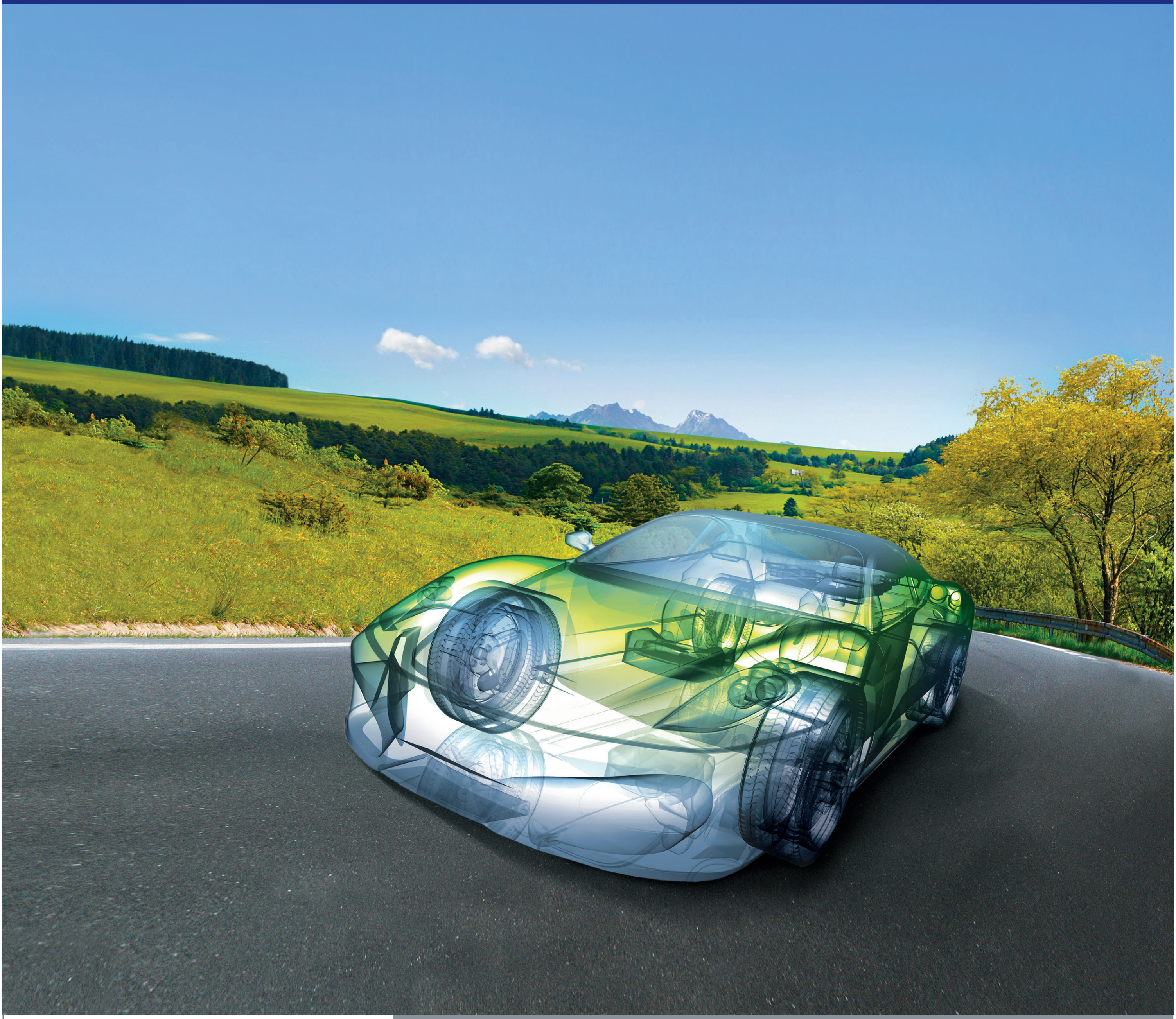
Charging System for Fuel Cell Applications



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Charging System for Fuel Cell Applications

Vehicles with fuel cells become increasingly important, as OEM have announced to introduce fuel cell vehicles into the market starting in 2015. Similarly to a combustion engine, the fuel cell also needs compressed air to provide for a high power density. For a longer period, BorgWarner has now collaborated with different OEM and has developed a turbocharger with high maturity level, which is scalable to support various applications.

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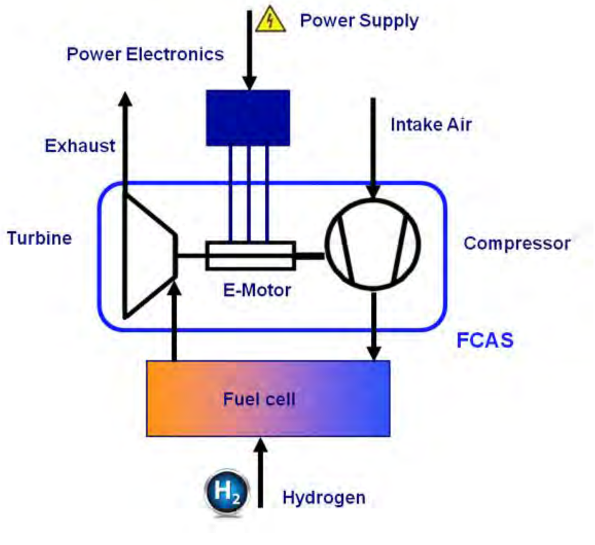
Motivation and Requirements for the Fuel Cell Air Supply

To fulfill future emission regulations for passenger cars, vehicles which locally generate no emissions will be mandatory for the USA. The legislation CARB LEV III requires a share of 4.5 % zero emission vehicles (ZEV) for 2018 [1]. Moreover, electric vehicles and fuel cell vehicles receive high credits in the USA, so that they positively affect the CO2 balance of the car manufacturers. The capacity of batteries is and will stay limited. Since a breakthrough in battery technology is not to be expected, fuel cell electric vehicles (FCEV) are seen as the only solution to allowing emission-free driving with a satisfactory driving range for the medium and long term future.

The fuel cell vehicle generates electricity in the fuel cell. Hydrogen from the vehicle tank reacts with oxygen from the surrounding air generating electricity. Water vapour is the only reaction product being emitted. Auxiliary systems supply air and hydrogen in the correct ratio. Like in a standard international combustion engine compression of the intake air leads to an increase in efficiency and power density. In order to reduce costs, current applications avoid batteries with high capacity which could serve as a buffer during transients. Thus, the fuel cell must provide its energy dynamically according to the driver’s demand. This requires a highly



System layout fuel cell with FCAS system transient operation of the air supply system.

In some respect the requirements for the charging systems of fuel cells and internal combustion engines are similar. In both applications, the air supply system can be considered as a key component. To emphasize its special purpose for a fuel cell application, BorgWarner has named the charging system Fuel Cell Air Supply (FCAS).

Concept of an Air Supply for Fuel Cells

In general, most of the known charging technologies for internal combustion engines are applicable to fuel cells. In comparison to the supercharger, the turbocharger with radial compressor and turbine achieves higher system efficiency not only because the turbine recovers the exhaust gas enthalpy of the fuel cell. Other important drivers to substitute the supercharger in the fuel cell system with a turbocharger are the considerably better NVH behavior and the lower packing space needed, [2].

The process temperature of modern fuel cells for cars is rather low. Therefore, the exhaust gas enthalpy provided to the turbine is not sufficient to drive the compressor. Hence, a powerful electrical motor is necessary to drive the compressor; in fact, it is an essential component of the FCAS system. Even a variant of the FCAS system without a turbine is available as part of the FCAS family.

The required compressor drive power is calculated with Eq. 1:

$$P_c = T_1 \cdot \left[\pi_c^{\left(\frac{\kappa_{air}-1}{\kappa_{air}}\right)} - 1 \right] \cdot \dot{m}_{air} \cdot c_p^{air} \cdot \frac{1}{\eta_c}$$

P_c stands for the compressor power, T_1 for the compressor intake temperature, π_c for pressure ration of the compressor, κ_{air} is the isentropic exponent, $\dot{m}_{air}$ the air mass flow compressor and n_c the compressor efficiency.

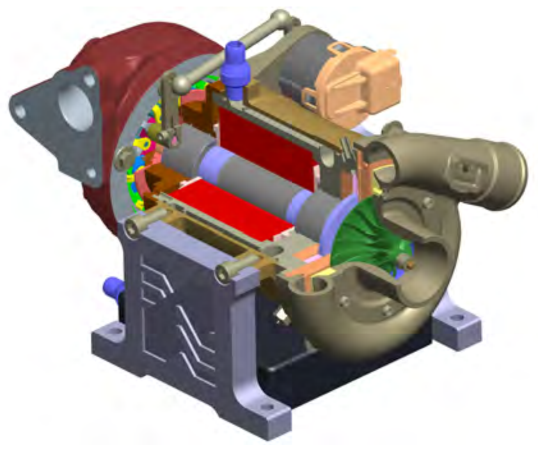
The steady-state required electric power can be derived from the compressor drive power and the power losses from the electrical motor and the power electronics. If a turbine is available, the generated power can be subtracted. The targeted transient behavior determines the dimensioning of the electrical motor since the maximum power demand during transients can be as much as 150 % above the stationary demand.

Layout of the FCAS

The FCAS consists of:
- a bearing system with two journal bearings and one bi-directional thrust bearing
- electric drive with stator and rotor
- water cooling
- radial compressor
- optional turbine with variable turbine geometry.

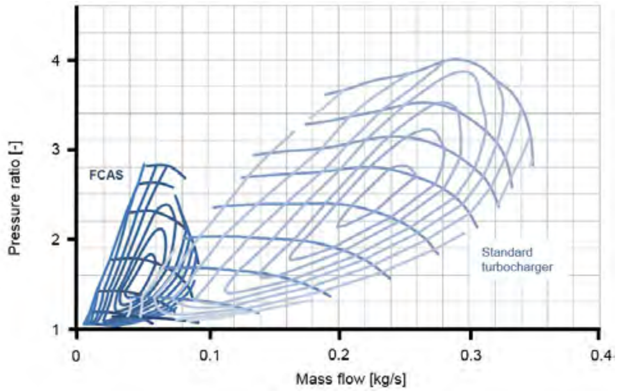
Compressor and Turbine

The radial compressors used for the FCAS as well as for the internal combustion engine are similar. Basis for the development of the FCAS



Fuel cell air supply (FCAS)

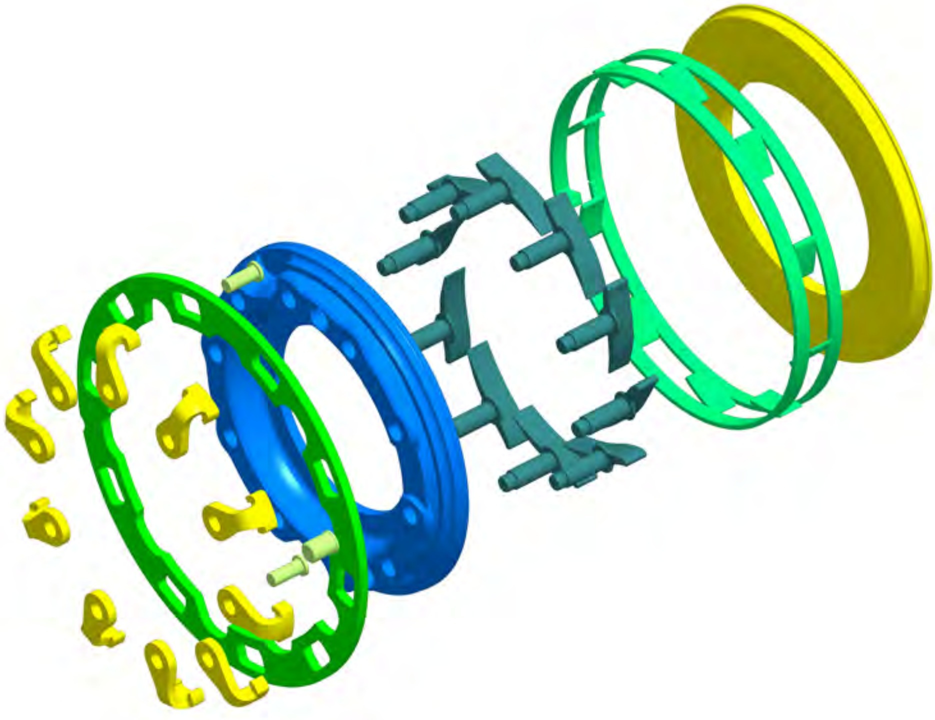
compressor was the huge range of available variants which allows to optimally match the characteristics of the fuel cell regarding specific mass flow and pressure ratio. In general, the compressor map is shifted towards smaller mass flows and pressure ratios. The mass flow range is smaller, so the compressor map can be narrower which leads to higher efficiencies. The turbine geometry can be taken over from the conventional turbocharger with just the matching being different. For cost reduction purposes and because of lower temperatures, the turbine material can be downgraded to for example aluminium. The lower enthalpy can be optimally used by means of the variable turbine geometry with adjustable guided vanes (VTG). For the FCAS system, the newest VTG generation 6 was chosen, which features high efficiencies with closed vanes. On the turbine side, a comprehensive modular choice of variants is available as well as to match the FCAS to the desired fuel cell application.



Comparison of FCAS and standard turbocharger

Electric Drive

For the FCAS the most important factors are best efficiency factors and high power density. Hence, a permanently excited synchronous electrical motor was selected for driving the FCAS system. Two variations which differ only in their design length are available for the use with and without turbine. In addition, the power output of both variants is scalable. In each case the operating voltage ranges from 280 to 400 V.



Cartridge VTG generation 6 (guide vanes in the center)

The following power output can be achieved in steady state operation:

- FCAS system with turbine up to 10 kW
- FCAS system without turbine up to 20 kW.

The efficiency of a turbo machine is depending on the Mach and Reynolds number. For a compact and efficient machine, high speeds are an advantage. However, with rising speed the centrifugal forces on the permanent magnets in the rotor also increase limiting the maximum circumferential speed. A further limit is set by the first critical bending speed of the rotor which must be above the operating speed. With increasing rotor speed the cooling system of the electrical motor becomes more challenging. A target speed of 120,000 rpm at rated power has turned out to be the best compromise between costs, efficiency, overall size and transient behavior. It is significantly higher than other well known applications [3].

Oil-free Bearing

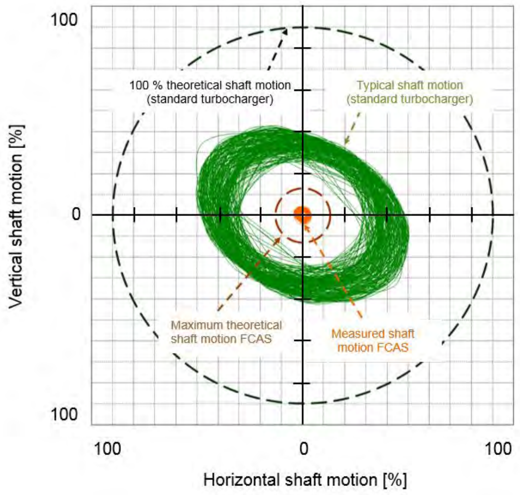
The fuel cell must not be polluted with hydrocarbons or other chemicals. A perfect oil sealing is difficult to achieve with the standard oil-lubricated journal bearings usually being used for turbochargers. Hence, a new kind of bearing system had to be developed. Due to the high complexity and the low load-carrying capacity, magnet bearings were not an option. Instead, foil bearings, also called air bearings, were applied [4].

Foil bearings have the following advantages:

- oil supply not required
- low noise emission
- high speeds possible
- low power losses at very high speeds
- maintenance free
- robust against acceleration and vibration.

There are also disadvantages:

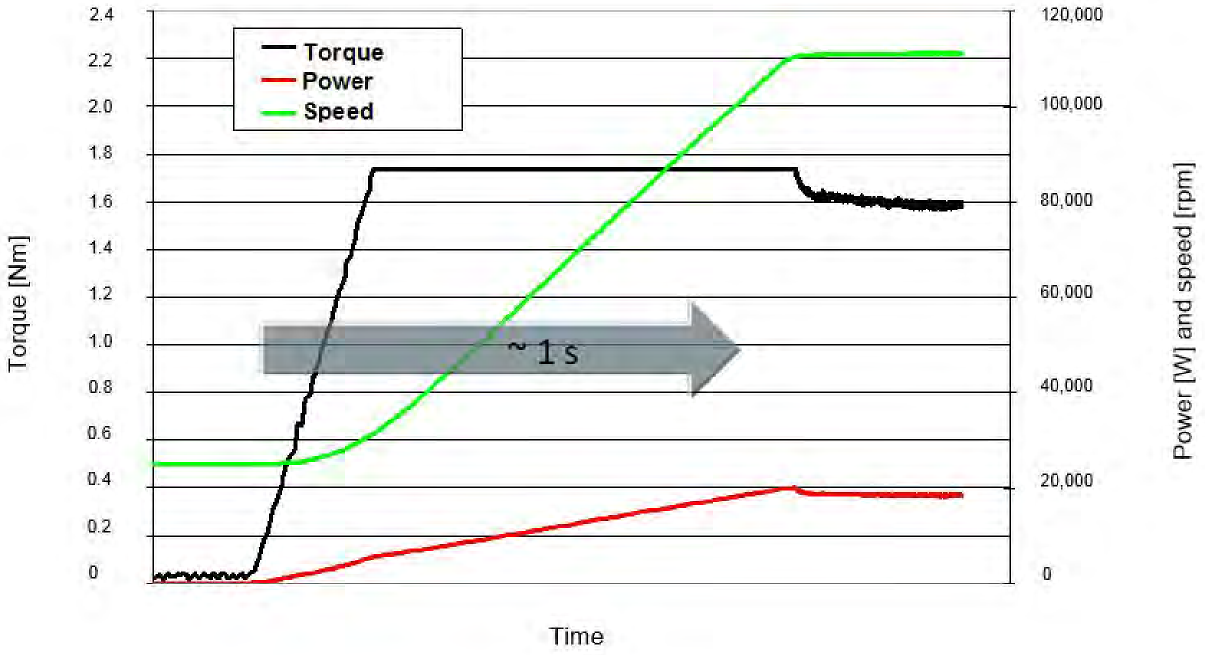
- increased start up torque



Measurement of shaft motion comparison of FCAS vs. standard turbocharger

- overall size and weight
- minimum engine speed necessary
- so far lack of experience in terms of series application.

Based on the state of the art technology, a hydro dynamic air bearing was developed specially for the FCAS. A robust design for automotive applications was essential. A high life span with up to 100,000 stop-starts had to be achieved. Furthermore, good damping qualities were required with high efficiency. The cooling of the foil bearings had to be realized without external air supply. Oil free bearings offer a new degree of freedom for the design of the turbo machine. On a standard turbocharger, an oil spill across the piston rings to the compressor must be avoided by carefully balancing the static pressure inside the bearing housing and the compressor. The bearing has to be oriented horizontally. With the oil free FCAS bearing system both is not an issue anymore allowing more flexibility in the compressor design and in the orientation of the device. A defined purging with air from the compressor is asked for and it also reduces the bearing temperature. Another advantage of the



Measurement of transient ramp-up with FCAS

air bearings appears to be the much higher rotor stability compared to a conventional turbocharger. The shaft motion is reduced by up to the factor of 10, so smaller gaps are realized in the compressor and the turbine which result in higher efficiency.

Power Electronics

Only direct-current is available in the fuel cell vehicle. Therefore an inverter (power electronics) is employed to provide current and to control the synchronous electrical motor of the electric turbocharger. The targeted high speed imposes high demands on the power electronics. The following tasks must be fulfilled:

- enabling maximum power with high efficiency
- scalability for different system power requirements (modular system)
- high quality current signal for the electrical motor (high frequency) to minimize losses inside rotor and stator of the FCAS system
- robustness and suitability for automotive application
- compactness and low cost.

The inverter technology known from industrial applications and automotive drives can not be used for the FCAS. However, it was the base for further development. The essential part in the inverter development was the use of semiconductors, which are approved for automotive applications. Furthermore, other aspects such as lifetime, conformity with the automotive standards of the electromagnetic compatibility (EMC) and high voltage safety had to be considered. The inverter is an important cost factor of the system and cost optimization is the main focus for all further development.

Demands for Transient Response in Automotive Application

The fuel cell must be able to deliver the dynamic power required to fulfill the demand of the driver. The available system power is directly correlated to the supplied air mass flow and the boost pressure. Therefore, the air supply system needs to be highly transient too. For a turbocharger, the pressure is directly linked to the circumferential speed of the compressor. Thus high speed gradients are necessary for a good transient behavior. The ramp-up time can be estimated in advance by taking into account the limits for the electric power and the demanded compressor power, the bearing friction power to be overcome and the efficiency in the electric chain. The ramp-up time was an important feature in the development of the FCAS. In experimental investigations a ramp-up time $t_{90\,\%}$ of 1 s was realized.

Conclusion

Based on the experience with conventional turbochargers, BorgWarner Turbo Systems has developed an air supply system for fuel cell vehicles. The system will be a major contribution for enabling future zero emission propulsion concepts. The so-called fuel cell air supply features innovative technologies like a high-speed electrical motor and air foil bearings to fulfill the specific requirements of the fuel cell.

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