), the compressor requires only 50% of the energy in stand-by compared with strategy 2 (Fig. 6). With the increase of requested power, the advantage of strategy 1 regarding energy consumption of the air supply reduces dramatically. For full load operation, the energy consumption for the air supply is similar for both operation modes.

Consequently operating strategy 1 leads to a better energy efficiency of the fuel cell systems especially for part load operation as it is regularly appearing in automotive usage. Therefore, this strategy is to be preferred from the energetic point of view for automotive applications and is applied to the fuel cell vehicle HyLite®.

3.2. *Fuel cell stack and system dynamic in interaction with the air supply*

3.2.1. *Stack and system dynamics*

Among the efficiency, the dynamics of the fuel cell stacks and the system dynamics are of importance as well. One possible characteristic describing the stack and the system dynamics is the current slew rate d*I*/d*t*. This slew rate describes the ability of increase of current, respectively, increase of power under compliance with required operation conditions and limit values as described in Section 2.2. Fig. 7 shows a comparison of the maximum current slew depending on the applied operation mode, that is reachable with the above described test bench. In the field of lower and medium current values, the slew rates using operation mode 2 are clearly superior from the dynamic point of view, while operation mode 1 reaches advantageous slew rates in field of high current values. The reasons for the limitation up to 100 A are system immanent. They reflect the necessity of an adjusting time period for pressure and mass flow, considering the pressure difference of maximum 0.4 bar allowed between the anodic and cathodic side of the stacks. This restriction determinates the maximum applicable current slew in different ways for the operation strategies 1 and 2. The stack dynamics with the boundary condition of min cell voltage of 0.4 V determinate the dynamic above 100–115 A reducing the slew rate. In the region above 115 A the increase of stack power is performed oscillated

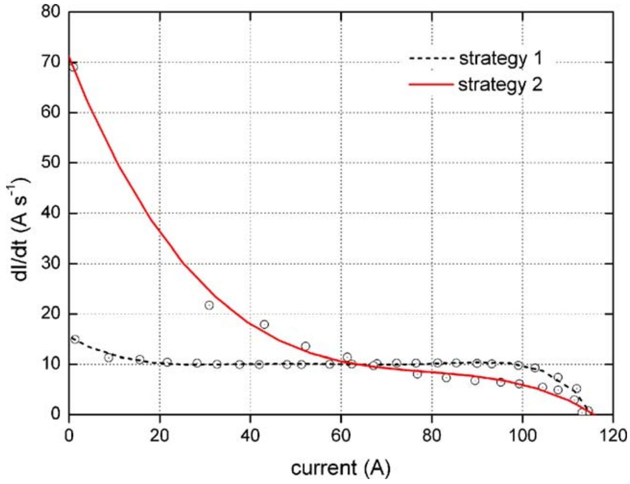

Fig. 7. PEFC system dynamic slew rate d*I*/d*t* with different operation strategies for the air supply.

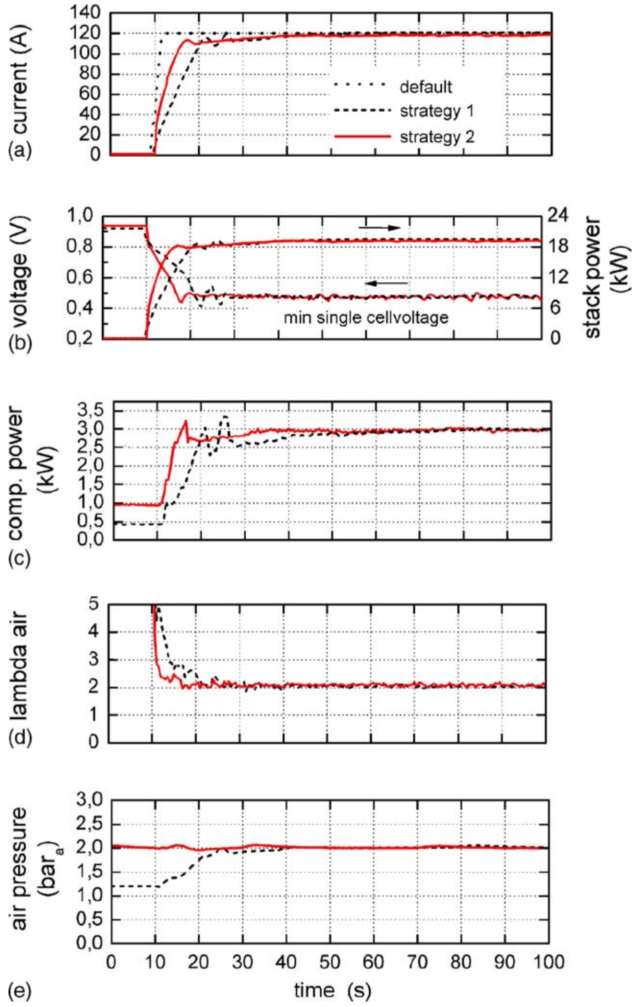

Fig. 8. (a–e) Results for a the full load-test, current increase up to the maximum current following the operation strategies 1 and 2.

as visible in Fig. 8 affected by the value of the minimal single cell voltage. To avoid damage to the stack, a control function is implemented, which limits the maximum positive rise in the current depending on the reversal acceleration as well as on the voltage value of the lowest single cell. This safety algorithm implemented in the ECU does not allow a fall of a single cell voltage below 0.4 V.

3.2.2. Full load-examinations

Using the evaluated operation parameters (described above) for strategies 1 and 2 regarding the energy and dynamics of the air supply investigations for full load acceleration were performed. Fig. 8 shows the results of the full load examinations. Diagram (a) shows the default value (dotted line) of demand (Section 2.2, examination A) and the achievable progression of current value using operation strategies 1 (dashed line) and 2 (continuous line). Diagram (b) shows the increase of stack power and the voltage of the lowest single cell. For the operation strategy 1 it is especially obvious, that in the moment of arriving at the limit of 0.4 V by the lowest single cell the control reacts by limiting the stack power until recoverage of the cell. This leads to an oscillating behaviour of the system. Diagram (c) shows the total input power of the air compressor and diagrams (d and e) give of the current-modulated air flow (shown as air ratio) and the air pressure, respectively. These diagrams point out the operation strategies. It is visible in both cases, that the air mass flow for both operation strategies and the pressure for strategy 1 are adapted to the current. Diagram (e) shows the differences between both strategies. In strategy 1 the pressure value rises from 1.2 bar_a at 0 A to 2 bar_a at 120 A, as in strategy 2 the pressure is kept at 2 bar_a for all current values. After 30 s for both operation strategies the system reaches the same operating values at full load regarding to the air supply. The increase of the air ratio (diagram d) for the stand-by operation and below 40 A, causes in a basic air supply also requested from the stack manufacturer. Therefore, the air ratio starts at a high level and trends to the value of 2 for 120 A.

The specified full load profile rising the current value from 0 to 120 A within 3 s was not reached by one of the strategies. Strategy 1 needed 8 s and strategy 2 needed 12 s to reach 95% of the maximum default current value. The slew rate up to this point is basically influenced by the supply systems and its components. The manipulating speed of the pressure control valves, the dynamic behaviour of the compressor and the gas volume of the entire air supply system are figured out to take major influence at lower and medium current density. In the high current density region, the influence of minimum single

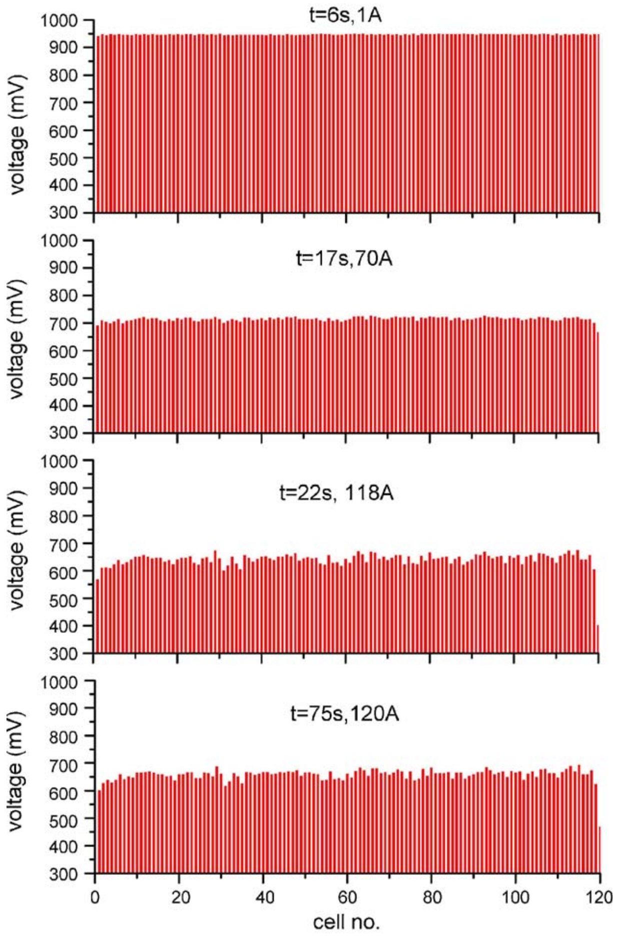

Fig. 9. Single cell voltage as a function of time during the full load-test described in Fig. 4.

cell voltage increases. For reasons as described in Section 2.2 in detail, the minimum single cell voltage restricts the increase of current. Thus, it causes a short-time oscillation, due to the direct interaction between air flow and current value, as presented in Fig. 8c. The related cell voltage distribution is shown in Fig. 9.

The limitations of the stack especially in its dynamic behaviour are given by the lowest single cell voltage. Fig. 9 shows the single cell voltages of a stack during the full load examination applying operation strategy 1. After 22 s, and current rising 120 A, the voltage of Cell no. 120 falls down to 04 V (compare Fig. 8a and b). During the following constant operation phase at 120 A, Cell no. 120 recovers up to 0.47 V after 75 s. Fig. 9 makes explicitly obvious that several cells in the fuel cell stack show a strong deviation 'from the stacks' average voltage values. In this case the deviation of Cell no. 120 is extremely high and determinates the stack dynamic notably.

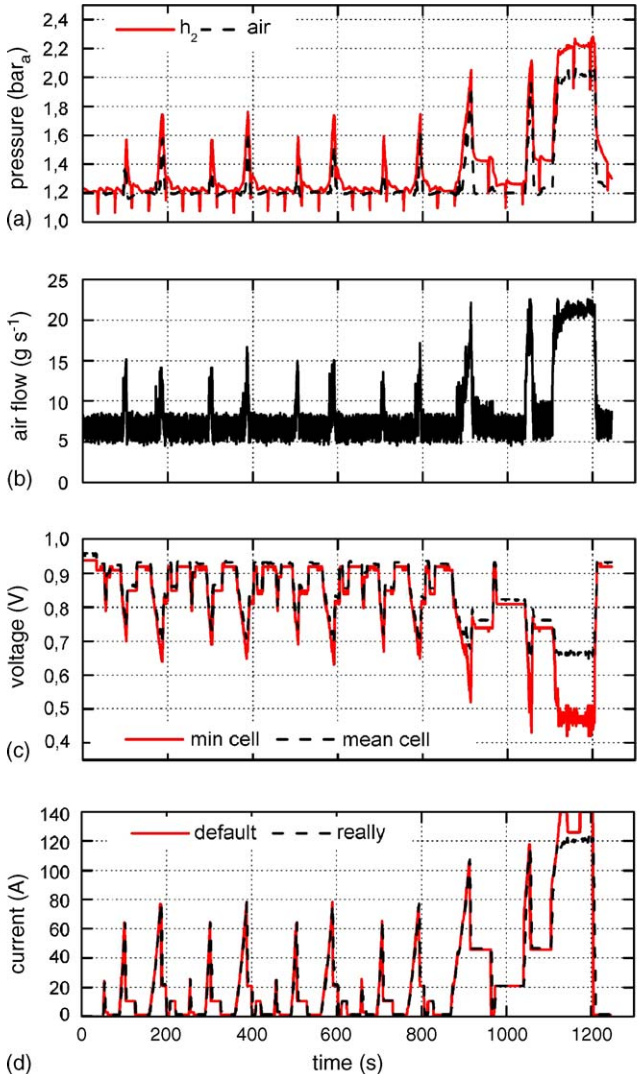

Fig. 10. (a–d) Results for the NEDC-test for a PEFC system operation strategy 1 for the air supply (pressure and mass flow rate of the air follows the load).

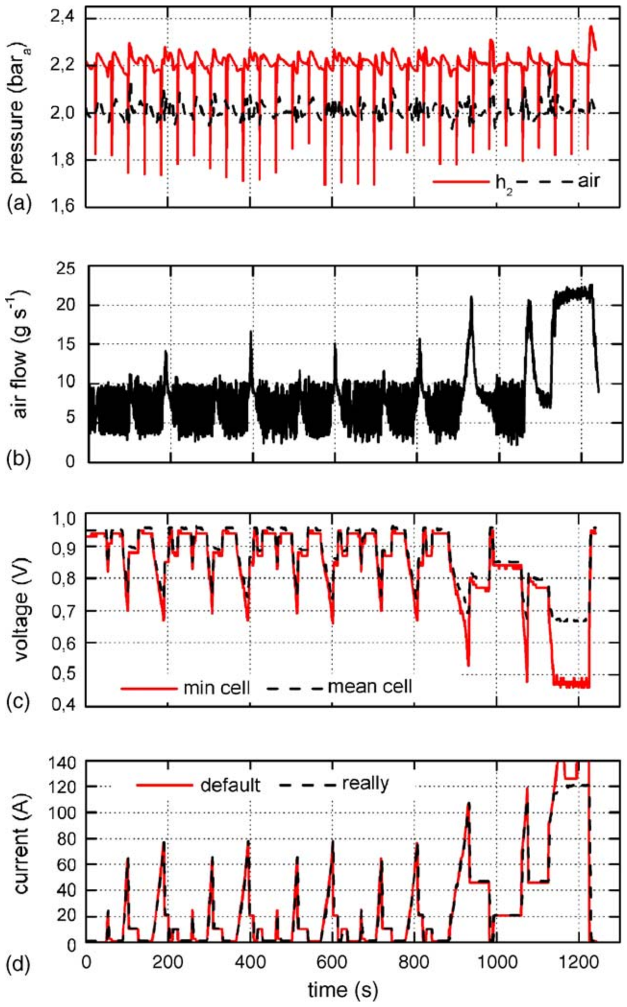

Fig. 11. (a–d) Results for the NEDC-test for a PEFC system operation strategy 2 for the air supply (constant pressure, mass flow rate of the air follows the load).

3.2.3. NEDC-test

For testing of the different operation modes regarding their applicability for automotive use, NEDC-test was performed. Figs. 10 and 11 show the results of the examinations for the defined operating strategies 1 and 2. In diagrams (a and b) the pressure and the air flows for both strategies are given. Diagram (c) of Figs. 10 and 11 reflects the dynamic behaviour of the stacks with the minimal and average cell voltage. The lower diagram presents the current nominal–actual value comparison, the result of the NEDC-tests.

Diagrams (a and b) of Figs. 10 and 11 clarify the operating strategies reflecting the varieties. In Fig. 10 (strategy 1) the hydrogen and the air pressure as well the air mass flow follow the requested power demand profile of the NEDC. Applying the operation strategy 2 (Fig. 11) the pressure for air and subsequently for hydrogen is nearly constant at the highest level during the dynamic NEDC operation. The transient spikes are caused by hydrogen purging (Section 2.1). The mass flow is also higher in its average value for the operation strategy 2.

Diagrams (c and d) of Figs. 10 and 11 show, that in contrast to the full load-test, both operation strategies for the air supply fulfil the requested dynamic behaviour for the NEDC and are suitable for the automotive application from NEDC-dynamic point of view.

Considering the dynamic behaviour and the energy consumption of the fuel cell system, it can by concluded that – for an automotive application – the air supply strategy 1 is advantageous taken the energy efficiency into the account and accepting a slower speed up acceleration.

4. Conclusions

- The test bench assembled at DLR-FK for a power train, including a PEFC system is suitable for the investigation and development of fuel cell components, systems and operation strategies.
- The interaction between the air supply subsystem and fuel cell stacks, regarding the dynamic response and the resulting system efficiency for different air supply modes as operation strategies was investigated in detail. Therefore, stack characterisation, investigation of the energy balances and the analysis of dynamic behaviour in respect to the operation parameters were done.
- The investigation of the power consumption led to an improved and optimised operating strategy regarding the air supply to minimise internal energy consumption of the PEFC-system for dynamic automotive operation which leads to save up to 50% of the compressor energy consumption. The compressor requires with the operating strategy 1 that means adjusting the air mass flow as well as the pressure only 50% of the energy in stand-by as with strategy 2. With higher and constant fuel cells power performances the energy requirement of both strategies is approximately alike. The operating strategy 1 is thus suitable for automotive applications particularly. Therefore, a special operation strategy to reach a instantaneous, current depended, and sufficed air supply with the lowest energy consumption was developed, approved, and applied in the fuel cells vehicle HyLite®.
- The comparison for the air supply modes, shows, that using strategy 2 higher current slew rates can be reached. In addition the system tends to swing less, because only one parameter is varied compared to strategy 1 where two parameters are varied at the same time. As factor limiting the slew rate emerged the dynamic behaviour of the system and its components for low and medium current densities. For high current densities, the slew rate is limited by the dynamic behaviour of the fuel cell stack itself. Due to the modulation of air flow adapted to the current, operation strategy 2 is of significant higher efficiency in particular in part load.
- The performed investigations allowed a separation and determination of the dynamic limitations caused by the fuel cell stack or system, respectively.
- The investigation of the PEFC stacks shows the limitation of the stack dynamics at high current caused by the lowest voltage of a single cell.
- The dynamic limitation of the system dominated mainly in the lower current range and caused by the speed of the values, compressor behaviour, and volume of the air supply itself. The examination of the fuel cell system shows that the dynamic response of the realised fuel supply of air and hydrogen is fast enough for a requested NEDC load profile.
- Both investigated operating strategies for the air supply fulfilled as far as possible the given profile of the NEDC and are suitable for the use in automotive applications.
- Substantially for the estimation of the air supply operating strategies is not only the dynamic behaviour of the PEFC system representative, also the energy consumption of the compressor as one of the main energy consumer in a fuel cell system is important.

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