

Design and Characterization of an E-booster Driven by an High Speed Brushless DC Motor

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ABSTRACT

Engine downsizing has become one of the main strategies to reduce CO₂ emission. Turbochargers are well-adapted to this purpose but one of their biggest drawbacks is the turbo-lag which reduces the driving comfort especially during acceleration. Electrically driven compressors also known as E-compressor or E-booster could be a well-adapted solution to boost the engine intake pressure in order to reduce the turbo-lag. Since centrifugal compressors operate at high rotational speeds, high speed electric machines are therefore required. To achieve a significant reduction of the turbo-lag, a very fast response time is needed leading to the development of electric machines able to typically spin from idle to 75kRPM in less than 300ms.

With 20 years of expertise in the development of innovative brushless DC motors for automotive applications, MMT has recently investigated the design of such high power-high rotation speed motors. After first integrated an electric motor into a turbocharger described in [1], MMT has decided to optimize the complete system in collaboration with SwissAuto Wenko AG, a specialist in the design and characterization of advanced charging systems. The initial specification was an overpressure of 1.3 within 300ms, reached by using a 2kW@80kRPMs electric motor. The motor optimization, the mechanical design of the system as well as experimental measurements are presented. Details about the brushless DC motor design will be given as well as compressor maps and transient response behaviors. Results will also show that the transient state performances are better than expected.

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I. INTRODUCTION

For several years, CO₂ emission reduction has become a leitmotiv for automotive industry. One strategy to achieve it is engine downsizing. Engine downsizing consists, as the name suggests, in reducing the cubic capacity of an engine while maintaining its level of performance. Most of the time, this downsizing also provides an efficiency improvement therefore a CO₂ emission reduction. One well-known technology to achieve this downsizing is turbocharging which works best at middle and high speed (engine rotation speed) but not at idle speed. We all have experienced it, when we step on the gas pedal when the car is stopped or at low speed, it seems that the car doesn't want to rev up. This phenomenon, called turbo-lag, is due to the fact that turbochargers do not have enough energy coming from the engine exhaust gas to accelerate. Several solutions exist to compensate this turbo-lag; most of them are based on the same principle: by increasing the intake pressure of a turbocharger in order to decrease the acceleration time of its compressor wheel. We can also mention for example, the

two-stage turbocharger, the mechanical supercharger and the electric supercharger. The electric supercharger also called e-booster is the subject of this paper. This type of system is based on the coupling of a compressor and an electrical machine. Since two different types of compressor exist (in the automotive industry): centrifugal and roots type; two different types of electrical machines are needed. Roots type superchargers rotate at "low rotational speed", typically lower than 25kRPM where centrifugal compressors spin around 100kRPM.

This paper focuses on the optimization of an e-booster using a centrifugal compressor coupled with a high speed electrical machine. This work was done in collaboration with the Swiss company SWISSAUTO WENKO AG, specialist in the design and characterization of advanced charging systems. First, section II introduces the selected machine and the MMT high speed technology chosen. Then section III exposes the initial choices made in terms of power, size, etc. Section IV gives an overview of the different models used to characterize the system. The optimization method as well as

some results is described in section V. Some photos, illustrations and measurements of the prototype are shown in section VI. Finally, a conclusion is given as well as the next step for the future research on this topic.

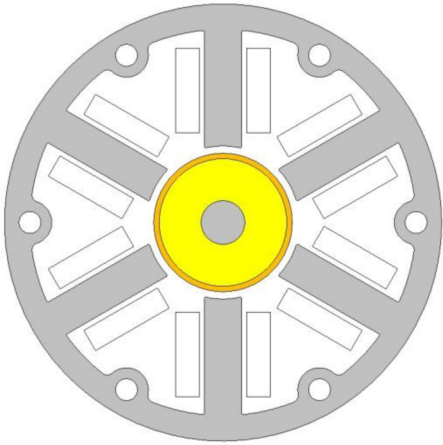


Figure 1. Example of a typical MM132 structure.

II. ELECTRICAL MACHINE SELECTION

Permanent magnet brushless machines are well-adapted to high speed requirements. Their high power density allows them to provide a high efficiency in a small volume. This is the reason why they are increasingly demanded on the market [1]. These machines could be split into two different categories slotted and slotless. The slotless configuration offers less iron-losses [2] but usually develop less power density than the slotted one. That's why MMT has chosen a slotted design for its high speed technology. This patented technology called MM132 is based on a P pole pair magnet and a 3xP teeth stator. Most of the time, 2 pole pairs and 6 teeth structure is used. The cross section of such a machine is illustrated in Figure 1. As all the MMT BLDC designs, the MM132 design has straight teeth allowing to wind the bobbins offline and then to slide them onto the stator making this configuration well suited for automated mass production. This MM132 technology also features a sinusoidal flux induction in the airgap to minimize the iron losses.

III. INITIAL CHOICES

The initial goal of this project was to build an e-booster capable of reaching an overpressure of 1.3 within 300ms. Indeed, this specification with a sufficient flow rate allows a great improvement of the transient behavior of a turbocharger. To reach this target, it has been decided to set the motor power and speed to respectively 2kW and 80kRPM.

Following this, SWISSAUTO recommended a compressor able to meet all of these requirements. This compressor is originally used on a 2L diesel engine. In the meantime, MMT started the optimization process to find the

best structure able to accelerate the compressor up to 80kRPM within 300ms.

Table 1. System main specifications

Acceleration time (0 to 80kRPM)	300 ms
Nominal speed	80 kRPM
Nominal output power	2 kW
Power supply voltage	48 V
Peak current	170 A

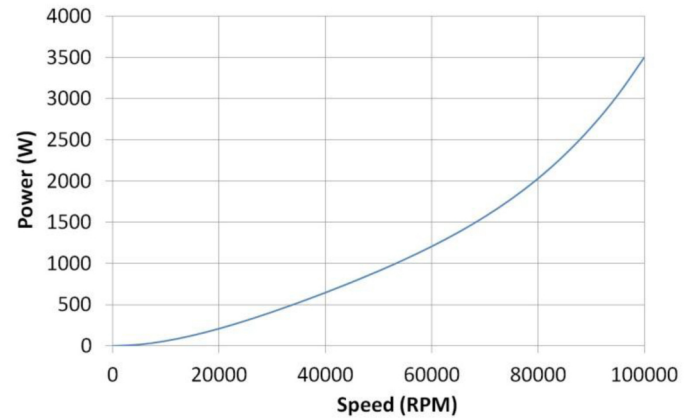


Figure 2. Compressor load power

IV. ANALYTICAL MODELS

Before proceeding with the optimization process, some models are initially needed. They are described in this section.

a. Specifications

A summary of the motor specifications is given in Table 1.

b. Compressor and Hydrodynamic Bearing

In order to be able to calculate the acceleration, some parameters on this system need to be assessed first. First one, the power load due to the compressor wheel (assuming the worst case in terms of load, meaning the inlet of the compressor is nearly fully opened). This load curve $P_{\text{compressor}}$ can be seen in Figure 2. The inertia $J_{\text{compressor}}$ of the compressor wheel is $5.5 \times 10^{-6} \text{ kg.m}^2$. The load power due to hydrodynamic bearing is far from being negligible. The losses of such a bearing have been measured during a previous study [3]. Figure 3 is representing the power P_{hydro} lost in this type of bearing.