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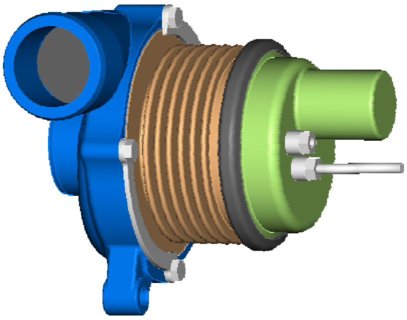

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The eBooster from BorgWarner Turbo Systems

The key component for a new automobile charging system

Academy

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1. Introduction

Through the use of fossilized energy resources, the concentration of carbon dioxide and other trace gases in the atmosphere are constantly increasing. One effect of these gases is a change in the radiation balance of the Earth so that we can already clearly see the changes in the climate with their harmful and sometimes irreversible effects on people, culture and the environment. These problems send us a warning to reduce consumption and reduce the emissions of harmful gases as much as possible. Added incentive is provided by the limited reserves of fossilized energy resources, which seen from today's point of view, the economically useful reserves of petroleum will only suffice for several decades. Since carbon dioxide is an end product of complete combustion, a reduction in the fuel consumption is synonymous with a reduction in CO_2 emissions.

In this context, though, the obligation made by the European Automobile Manufacturers Association to reduce the average carbon dioxide emissions to 140 g CO_2 / km by the year 2008 represents a major contribution. 140 g CO_2 / km means a fuel consumption of 6.0 l / 100 km for gasoline engines and 5.3 l / 100 km for diesel engines. This milestone may only represent an intermediate step, though, because there are already discussions underway today to decide if an EU-wide threshold of 120 g CO_2 / km is realistically achievable by the year 2012. If one realistically appraises the situation today, the obligation made by the automobile manufacturers and suppliers represents a great challenge.

A pioneering innovation is the reduction of the displacement of the combustion engine and a reduction in the number of cylinders. This idea has been termed "downsizing". Engines with low engine capacities yield significant advantages with respect to fuel consumption and emissions, although the torque produced by a small engine is pronouncedly less than that of a large engine. The demand for driving performance and driving comfort will stay the same at least from the point of view of the end customer, i.e. the displacement can be reduced, but if and only if the characteristics of the large displacement engine are maintained.

An innovative solution for compensating the lower torque is the use of a suitable, high-performance charging system. When a charging system is used, the features of a large-displacement, naturally aspirated engine must be attained with respect to the steady-state response as well as to the transient response. Turbochargers designed to use state-of-the-art technology have achieved high efficiencies, but cannot completely fulfill these high demands. In order to perform this difficult task, the next step towards a charging system with higher performance must be taken.

2. Electrically driven charging

The many important advantages of turbocharging using the existing state-of-the-art in technology are accompanied by a complete dependency on the amount of exhaust offered, however. Its capabilities are limited, especially in speed ranges in which there is not much exhaust gas available.

A significant improvement can be achieved using turbochargers with variable turbine geometries. Examples of this are turbochargers with a variable turbine guide blade (VTG), which are used in production today in diesel applications and which are currently being refined for the higher demands in gasoline engines, or turbochargers with a variable slider ring turbine (VST), an operating principle that can already be used today at exhaust temperatures of up to 980°C and that can be used for common charger sizes as well as for the smallest charger sizes (the smallest turbine wheel diameter today is 31 mm). With chargers with a variable turbine geometry, the steady-state limits of the compressor map can generally be reached quickly, i.e. the transient response is significantly improved in certain ranges. The steady-state characteristics (torque and performance curves), however, can only be changed within the limits of the map. The startup torque can only be improved slightly with these types of chargers.

An interesting way to significantly improve the steady-state and transient performance characteristics is to connect two differently sized turbochargers in series with integrated components to regulate the system, also referred to as two-stage regulated charging.

Another way of equipping small engines with performance features like those inherent in larger naturally aspirated engines is to supply a defined amount of extra power for charging. This power may take, for example, the form of electrical energy, and is independent from the exhaust gas energy and the operating state of the engine. The limitation of conventional turbochargers with respect to their total dependency on the amount of exhaust gas offered is therefore eliminated, which is a weakness that can only slightly be compensated for, especially at low engine speeds.

On the one hand, electric motors and the corresponding inverters with enough output and high torque densities can be designed to be sufficiently compact. On the other hand, though, the introduction of the 42 V vehicle electrical system could provide the additional electrical power required at technically feasible current levels in the vehicle. The legal guidelines regarding permissible levels of pollutant emissions and the obligation the industry made to itself in this regard will lead to small, turbocharged engines that will need to be equipped with an extremely powerful charging system in order to be able to exhibit transient performance characteristics similar to those of larger displacement, naturally aspirated engines. In particular, compensating for the low latent startup power of small displacement engines will require extra power to be provided regardless of the operating state of the engine. Electrically driven charging will be able to do this.

2.1 The electrically driven turbocharger (eu-ATL)

One way to provide electrical motor drive energy to the exhaust turbocharger is to integrate a suitable electric motor in the turbocharger shaft, for example between the turbine and compressor impeller (
Figure 1). The use of currently available electric motors with high power densities increases the axial range of the eu-ATL only by about 25 mm over the basic version. In addition to the electric motor, other components also need to be included such as the control and power electronics, which currently need to be placed separately at a suitable location. This is due to the thermal load from a turbine pressurized with exhaust gas and the mechanical load from the operation of the combustion engine. Depending on the voltage level of the vehicle electrical system and the output of the electric motor, these electronics are connected to the turbocharger by an appropriately sized cable.

This integrated system results in a noticeably improved transient response at operating points where there is not much exhaust gas available in spite of the increase in the mass moment of inertia of the rotating blades. The potential for improvement in the transient operating characteristics depends primarily on the amount of electrical power available and the electrical infrastructure of the vehicle. There are limits, however, to the increases in the steady-state characteristics since improvements can only be achieved within the given compressor map limits due to the single-stage process management of the system.

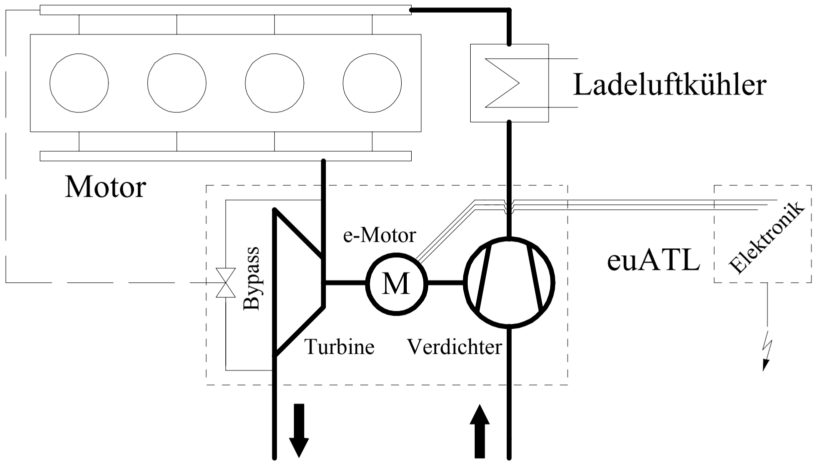

Figure 1: Diagram of the electrically driven exhaust turbocharger

2.2 The eBooster™ charging system

Another important way to provide extra electrical power for turbocharging is by connecting a turbocharger and a flow compressor driven by an electric motor in series, which is the concept used by the "eBooster" (Figure 2). The concept is based on a regulated, two-stage compression. At operating points where there is little exhaust gas available, the two-stage compression reaches a higher overall charging pressure level earlier.

Thanks to its electric drive, the eBooster is completely independent from the turbocharger and the thermal energy of the exhaust gases. The benefits that can be gained using the eBooster system in terms of the transient response are determined solely by the capacity of the vehicle electrical system. Depending on the design of the turbocharger, one way of working with this system is to enable integrated operation of the eBooster and turbocharger below engine speeds of 2000 rpm when starting up and accelerating (that is, during transient operating phases), then, during steady-state operations (or above this engine speed) the turbocharger alone is responsible for obtaining the supply of air.

An increase in the steady-state torque at low engine speeds is possible, in contrast to the electrically driven exhaust turbocharger, if the electrical power required can be made available by the vehicle electrical system.

The eBooster can be placed before or after the exhaust turbocharger in this system, although placing it before the ATL compressor provides more flexibility in terms of the mounting position, while placing it after the exhaust turbocharger compressor allows for shorter cable lengths. Figure 2 shows the eBooster when placed before the exhaust turbocharger.

Numerical simulations have determined that there are minor advantages in terms of power when the eBooster is located before the turbocharger.

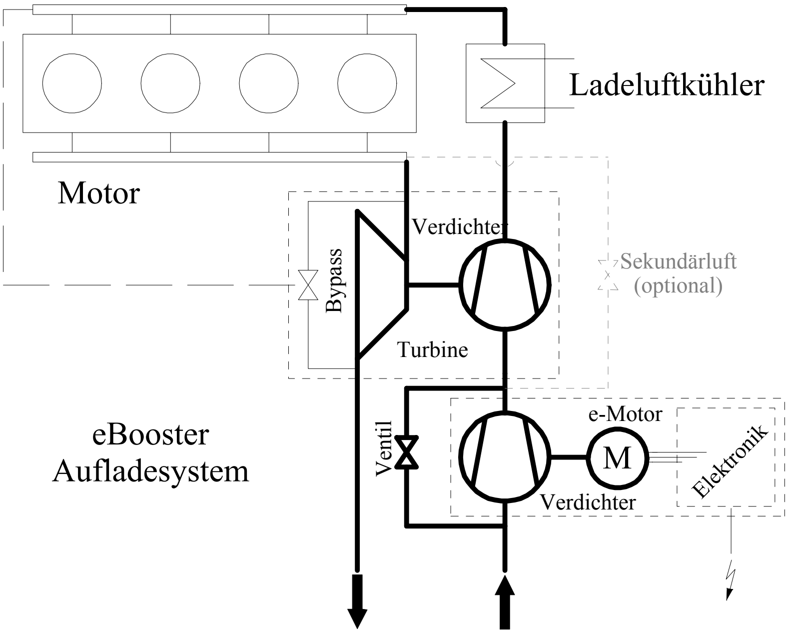

Figure 2 : Diagram of the eBooster charging system

3. Comparison of electrically driven charging concepts

3.1 Potential for improvement in steady-state and transient engine characteristics, map width

The map of a flow compressor, i.e. a graph of the pressure ratio over the volume flow rate with lines of constant speed as parameters, has inherent technical limits. It is characterized on the one hand that the flow dissipates in the blading system starting at certain pairs of values for the pressure ratio and volume flow rate, the result being the so-called "pumping" in the system, so that the pressure cannot be increased further at a constant volume flow rate. On the other hand, it is characterized in that at very low pressure ratios and comparably high volume flow rates the flow rates approach the speed of sound, and an additional increase in the volume flow rate at a constant pressure ratio is not possible. Safe operation of a compressor is only possible within these limits.

The eu-ATL is a electrically driven, single-stage charging device. In single-stage charging, the higher degree of charging necessary to push the intermediate pressure curve to a higher pressure level is only possible within the prescribed compressor map limits. The eu-ATL therefore has no appreciable potential for increasing the steady-state torque values when compared to current exhaust turbochargers.

The eBooster charging system is a concept based on regulated, two-stage compression. The main advantage of two-stage systems over single-stage units is that two different sized compressors can be connected in series so that an optimized map is available for each air flow rate range. When the two maps are combined, the resulting map has a power curve with a significantly expanded useful map width. The eBooster charging system allows, as a two-stage compression variant, an increase in the intermediate pressure curve regardless of how much exhaust gas is available. The potential is only limited by the electrical system of the vehicle.

3.2 Mass inertia of the rotor

While only the motor shaft and compressor impeller need to be accelerated in the eBooster, the mass inertia of the turbine wheel must also always be overcome in the eu-ATL. In this case the mass moment of inertia of the turbine wheel is about three times that of the compressor impeller since it needs to be manufactured using a relatively high-density nickel alloy due to the high exhaust temperatures. A significantly improved dynamic response is therefore to be expected from the eBooster for the same boundary conditions. Numerical simulations show that the power consumption of the eBooster system is much lower than that of the electrically driven exhaust turbocharger.

3.3 Bearings

The rotors of exhaust turbochargers manufactured today are equipped with friction bearings and a separate axial bearing that comprises a comparably large percentage of the overall loss. The eu-ATL must cover a speed range as wide as that of a standard charger, and in contrast to the eBooster unit it needs oil-lubricated friction bearings with separate axial bearings due to the higher speeds and the thermal load of the turbine.

Numerical analyses show that the maximum operating speeds of the eBooster in the charging system are significantly below 100,000 rpm. No thermal load is placed on the unit by components conducting hot gases. The rotor of the eBooster can be designed with roller bearings for operation below these boundary limits. The axial loads as well as the radial loads could be withstood by a suitable ball bearing when designed accordingly so that a separate axial bearing is not needed.

Furthermore, bearings lubricated for their entire service life that do not need extra lubrication can be used in the eBooster for operation at these speeds and at the temperatures to be expected in the unit, and the connection to the oil supply and the supply line itself would therefore not be necessary anymore.

3.4 Mechanical and thermal load

In general, electronic components and circuits react sensitively to high operating temperatures and mechanical impacts or vibrations, and the acceleration of the components on the gasoline engine due to mechanical influences can be up to seven times the acceleration due to gravity. Future gasoline engines will work with exhaust temperatures on the order of 1050°C, which results in engineering and material science challenges even for standard turbochargers [5].

In general, complex, expensive technical measures are necessary to further refine the components that must operate under these conditions and require such a service life. In addition, the component volumes of electronic components resistant to higher temperatures are generally much higher. For example, a commercially available 15,000 F condenser certified for operation at temperatures up to 105°C has almost twice the volume of a condenser of the same capacity and voltage class that is certified for operation at temperatures up to 85°C. The costs for higher temperature-resistant electronic components are also generally unproportionally higher.

To design a reliable electric motor, extensive measures are necessary because the eu-ATL by necessity must be mounted rigidly to the engine and the electric motor and hot exhaust turbocharger turbine are integrated into one unit as well. An even more complex task would be to equip the eu-ATL with integrated power electronics that are guaranteed to function when operated at the thermal and mechanical boundary limits. This would be especially advantageous in terms of electromagnetic compatibility. The units presented to date have power electronics located externally in a box that can be placed in a suitable position on the vehicle and that are connected to the eu-ATL with appropriately sized cables. Even when the electric motor of the eu-ATL is inactive, it is subject to a considerable thermomechanical load due to the high charger speeds and the exhaust gases flowing through the turbine.

In the eBooster charging system the exhaust turbocharger and the electrically driven compressor represent two separate units. There is no direct thermal load placed on the electric motor by the hot turbine. The exhaust turbocharger of the system is a thermally and mechanically resistant component that can be constructed using proven methods. As such, it is designed to be attached to the manifold on a flange or integrated into the manifold. In contrast, the thermally and mechanically more sensitive components and the integrated electronics can be placed at a suitable location in the motor compartment and can be connected by pipes to the exhaust turbocharger or a charging air cooler so that they are vibrationally isolated. Even when the eBooster unit is attached to the motor block, it can be mounted using simple and proven methods so that it is thermally and vibrationally isolated. When the eBooster is inactive, it is only subject to the temperature of the motor compartment.

3.5 Cooling

The question of the thermal load was already mentioned implicitly in the context of the criteria discussed above. Due to the integrated construction and the significantly higher thermal load, the eu-ATL requires more cooling than the eBooster unit. This problem will intensify due to the increasing exhaust temperatures of future gasoline engines. Even today, at exhaust temperatures around 950°C, the bearing housings of modern turbochargers for gasoline engine applications are water-cooled. Even when the electric motor is not in operation and therefore produces no thermal dissipation losses, the bearing housing is subject to the high thermal load of the turbine and must be cooled constantly by the oil system or the water cooling system. The same applies to the power electronics as well when they are integrated into the manifold.

If the eBooster is used to improve the transient engine values, then its operating time per activation is very short each time. Even when the eBooster is operated multiple times, for example in city driving conditions, the total amount of heat to be extracted is small and can be released into the air in the motor compartment through an appropriately designed surface.

If the eBooster charging system is used to increase the steady-state characteristics as well as to improve the transient performance, then the eBooster goes into steady-state operation after a defined time period. Depending on the steady-state power consumption of the eBooster unit, a defined incident flow must flow over the housing in addition to the finning. One solution would be to place the unit so that the wind generated by the motion of the vehicle or the combustion air taken in flows over the unit and cools it. Another possibility is to design a connection to the cooling system of the engine while eliminating the finning.

3.6 Energy recovery system, generator operation

Emphasis is usually placed in modern exhaust turbocharger designs on a nice, plump motor torque curve in the middle speed range and good startup response from the charger, i.e. on a mass moment of inertia of the rotating blades that is as small as possible. This type of design results in a comparably "small" turbine that would be accelerated into inadmissibly high speeds in the upper speed range when operated at the exhaust gas volumetric flow rate so that some of the mass flow would need to be redirected in a controlled manner through a bypass around the turbine to prevent a charging pressure that is too high or the destruction of the charger.

An eu-ATL was also equipped with as small a turbine as possible so that the rotating blades have a small mass moment of inertia in order to guarantee favorable response and to keep the acceleration performance requirements placed on the electric motor as low as possible. If equipped with the corresponding electronics, a load can be placed on the eu-ATL by the electric motor when there is an oversupply of exhaust gas. The eu-ATL would then operate as a generator in a controlled manner, i.e. braked, so that a predefined rotating blade speed, meaning a suitable charging pressure, is attained. The braking energy is released as electrical power into the electrical system of the vehicle in accordance with the efficiency chain. Since this power cannot be applied directly to the battery under some circumstances, an additional accumulator must be integrated into the vehicle electrical system. It still remains to be determined if the utilization of this potential will be of any significance in the field of passenger cars. This potential appears to be interesting for the field of utility vehicles, though, because the eu-ATL also contributes to the braking of the motor [3], [9]. In an eBooster charging system, though, there is no way to utilize an energy recovery system due to the separation of the turbine and electric motor.

3.7 Installation space and mounting position

The amount of space in the motor compartment is limited for reasons of vehicle aerodynamics and design. The space required for a charging system is an important criterion due to the extremely limited amount of space available and the number of units that need to be located in the motor compartment.

The axial distance spanned by the eu-ATL increases by about 30 mm due to the integration of an electric motor. If the power electronics can be integrated or mounted directly on the charger, then the volume of the unit increases even more. If it is not possible to integrate the electronics for thermal, mechanical or service life reasons, then the power electronics must be placed in a box and mounted externally. The eu-ATL itself must be placed on the manifold.

In contrast to the eu-ATL, two units need to be integrated into the eBooster system, but their volumes are lower than that of the eu-ATL, however. The exhaust turbocharger of the system can be mounted on the manifold or integrated into the manifold, while the eBooster can be mounted at suitable location somewhere in the motor compartment. The control electronics are always integrated into the eBooster housing. The mounting position of the eBooster unit can be chosen as desired due to the bearing concept, i.e. the eBooster offers more freedom when selecting the mounting position for the unit.

3.8 Synthesis

Significant advantages result from the separation of the turbocharger and electric motor-driven flow compressor when compared to the integrated solution. This is a core feature of the eBooster charging system. In this case we would like to especially point out the two-stage process management with its ability to extend the map, the lower mass inertia of the rotating blades as well as the lower mechanical and thermal load of the electrical components. Both electrically driven concepts require the installation of larger units and/or additional components. The eu-ATL only has an advantage over the eBooster system in terms of its potential for the utilization of an energy recovery system, although it still needs to be tested if this potential is relevant when examined in terms of its complexity and usefulness.

After systematically analyzing the electric drive concepts, we at BorgWarner Turbo Systems favor the eBooster system and are developing this concept as an innovative charging solution to improve the transient operating characteristics in the lower speed range for gasoline and diesel engines. In addition to other goals, the eBooster charging system should present itself as a key component in the realization of future small displacement engines that have a transient torque response that approaches that of large displacement, naturally aspirated engines.

4. The eBooster – Development status

Emphasis in the first project phase was placed on the development and presentation of eBooster demonstration models to verify the functionality of the unit in test bench operations. The development status and initial experimental as well as numerical results will be shown in the following.

4.1 Performance characteristics of the system – results from numerical simulations

Parallel to the development work mentioned above, simulations were run at the *Institut für Verbrennungsmotoren* (Institute for Combustion Engines) at the TU Dresden, Germany, using a suitable method [10],[11] to demonstrate the potential of this charging system when inputting various amounts of extra electrical power. Comparative tests between the eBooster charging system and the eu-ATL were also made at the same time.

As expected, the intermediate pressure was reached considerably faster by the two electrically driven systems when compared to the conventional exhaust gas turbocharged engine, but the eu-ATL always remains behind the performance of the eBooster charging system for the same boundary conditions due to the greater mass inertia of the rotating blades. The analysis of the electrical power consumption indicated that about 40% less energy was consumed by the eBooster system compared to that of the eu-ATL.

Figure 3 shows the development over time of the referenced intermediate pressure of a gasoline engine charged by a turbocharger of modern design when a vehicle accelerates from 60 to 100 km/h. The simulation reflects the well-known protracted build-up to the intermediate pressure turbocharged engine. The simulation reflects the well-known, delayed build-up to the intermediate pressure turbocharged engine. If the turbocharger is replaced by the eBooster charging system, the intermediate pressure is built up considerably faster as the electrical power input to the electric motor increases. A comparatively small additional electrical input of 1.8 kW results in a significant improvement, however, increasing the electrical power input to the electric motor to an (unrealistic) value of 8 kW only yields a slight improvement. It must be taken into account, though, that a larger electric motor is needed to convert 8 kW, which then unproportionally increases the mass moment of inertia of the rotor. The output capacity of the electric motor alone is not very significant. The ratio between the torque of the electric motor and the mass moment of inertia of the rotor is the deciding factor with respect to the efficiency of the system.

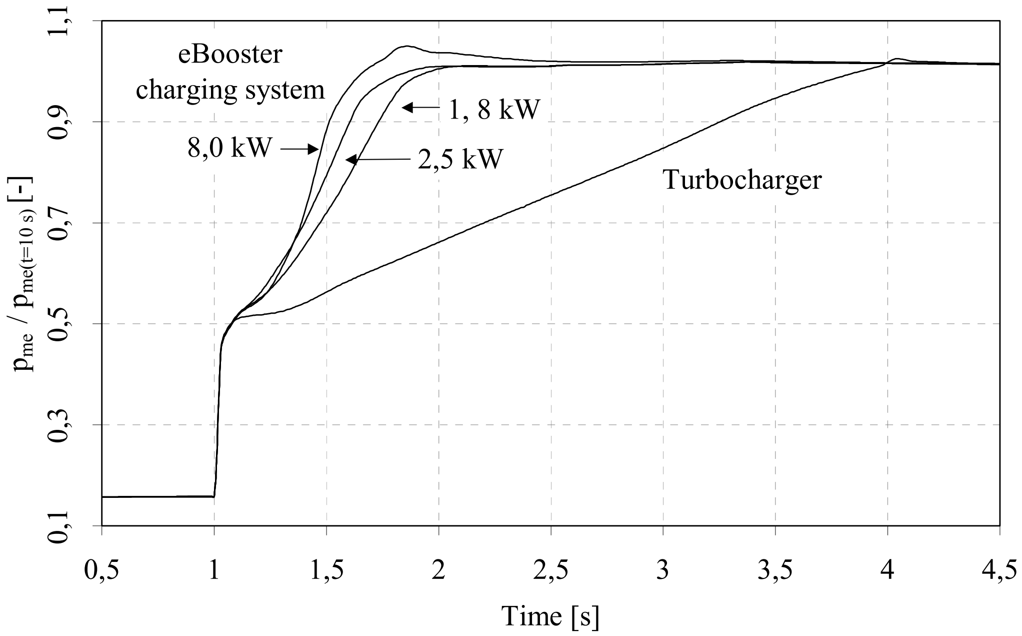

Figure 3: Development over time of the intermediate pressure

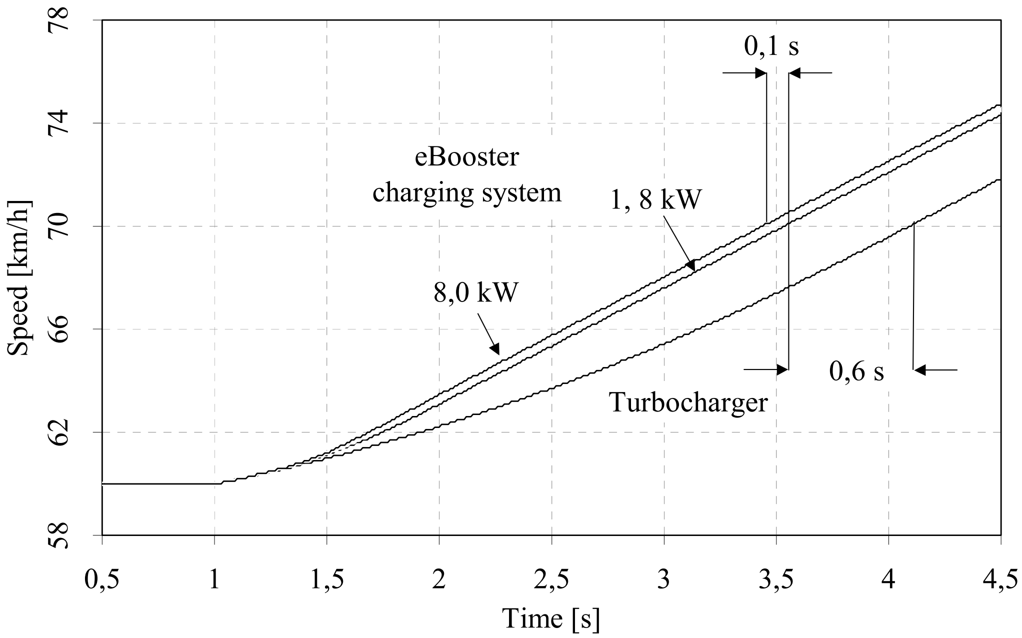

Figure 4: Acceleration performance of the vehicle (60 – 100 km/h)

Figure 4 illustrates the effect of the faster intermediate pressure build-up on the acceleration performance of the vehicle. About ½ second after the vehicle begins to accelerate, the added effect of the eBooster system as compared to a standard exhaust turbocharger is apparent. The effect is recognizable for 1½ second in terms of significantly faster vehicle acceleration. The vehicle charged with the 1.8 kW eBooster system reaches the final speed 0.6 s faster than the conventionally turbocharged vehicle. The effect of building up the charging pressure faster through the use of a higher performance electric motor is only marginally apparent in the acceleration time of the vehicle. Taking these results into account, the extra amount of electrical power that needs to be supplied quickly by the vehicle electrical system in order to achieve effective improvements is between 1.8 and 2.5 kW when using a rotor with this mass inertia.

4.2 Engineering

The possible advantages of the eBooster system discussed during comparison of the two electric charging systems were implemented in the design of the eBooster unit. Figure 5 shows a cross-sectional diagram of the first generation of the eBooster. The unit can be divided into three main components: the flow compressor, the main housing with the electric motor and bearings and the integrated power electronics.

The first generation demonstration model has a water jacket for cooling permitting us to conduct temperature tests on a test bench. The eBoosters in the next generation, when used for transient operations, will only have one cable for supplying power and one cable for control in addition to an intake and outlet connection fitting. The unit will not have any oil or water connections.

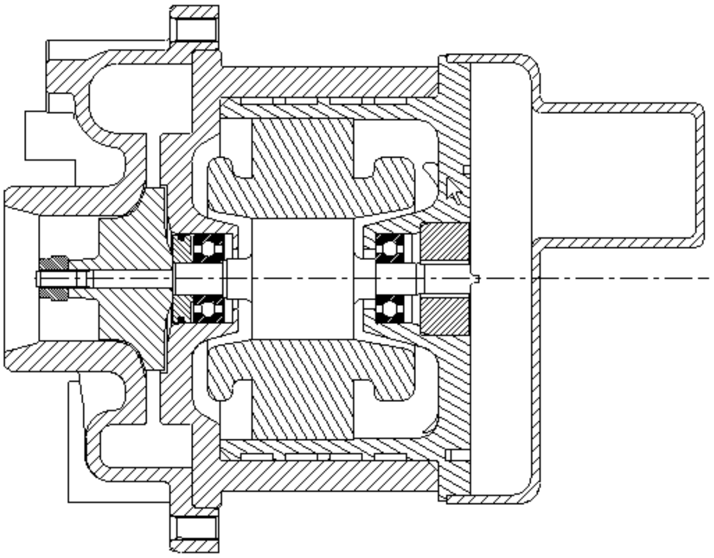

Figure 5: Cross-sectional diagram of the eBooster unit

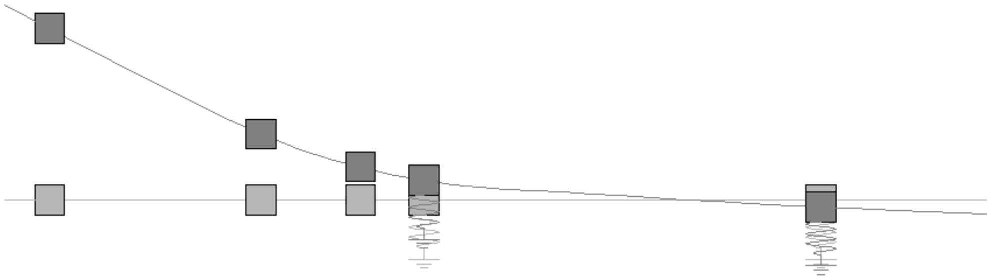

Figure 6: Normal and deformed structure at the first critical bending resonant frequency

The significant advantages of ball bearings come with the disadvantage of a rather unfavorable damping capability. This is one of the reasons that the engineering of the shaft is considered to be so important. The shaft of the eBooster is a compact design and is conceived so that no critical bending resonant frequencies lie anywhere within the entire operating range of the eBooster. The engineering design of the shaft was accompanied by numerical analyses conducted while the bearings were being developed. To do this, the rotor was modeled in a suitable program using mass, spring and beam elements, and the resonating shapes were determined. An important boundary condition for the numerical simulation is the determination of the correct bearing stiffnesses, which depends on the axial preload placed on the bearing as well as other influencing factors. The stiffening effect of the shaft nut / compressor impeller combination on the shaft was taken into account in the numerical analysis.

Figure 6 shows a diagram of the normal shaft structure and superimposes the deformed structure at the first critical bending resonant frequency. This frequency is above 2000 Hz and therefore lies clearly outside of the maximum operating speed. The second critical bending speed is at 3250 Hz. No resonant frequencies were found within the operating range during the experimental tests so that the boundary conditions used in the numerical analysis could be confirmed as valid, at least for this range of frequencies.

The damping capability of the ball bearings and therefore the acoustic transmission behavior can be influenced as well by secondary design measures. Suitable secondary design measures are, for example, placing the outer race of the bearing in a shaft spring washer, backfilling the bearing ring with a suitable plastic material or the use of O-rings for damping purposes. To date, no secondary measures have been implemented in the eBooster to change the damping of the bearings.

Proven production components were used in the first generation demonstration model for the flow components. During the development of the production model, the design of the compressor impellers will be changed as required for a specific project. The type of modifications depends on the boundary conditions and the goal is to completely exploit the potential of the two-stage system.

4.3 Bearings

A deliberate omission of lubrication connections was a requirement right from the start of the development of the eBooster. For these reasons, a suitable ball bearing lubricated for its entire life span was designed in close cooperation with a ball bearing manufacturer for the complex load collective presented here (Figure 5).

Depending on the mounting position, the bearing is loaded radially primarily by the dead weight of the shaft, which acts as a circumferential load on the inner ring, and by a residual imbalance that moves along the inner ring as a point load. The bearing is loaded axially when the shaft is positioned horizontally mainly by the axial thrust of the compressor impeller, which is not inherently partially compensated for as is the case for a standard exhaust turbocharger. Due to the transient operating principle of the eBooster, the relevant forces also appear transiently. The shaft of the eBooster is accelerated in a short time from a complete stop to about 80,000 min^{-1}. At the beginning of this acceleration phase, transitory speed gradients well beyond 4000 $1/\text{s}^2$ appear in the current eBooster design (Figure 9). It is clear that the balls and bearing retainer are subject to a high level of dynamic stress. Conventional bearing calculation methods can only offer partially applicable results for this load collective.

The grease becomes very important on the one hand because it must guarantee sufficient operating characteristics at very low temperatures, but on the other hand it needs to demonstrate sufficient lubrication characteristics and durability at the operating temperatures present in the motor compartment. In addition, the grease is mixed and turned each time the eBooster is started up and is therefore subject to substantial shearing loads. The shear strength of the grease used is to be guaranteed by the manufacturer for a characteristic speed value (n [min^{-1}] xd_m [mm]) of up to 1.2 x 10^6.

The grooved ball bearings to be used in the future are special hybrid bearings almost ready for mass production with metallic bearing rings and ceramic bearing balls (silicon nitrite Si_3N_4). Due to the thermal boundary conditions arising during operation, a specific, predefined radial bearing clearance is calibrated when the bearings are manufactured.

Hybrid bearings expand the application limits of metallic ball bearings, especially in terms of speed and when there is not enough lubrication. The favorable wear characteristics of ceramic bearing balls on the metallic track should be pointed out here. They permit relatively high speeds for a bearing lubricated with grease and achieve the required service life as well when a suitable lubricating grease is used. The amount of lubrication required is significantly less than that required for metallic bearings. Due to the low density of the ceramic bearing balls, smaller dynamic forces are applied to the set of bearing balls for the same boundary conditions.

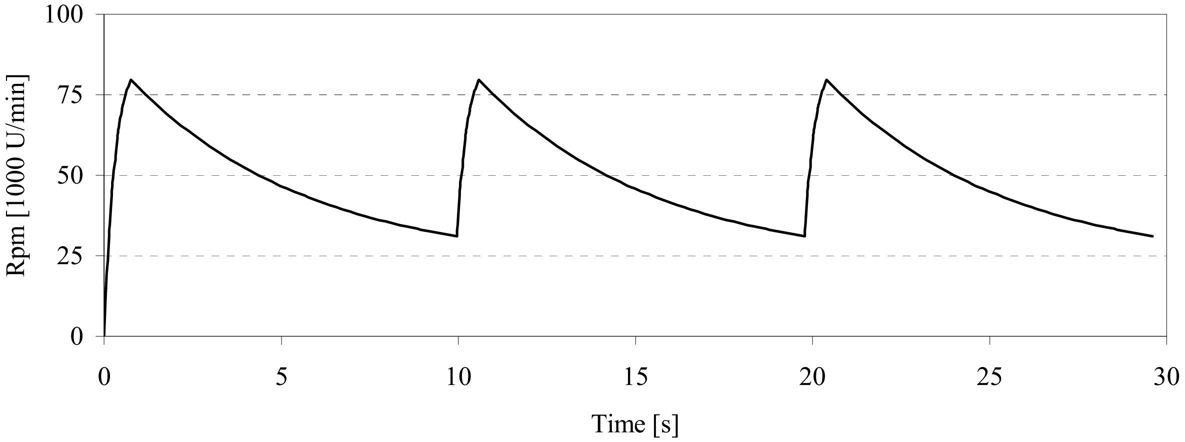

Figure 7: Test cycle for experiments on a test bench

In addition to the design of the bearing seats on the housing and shaft, a defined constructive axial preloading of the bearing becomes increasingly important. A suitable combination of disk springs is used to accomplish this. The spring pack guarantees that the bearing is always loaded axially by a defined minimum force and simultaneously compensates within certain limits for the thermal differential expansion that is unavoidable during operation.

The suitability of the function of the bearing was tested on a test bench. Emphasis was placed a continuous cycle test during the first phase of experiments. In these tests the eBooster was accelerated to its maximum and then allowed to spin down to about 30,000 rpm, after which it was then accelerated to its maximum again. Figure 7 shows a diagram of the speed ranges tested. A total of 15,250 cycles were run on the test bench. The bearing was not removed and the bearing balls were never replaced during the entire test. No damage was detected on the bearing or on the ball bearings themselves during and after completion of the experiments.

4.4 Electric motor and electronics

The demands placed on the electric motor to drive the eBooster compressor are very high.

High speeds and comparatively high outputs are required due to the thermodynamic boundary conditions (mass flow rate, pressure ratios) and the small dimensions of the compressor impeller (
Figure 8). With respect to the main task of the system - to make a higher charging pressure available faster - the acceleration capabilities of the unit, i.e. the ratio of the amount of surplus torque available from the motor to accelerate the rotor to the mass inertia of the rotor, become increasingly important. When used in production vehicles, requirements for low acoustic output and electromagnetic compatibility, reliability and service life also arise in addition to the basic requirement to fulfill its function already stated above.

The electric motor and the power electronics in the first eBooster functional prototypes were developed at the GfAS mbH company in Wasserburg/Lake Constance, Germany. Emphasis was placed during development on the integration of the power electronics and to demonstrate an electric motor with a high torque density. After comparing and examining various motor concepts such as synchronous machines, asynchronous machines and reluctance motors, the drive of the eBooster was designed as an alternating current asynchronous machine with 3 phases and 2 poles. One of the primary reasons for this decision was robustness.

The motor is designed for operation with 42 V DC voltage, whereby the motor and electronics must remain functional within a voltage range between 29.5 and 55 V in order to fulfill the guidelines for a 42 V vehicle electrical system. In principle, such an electric motor could also be designed for a 12 V electrical system, although in this case the windings of the motor and the DC-AC converter would become more complex. The high current levels and the associated increase in losses are not the only reasons why the power consumed in the case of a 12 V solution needs to be limited to a maximum of 1.8 kW.

All power electronics were already designed to be compact during the prototype phase and as such they are mounted directly on the motor housing. This proximity represents an important milestone in terms of the electromagnetic compatibility of the system in the vehicle. Apart from the power transistors, all electronic components are placed on one board with a diameter of about 80 mm. The power transistors are located below this board in a specific manner due to electromagnetic reasons. They are mounted so that it may well be possible to conductively divert its losses dissipated in the form of heat. The detection of the speed of the rotor is made possible by a Hall sensor and by appropriately designing the electronic components at the end of the shaft. A 12 V version of the power electronics could also be designed with the inherent disadvantage of greater losses.

After conducting a feasibility study, two similar asynchronous motors (Model C and Model D) with different outputs were engineered with integrated power electronics at GfAS mbH. The rotor has the same geometry in both motors. In the course of the engineering work, two additional motors (Model E and Model F) were developed based on the results from the first models whose rotor is characterized by a substantially reduced mass moment of inertia, and yet the maximum output of these motors is only slightly below that of models C and D. The main parameters for these motors are summarized in
Table 1.

Designation	**Model C**	**Model D**	**Model E**	**Model F**
Electric power consumption [kW]	1.8	2.9	1.8	2.5
Rotor mass moment of inertia [10^{-5} kgm^2]	2.87	2.87	1.55	1.55
Acceleration time [s]	1.14	0.68	0.67	0.39

Table 1: Main parameters of the engineered motors

Simulations were performed at the *Institut für Verbrennungsmotoren* at the TU Dresden, Germany, to accompany the engineering phase of the motors. One result of this numerical computation work in which the transient response of the overall system including the motor was the focal point of interest is the speed of the eBooster at which the turbocharger in the system "passes" the eBooster, i.e. how fast can the turbocharger provide the degree of charging required without support from the eBooster. After this point is reached, the eBooster can be allowed to spin down naturally or can be regulated down in a controlled manner. The acceleration time specified in Table 1 is the time it took for the eBooster to reach this speed. The time that passes until the turbocharger surpasses the eBooster depends on the system, the size of the turbocharger and the dynamics of the eBooster as well. From Table 1 it becomes clear in which time frames the eBooster is actually in operation, i.e. in which time period electrical energy must be supplied by the vehicle electrical system to provide the necessary auxiliary electrical power.

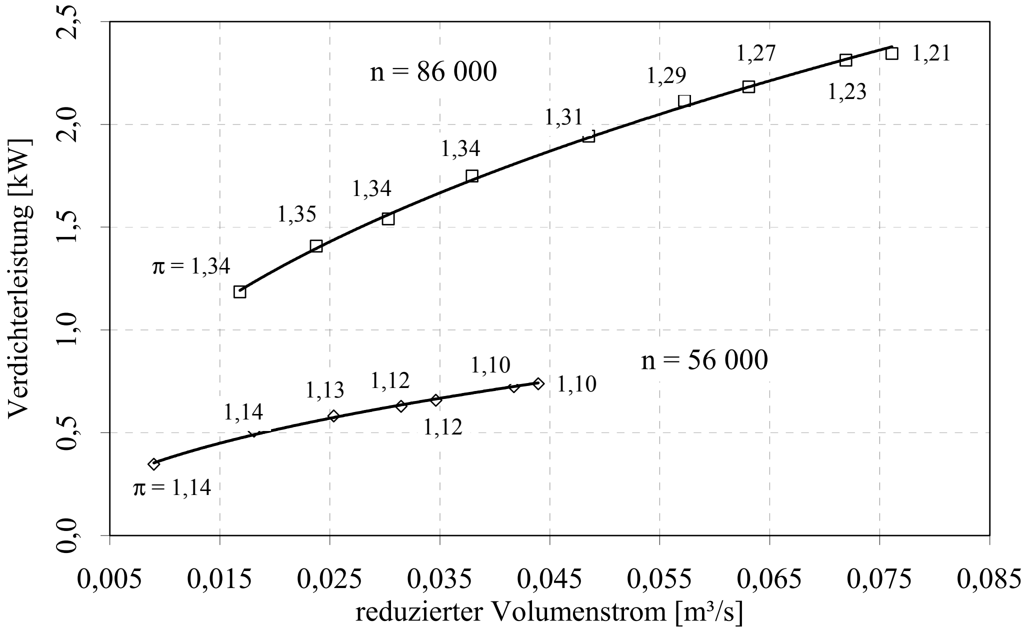

Figure 8: Steady-state power requirement of the compressor impeller used

Model D motors were designed, tested and installed in the first generation demonstration models of the eBooster. In the course of this development work, various rotor designs were developed and tested: solid steel rotors, rotors with layers of Al or Cu under the surface, solid steel rotors with silver-plated surfaces and steel rotors with an end ring. Solid steel rotors were used to obtain the experimental results shown below. Good results were achieved, even using this most simple rotor design. In terms of the efficiency, the plated rotor is the technologically superior solution.

The experimental tests run on the first functional sample were conducted at the GfAS mbH company. Figure 9 shows the progress over time of the speed of the eBooster when tested on the test bench.

The startup response of a flow compressor to attain a certain speed depends on the steady-state operating end point (V_{red},π) in the compressor map since the work performed by the compressor progresses along a line of constant speed as the volume flow rate increases (Figure 8). In this test series a throttle with a constant back-pressure of about 1.34 bar was used on the pressurized side (V_{red} π 0.038 m3/s).

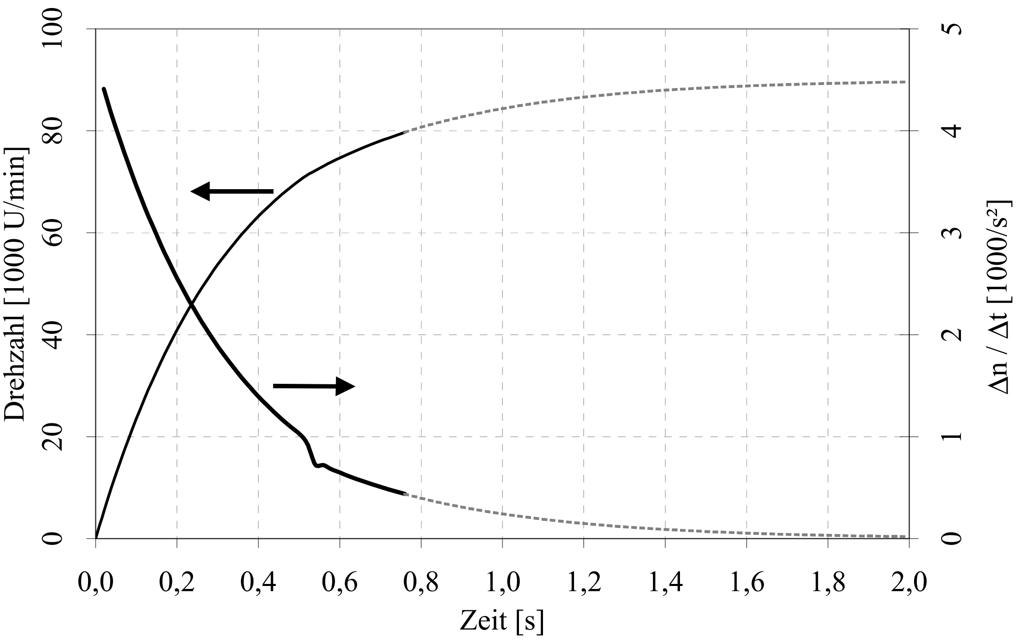

Figure 9: Progression over time of the speed and the change in speed

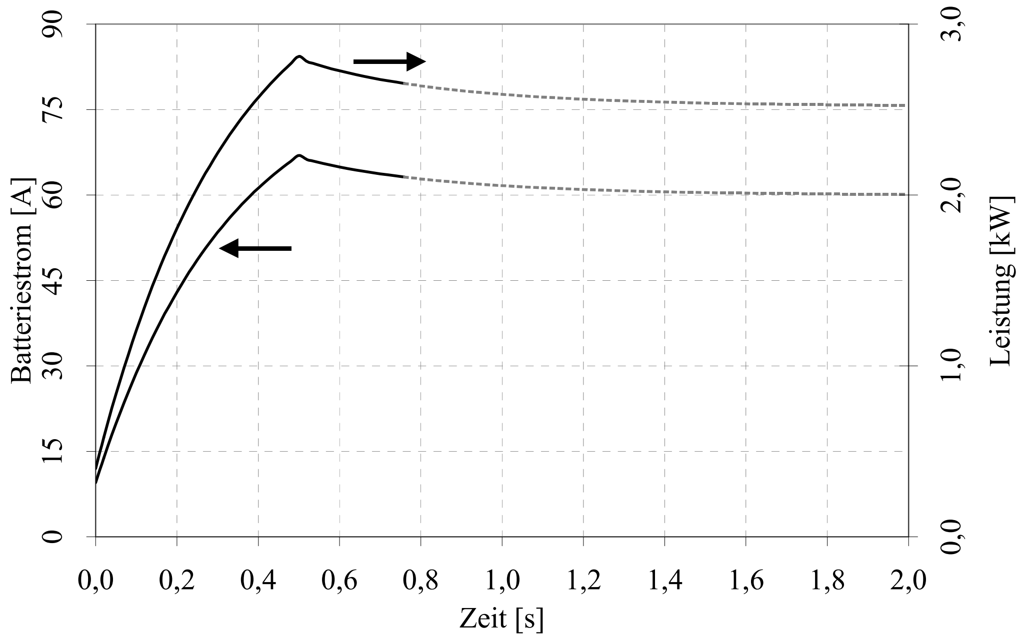

Figure 10: Progression over time of the battery power consumed and the current strength

In real applications of the eBooster charging system the back-pressure is time-dependent when the eBooster is starting up. It is also dependent on the dynamics of the turbocharger connected downstream, among other things. This dependency was taken into account in the simulations performed at the TU Dresden and can be determined experimentally in the motor test, but it was not simulated during the first test bench experiments of the eBooster unit, i.e. the results shown are valid for this constant back-pressure.

The eBooster reaches a speed of 80,000 rpm in about 0.8 seconds when subject to these boundary conditions and therefore meets our expectations. In the applications examined to date, 80,000 rpm is a speed that is much higher than the speed at which the turbocharger "passes" the eBooster and at which the speed of the eBooster is adjusted downwards.

By forming the difference quotient $\Delta n/\Delta t$, you obtain the change in speed per unit of time mathematically from the speed curve (Figure 9). It becomes clear that that the shaft of the eBooster encounters changes in speed well beyond 4,000 rotations/s^2 (corresponding to 240,000 rpm /s) at the beginning of the acceleration phase. The surplus energy created by the electric motor accelerates the rotor. As the speed increases, more work must be performed to overcome an equal difference in speed since the rotational energy increases with the square of the speed. In addition, the required air mass flow rate and therefore the power requirement due to the thermodynamics increases when starting up as the speed increases. While 70,000 rpm is reached in about 1/2 second, the final steady-state speed is reached after about 2 seconds.

Up to a speed of about 70,000 rpm the power consumption (Figure 10) increases with the speed and reaches a maximum of 2810 W, which corresponds to a maximum battery current output of 67 A. Beyond this speed the motor torque drops with the square of the speed and the power consumption drops accordingly. In the final steady-state condition – in which the mechanical and electromagnetic losses arise and the steady-state compressor output is achieved – the amount of power consumed is 2510 W at a battery current output of 60 A. If one integrates the performance curve numerically, then the resulting power consumption per eBooster startup from 0 to 80,000 rpm is 1.67 kJ. This corresponds to an electrical charge of about 11 mAh.

4.5 Outlook, additional procedures

The experimental tests conducted on the prototypes of the first generation on the test bench will be expanded in the future to include testing of the fatigue durability of the bearing and of the electric motor and integrated power electronics. The focal point of the experiments is currently on testing the eBooster charging system on a gasoline engine with the goal of testing the function of the charging system and comparing the measured values to the expected (calculated) values. The development work on the eBooster charging system will be continued and brought from the prototype phase to the series production phase. To do this, functional models of second generation will be shown in the next step. These models will be characterized mainly by an electric motor with a considerably better torque:mass-moment-of-inertia ratio and the lack of a water jacket, among other modifications. The rotor used will be a plated rotor to obtain an efficiency increase. These measures will improve the eBooster charging system dynamically and reduce the energy consumption. An additional, important milestone will be reached due to its more compact design.

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