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Analysis of dynamic requirements for fuel cell systems for vehicle applications

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Abstract

Conventional vehicles with internal combustion engines, as well as battery powered electric vehicles, achieve one of the most important customer requirements; achieving extremely short response times to load changes. Also, fast acceleration times from a cold start to full power in the range of seconds are practicable.

New fuel cell-based propulsion systems, as well as auxiliary power units, have to fulfill the same demands to become competitive. This includes heating-up the system to operating temperature as well as the control strategy for start-up. An additional device to supply starting air is necessary, if the compressor motor can only be operated with fuel cell voltage. Since the system components (for example, the air supply or the fuel supply) are not mechanically coupled, as is the case with conventional internal combustion engines, these components have to be controlled by different sensors and actuators. This can be an advantage in optimizing the system, but it also can represent an additional challenge.

This paper describes the fuel cell system requirements regarding transient operation and their dependence on system structure. In particular, the requirements for peripheral components such as air supply, fuel supply and the balance of heat in a fuel cell system are examined. Furthermore, the paper outlines the necessity of an electric storage device and its resultant capacity, which will enable faster load changes. Acceleration and deceleration of the vehicle are accomplished through the use of the electric storage device, while the fuel cell system only has to deliver the mean power consumption without higher load peaks. On the basis of system simulation, different concepts are evaluated for use as a propulsion system or APU and, then, critical components are identified. The effects of advanced control strategies regarding the dynamic behavior of the system are demonstrated.

Technically, a fuel cell system could be a viable propulsion system alternative to conventional combustion engines, as long as there is a sufficient amount of power output from the fuel cell available for low operating temperatures. An optimized air supply system meets the requirements for transient operation in vehicles; however, specially designed machines are necessary—in particular smaller, integrated units. The electrical storage device helps to minimize fuel cell system response times for transient operation. An even more important point is that the fuel cell can be downsized. Utilizing this potential can reduce cost, space and weight. Fuel processing is preferable for auxiliary power units, since they have to operate in vehicles that use either gasoline or diesel fuel. High losses during the start-up phase can be avoided by using a battery to buffer the highly fluctuating power demands. Only advanced control methods are acceptable for controlling the operation of a fuel cell system with several components. Fuel cell systems can be developed and precisely optimized through the use of simulation tools, within an accelerated development process.

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Keywords: Fuel cell systems; Simulation; Control; Rapid; Prototyping; Air supply; Fuel processing

1. Introduction

Fuel cell systems contain several system components depending upon the system application, such as a propulsion system or auxiliary power unit (APU). In the former case, there is a demand for high dynamics for transient operation, short starting time, high efficiency, low weight, and low volume and costs. However, for auxiliary power units, the response time for cold-start and the dynamics due to load changes are less critical, but should not exceed 1 min for proper usability.

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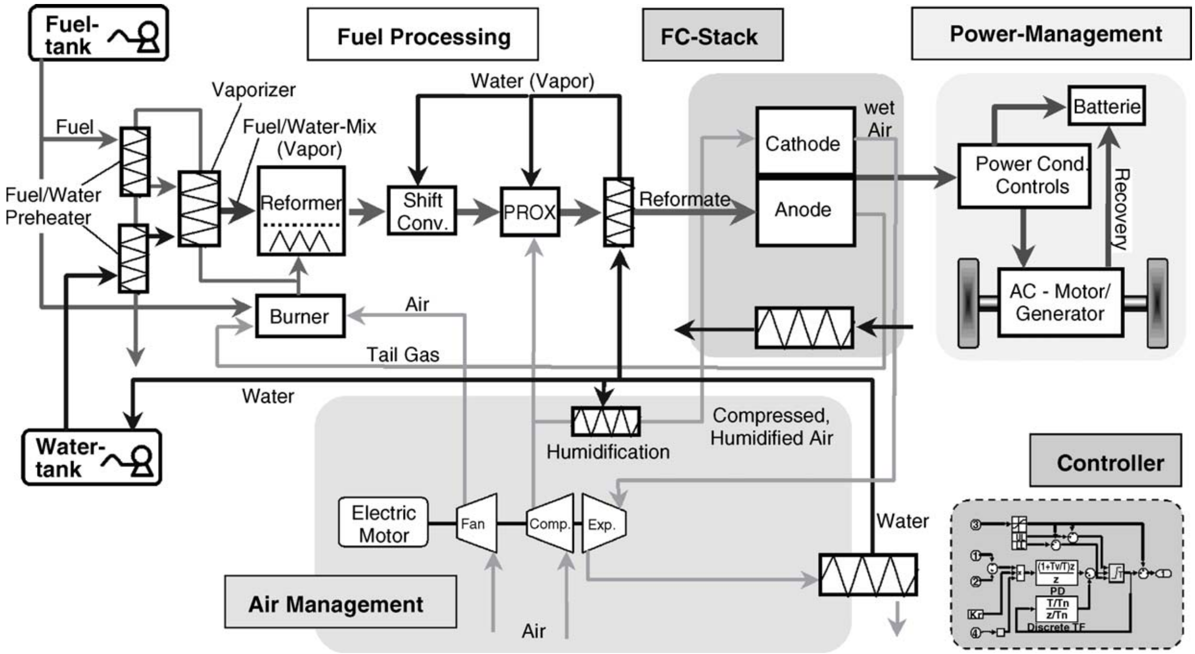

Fig. 1. Fuel cell system for vehicles with fuel processing [5].

A fuel cell system for vehicles with fuel processing is illustrated in Fig. 1 . The main components in the system are the drivetrain, with an electric motor for vehicle propulsion, the power electronics with the possibility of an electrical storage device and voltage converters, and the fuel cell itself with air and hydrogen supply. Unlike conventional internal combustion engines, most of the components of these groups or subsystems are not mechanically coupled, so that these components have to be controlled by additional controller devices with adequate sensors and actuators. Consequently, the dynamic behavior of the complete fuel cell system is not only reliant upon on the transient behavior of its components, but also affected by the quality of the control layout.

The ideal control design does not provoke additional response delays, so that the dynamics of the fuel cell system are only limited by the transient behavior of the components: The power electronics' electrical circuits respond very quickly, anywhere from a matter of milliseconds up to a maximum of about one-tenth of a second, depending on the electrical capacitance of the components used, including the fuel cell with its internal reaction limitations. The transient behavior of the air supply is restricted mainly by the rotational inertia of the system compressor or blower, which ranges from one-tenth of a second to about 1 s for full-load operation. The response times of a fuel processing system that generates a hydrogen-rich and nearly carbon monoxide-free anode gas flow are much slower, especially for system start-up. A response to load changes of about 1 s is attainable for optimized and specially designed units, but starting times can vary up to 10 min for laboratory prototypes.

2. System inertia

When designing fuel cell systems, different types of system inertia need to be considered. Mechanical components have to be accelerated and decelerated and the mechanical inertia of the components limits the response of the system. Acceleration of a typical passenger vehicle (1850 kg) from 0 to 85 km h^{-1} requires about 500 kJ or 500 kW s of energy. Based on these values, it can be calculated that it will take about 10 s to accelerate the vehicle, as long as there is 50 kW of constant mechanical power output available. An electrical motor must also accelerate the compressor in the air supply system. Using a mechanical compressor, about 1 kW s is necessary to accelerate the compressor and the motor from 0 to 10,000 rpm. Thus, the compressor will reach the rotational speed of 10,000 rpm in 0.1 s for a constant mechanical power output of the electric motor at 10 kW. The rotational inertia of an electrically accelerated turbocharger (turbo compressor with turbine and motor) is competitive (about 1.5 kW s for 0–200,000 rpm).

One major limiting aspect of the system's dynamic behavior is the inertia of temperature. Thermal components have to be warmed up to their operating temperature, which restricts start-up. Heating 100 kg of steel and carbon from 20 to 80 °C, used here to represent the fuel cell, requires about 4000 kW s of energy (combustion engine approximately 5000 kW s) (Table 1). Even with the 40 kW of available waste heat from the fuel cell, it would take up to 2 min for the fuel cell to reach its operating temperature. In fact, this waste heat is limited by the available power output of the fuel cell at lower temperatures. Consequently, the fuel cell stack in a propulsion system has to be able to operate properly with a sufficient power output, even at low temperatures. Otherwise, the fuel cell system would not be competitive to conventional combustion engines, even if an electrical storage device would be used.

The fuel processor for a typical Fuel Cell Vehicle (FCV) with about 80 kW of power has to be preheated before the reactors of the auto thermal reformer, the water-gas shift converters and the preferential oxidation light off. It takes about 3100 kW s to

Table 1
Energy contents for acceleration and heating-up of different system components

System inertia	Energy content (kW s = kJ = kN m)	Acceleration/heating-up
Vehicle with drive train	$E_{\text{kin}} = \sim 500$ kW s	0 → 85 km h^{-1}
Mechanical compressor + motor	$E_{\text{kin}} = \sim 1$ kW s	0 → 10000 rpm
Turbocharger + electric motor	$E_{\text{kin}} = \sim 1.5$ kW s	0 → 200000 rpm
100 kg of carbon/steel	$E_{\text{th}} = \sim 4000$ kW s (0.08 l gasoline)	20 → 80 °C
25 kg of steel (fuel processing)	$E_{\text{th}} = \sim 3100$ kW s	20 → light off
	$E_{\text{th}} = \sim 5800$ kW s (0.12 l gasoline)	20 → operating temperature
Conventional IC engine	$E_{\text{th}} = \sim 5000$ kW s	20 → operating temperature

reach this temperature from an ambient temperature of 20 °C. Even utilizing a start-up burner, which is limited in size for a fuel cell propulsion system, it will take about 2 min to reach the light-off temperatures. Achieving the normal operating temperatures of the components, which are necessary for high efficiencies and optimum conversion rates, requires an energy output of about 5800 kW s. The typical fuel cell system, using a gasoline reformer system, requires about 10,000 kW s or about 0.2 L of gasoline to start. Therefore, it makes less sense to use such vehicles only for short-distance traffic; whereas, a fuel cell system powered by hydrogen, potentially can compete with an internal combustion engine.

Additional delays in the response of fuel cell systems result from the inertia of pressure and flow. Pressurized systems utilize the compressor to fill up the volume of the system. Increasing the system pressure from 1 to 2 bar, absolute, on the cathode side, requires about 0.15 s when supplying an air mass flow of 60 g s^{-1} (full-load operation, volume of cathode side about 10 L) (Table 2). Due to the larger volume on the anode side of a reformer system (30.0 L), the lower gas mass flow (30 g s^{-1}) and the increased pressure (2.5 bar absolute), the pressure response here is slower (about 0.75 s). Indeed, the response times become much larger if operating under part-load. Furthermore, the gas mass that flows through all system components increases the dead times of the air mass flow from the compressor to the expander or throttle by 0.4 s and the dead times of the reformate gas from the auto thermal reformer to the anode by 0.75 s. These times increase again for part-load operation.

Finally, the response delays of the sensors and actuators that were used need to be taken into consideration for the layout of the system controllers. There are fast reacting sensors available for temperature or pressure, but these are not commonly used in conventional vehicles and will be more expensive. Furthermore, a dynamic closed-loop control of humidity—possibly required for injection systems—is not possible, since even state-of-the-art humidity sensors and dew point transmitters show dead times and response delays of about 3 and 5 s, respectively.

3. Air supply requirements

The air supply system consists of an air filter, a compressor driven by an electric motor, and a throttle or an expander (with an additional waste-gate for regulating cathode pressure). The air has to be humidified in order to prevent drying-out the membrane of the fuel cell. If water (liquid form) is injected for this purpose, water (liquid form) has to be recovered at the cathode outlet by a drain, or if necessary by an additional condenser. If there is not enough heat in the system to evaporate sufficient amounts of water, a heat exchanger can be integrated. Sensors for pressure and rotational speed of the electric motor are required for closed-loop control; a dew point transmitter can be used for monitoring during the development process. The air supply system for the HY.POWER fuel cell demonstrator vehicle, which was developed in a joint project with Paul Scherrer Institute, Volkswagen AG, FEV Motorentechnik and other partners, is illustrated in Fig. 2. A starting air supply device is necessary for start-up with 12 V dc, since the fuel cell does not deliver the required voltage for the compressor motor (200–400 V) [6,7,15].

The major focus in optimizing the transient behavior of such an air supply system is to control the necessary air mass flow for the desired air ratio of the cathode. This is accomplished by altering the motor speed and the cathode pressure level, depending on a throttle position optimized operating strategy. In a compressor–expander system, an additional waste-gate can be used to influence the pressure level. In the system presented above, the humidity and the temperature of the cathode inlet air is controlled by water injection. Using feed-forward maps, calculated by model-based simulation tools, an immediate response of water injection could be achieved for optimized operation at all operating points. A temperature or dew point-

Table 2
Response times due to pressure build-up, flow velocity and sensor technology

System inertia	Response time	Specifications
Pressure build-up, air	$t_{\text{fill}} = \sim 0.15$ s	1 → 2 bar absolute, 10 dm^3, 60 g s^{-1}
Pressure build-up, reformate	$t_{\text{fill}} = \sim 0.75$ s	1 → 2.5 bar absolute, 30 dm^3, 30 g s^{-1}
Flow velocity, air	$t_{\text{dead}} = \sim 0.4$ s	Compressor → expander, 10 dm^3, 60 g s^{-1}
Flow velocity, reformate	$t_{\text{dead}} = \sim 0.75$ s	Reformer → fuel cell, 30 dm^3, 40 dm^3 s^{-1}
Laboratory temperature sensors	$t_{63\%} = 20$ ms–1 s	Thermocouples
Automotive temperature sensors	$t_{\text{time constant}} = \sim 8$–60 s	Intake air/coolant
Humidity sensors	$t_{\text{T90}} = 3$–5 s/10–30 s/5–10 min	Different sensors and applications

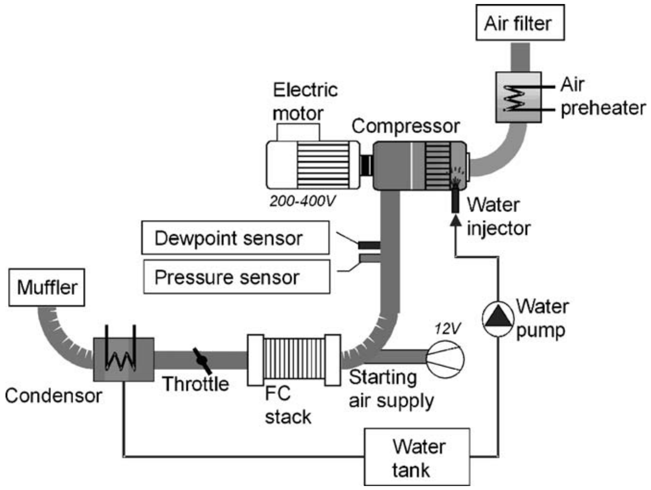

Fig. 2. Air supply system overview of the HY.POWER FCV [14].

based slow closed-loop control with anti-windup compensation can be applied to prevent deviations.

4. Fuel supply requirements

Due to the high complexity of a fuel processing system, an integrated fuel processor concept is necessary to meet the requirements for automotive applications. Since the different components have to be operated at different temperature levels, only a specially designed fuel processor concept with a compact layout can realize short response times (i.e. high power output and low emission). Furthermore, advanced control and start-up concepts are indispensable.

The product design for the fuel processing system of an Auxiliary Power Unit (APU) (2.5 kW) from FEV Motorentechnik and a related laboratory prototype is shown in Fig. 3. The compact layout reduces the heat capacity of the reactors and enables faster start-up times. The reformer is warmed by electrically heated inlet air up to the light-off temperature of about 250 °C. Then, fuel is injected into the reformer resulting in a catalytic partial oxidation. The excess heat is used for heating up the components to their normal operating temperatures. The reformate is oxidized in the catalytic burner in order to enable a fast steam supply. If the integrated heat exchangers are heated up, water is injected into the reformer, which is then operated in an auto thermal mode. Following the water injection, the water-gas shift reactors light-off.

Even, when illustrated at a simplified level (Fig. 4), it is evident that advanced control methods are necessary for the start-up process in order to sufficiently control the fuel supply system. FEV and VKA use finite state-machines as a part of the basis for the Stateflow® software tool. Apart from the start-up process, system stop, stand-by operation, and the error enquiries and fail-safe strategies also have to be implemented in the controller. The simplified schematics of the control software are illustrated in Fig. 4.

5. Power electronics requirements

The power electronics of a fuel cell system for vehicle propulsion consists of the fuel cell, the electric motor for propulsion, and, if integrated, an electrical storage device (e.g. a battery or super capacitors, and the necessary inverters). The powertrain of the HY.POWER fuel cell demonstrator vehicle, which also contains a one-gear transmission, is shown in Fig. 5. The layout for APUs may be similar, irrespective of the propulsion motor.

Li-ion and Ni-MH batteries can be implemented as electrical storage devices. Li-ion batteries have the advantage of a high energy density in the range of 50–80 W h kg^{-1} and specially designed cells can reach up to 140 W h kg^{-1}. The power density can range from 300 to 850 W kg^{-1}, although up to 1500 W kg^{-1} is thought to be possible. One disadvantage of these batteries is their sensitivity to over- and under-voltage. Ni-MH batteries are almost comparable in terms of energy density (20–80 W h kg^{-1}), but normally provide lower power densities. Very high performance cells can reach up to 1300 W kg^{-1}, but Ni-MH batteries are very sensitive to overcharging. Super capacitors, or "supercaps" for short, feature high power densities and high cycle efficiencies, but their energy density is low. Due to the early development stage for vehicle applications, the energy density of up to about 15 W h kg^{-1} and the power density (approxi-

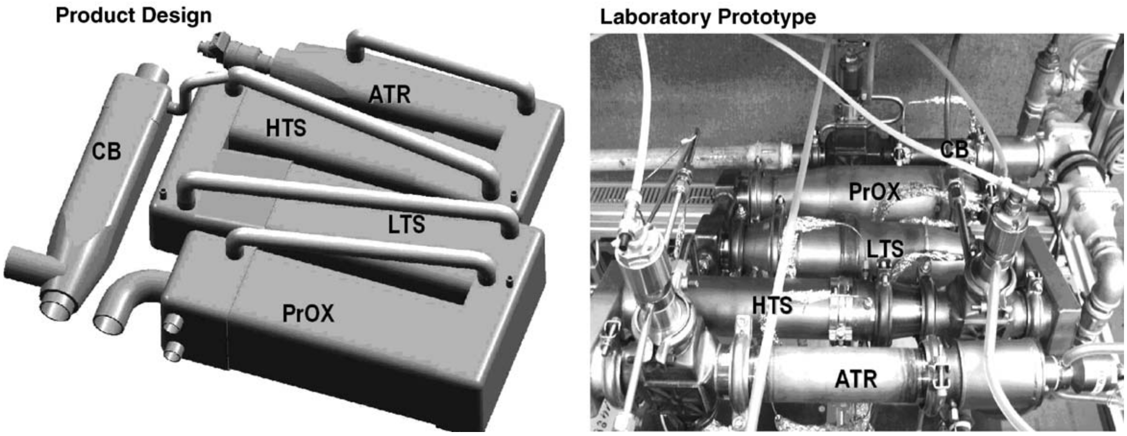

Fig. 3. Fuel processor packaging and laboratory prototype by FEV and VKA [2,3,16].

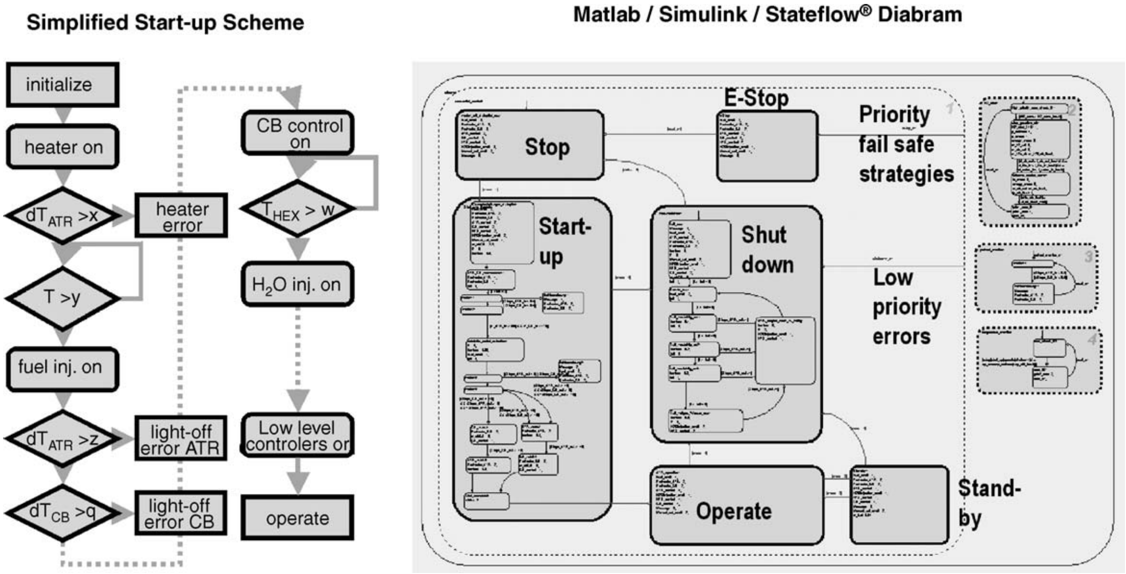

Fig. 4. Fuel processor control schematic by FEV Motorentechnik and VKA [1].

mately up to 15,000 W kg^{-1}) can vary over a wide range. A high number of charging cycles (more than 500,000) is beneficial [4,8,9].

Simulation tools can be used to determine whether batteries or supercaps should be recommended for a specific application, and how these units should be sized. Because there are several fields of application that highlight different demands, this paper can only address the basic design criteria. Appropriate calculations have to be undertaken for each specific task. Common driving cycles that are used to benchmark different vehicles and propulsion systems need a high power output during acceleration, but the average power demand is much lower (e.g. only 10–20 kW). Thus, supercaps are favorable for applications where the vehicle's power consumption occurs primarily in city traffic. However, when a higher power output is required during longer periods of operation, for instance on mountain passes or high-speed motorways, batteries can be more advantageous.

In addition to shorter response times, the use of an additional electrical storage device enables a downsizing of the fuel cell used, e.g. from 50 to 40 kW. In this way, about 20% of the fuel cell system's costs can be saved, including the costs for the fuel cell itself, the air supply with compressor, electric motor and humidifier, etc. Furthermore, the efficiency of the fuel cell system can be improved, since the system is only rarely operated in the idle mode. Installation of an electrical storage device also enables recuperation of braking energy by saving about 8% in fuel consumption within the driving cycle. Fuel processing can only be used in systems with electrical storage. The response times are too slow for exclusively propelling the vehicle and the vehicle dynamics have to be realized mainly by the storage device. For auxiliary-power-units, a battery is recommended for buffering the highly fluctuating power demands, in order to avoid high losses during the start-up phase.

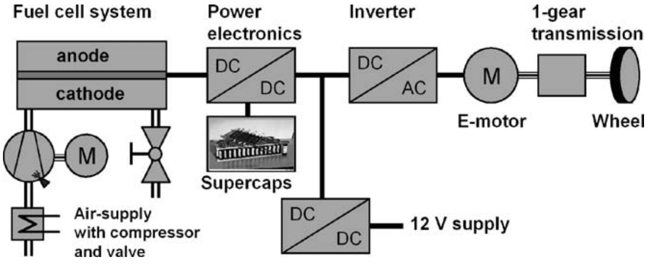

Fig. 5. HY.POWER powertrain with super capacitors [12–14].

6. Control layout requirements and rapid control prototyping (RCP)

The main targets of the control layout of dynamic systems are to realize the demands, the desired operational strategies, to implement the start- and turning-off procedures and to handle errors that occur. An optimized controller prevents oscillations and instabilities and does not delay the dynamic response of the system. In typical fuel cell systems, many components need to be actuated independently. However, since each component will affect other system components with its behavior, it is not possible to manipulate fuel cell systems sufficiently using simple controllers, such as the typically used PID controllers. For instance, on the cathode side, the speed of the compressor motor affects the pressure loss of the throttle, and the throttle position impacts the air mass flow supplied by the compressor (in a compressor–throttle system). But, the two set point values of air ratio and pressure level have to be controlled independently. Thus, without decoupling of the two closed loops, instabilities will appear.

In addition, when dealing with real systems, all actuators have a limited operating range. Using a conventional PID controller, the integral part will exceed the upper or lower limits of the actuator regulating range if the system is not able to realize the desired set value. If the system returns to normal operation, the control variable will overshoot the set point.

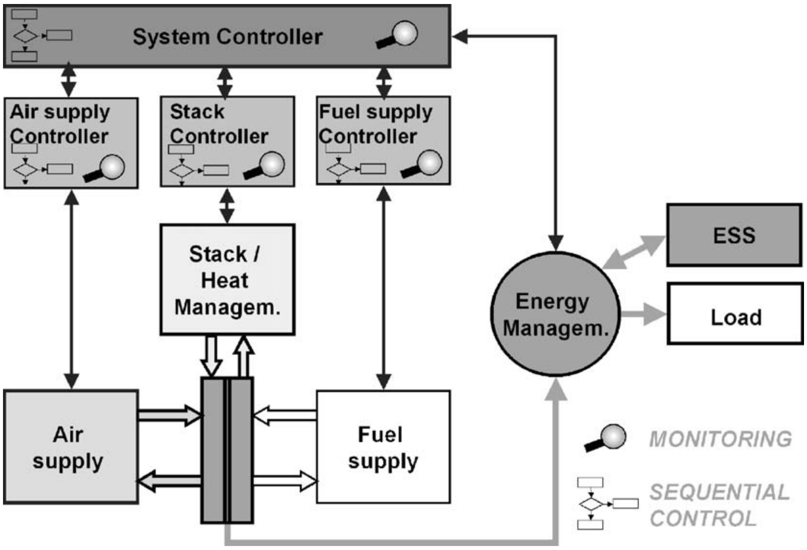

Fig. 6. Fuel cell system controller hierarchy [1,3].

Hence, PID controllers with anti-windup compensation have to be implemented for most closed-loop controls.

Furthermore, the behavior of the components is often nonlinear, although the system has to be stable over the full operation range and not only at one operating point (which is often sufficient in stationary applications). Thus, the system has to be "guided" during the operation. Predominant feed-forward control can undertake this task, but for enduring deviations an additional closed-loop control needs to be implemented. This approach is similar to the control of internal combustion engines, where mainly feed-forward injection maps control injection and lambda control (closed-loop A/F ratio control) to ensure precise compliance with the set point. The feed-forward control can be based on maps, evaluated by measurements on the test bench, or on model-based predictions.

Since the fuel cell contains several components and component groups, the controller layout must take into account this hierarchical structure. The first level controller of each vehicle is the driver, who controls the desired vehicle speed by pressing the accelerator pedal. The controller for the complete fuel cell system (or supervisory controller) outputs the set points for all subsystems, implements the operation strategies, and contains the procedures for error handling and start-up and shutdown. The subsystem controllers, as mentioned later, manage the different subsystems such as air supply, stack, fuel supply, and the powertrain. It is possible to accelerate and advance the development process for complete fuel cell systems, with such a structure of the system controllers (Fig. 6) [10,11].

Development of the controller and the optimization of the fuel cell systems operation were completed for the purpose of system layout. In a cooperative effort, FEV and VKA developed a comprehensive modular simulation tool, which is being continuously extended and optimized. Based on Matlab/Simulink® and Stateflow® software, a wide variety of components covering the entire fuel cell system are available within an extensive library. The simulation tool is valuable for the design of complex control systems, because the dynamic behavior was consistently considered in the simulation approach.

The functionality and the advantages or disadvantages of new system layouts can be evaluated at the software level with this tool. The first controller layout is also carried out in software before the hardware is tested. This approach, plant model and control model (combined in a software environment but separated as different sub-models with individual inputs and outputs) is often referred to as the Model-in-the-Loop (MIL). The MIL approach can be used on a system level as well as on a subsystem level. When components need to be tested in advance, their interaction with the fuel cell system can be analyzed by Component-in-the-Loop (CIL) measurements, where the other system components as well as the controller are simulated by software code running on real-time hardware.

If the controller software is developed in this way, it is relatively simple to implement the control in an Electronic Control Unit (ECU). The software can be compiled to real-time code and can be downloaded to ECUs with special micro-controllers, like the MicroAutoBox from dSPACE, the MICROGen from add2 or others. A simulation model for the air supply of a PEM fuel cell, with a mechanical compressor and expander, is illustrated in Fig. 7 . Parameters or software updates and data acquisition can then be transferred via the CAN-bus from a host computer to the ECU.

The functionality of the ECU can be tested with Hardware-in-the-Loop (HIL) tests. The ECU is the only hardware present in these tests, with the complete fuel cell system, including its input and output, being simulated by a software model running on real-time hardware. The fundamental advantage of these rapid control prototyping techniques is acceleration of the development process, cost savings due to the omission of a great deal of hardware tests, and advanced possibilities for system optimizations.

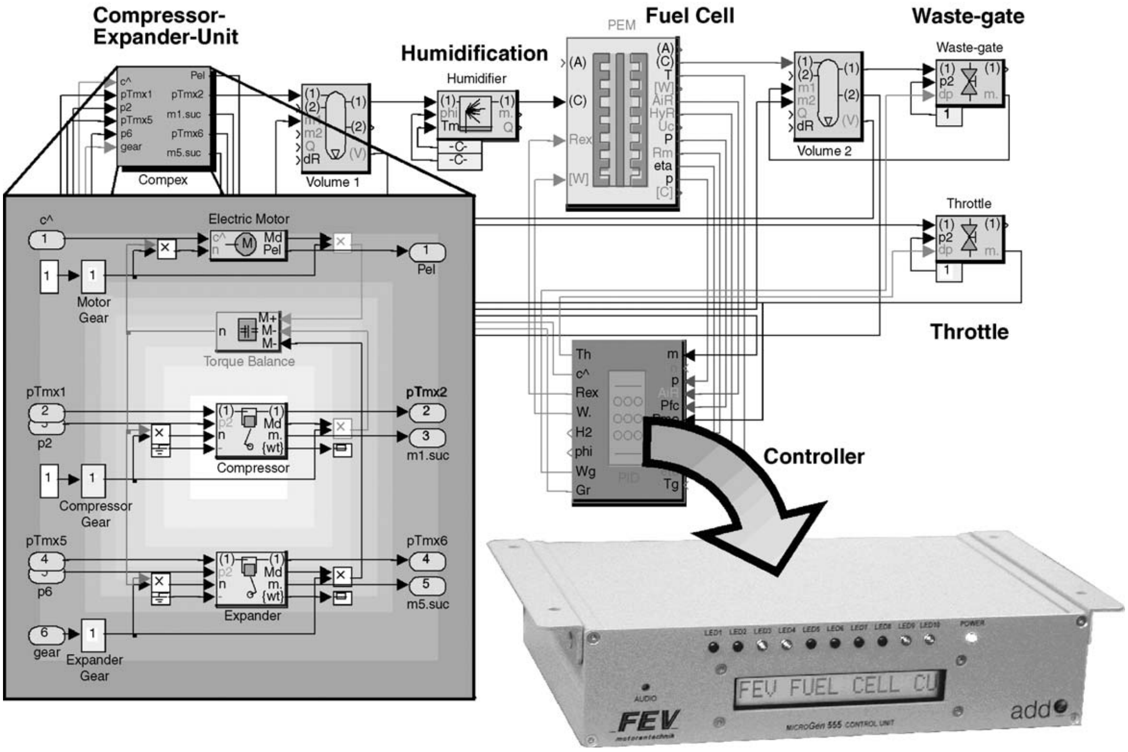

Fig. 7. Simulation model and controller software download.

7. Summary and conclusion

This analysis of the fundamental dynamics of the different components in fuel cell systems represents a systematic approach for the design of fuel cell systems in various automotive applications. The major system inertias were determined, from which it was able to estimate viable response delays for start-up and transient operation. The various requirements for the major fuel cell system components (e.g. air supply, fuel supply, power management and the control layout) were evaluated and demonstrated.

Technically, the PEM fuel cell could be a viable propulsion system alternative to conventional combustion engines, as long as a sufficient amount of power output is available for very low operating temperatures, including below 0 °C. To achieve this, the fuel cell has to operate, at least for the start-up phase of about 1–10 min, without humidification. An optimized air supply system meets the requirements for transient operation in vehicles; however, specially designed machines are necessary—in particular smaller, integrated units with compressors, expanders and, if necessary, humidification.

Electrical storage devices help to reduce the response times of a fuel cell system for transient operation. An even more important point is that the fuel cell can be downsized if it only has to provide the required power continuously, which is only a fractional amount of the power for acceleration in most driving cycles. In this way cost, space and weight can be saved. Depending on the specific requirements for the desired application, super capacitors or batteries can be applied. If high dynamics are required, super capacitors are recommended; however, for longer autonomous operation, storage batteries are more favorable.

Fuel processing is preferable for Auxiliary Power Units (APUs), since they have to operate in vehicles that use gasoline or diesel fuel. To avoid high losses during the start-up phase, a battery is recommended for buffering highly fluctuating power demands. The application of a fuel processor is a bigger challenge for propulsion systems, and can only be realized when the vehicle dynamics are taken care of by an electrical storage device.

To control the operation of a fuel cell system with several components, only advanced control methods are acceptable. A control layout with decoupling, anti-windup compensation, and predominant feed-forward control based on model-based predictions, arranged in a comprehensible hierarchical structure, is strongly recommended. By using simulation tools, fuel cell systems can be developed and precisely optimized, within an accelerated development process.

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