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 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.
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.

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>
<thead>
<tr>
<th>Table 1. System main specifications</th>
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</thead>
<tbody>
<tr>
<td>Acceleration time (0 to 80kRPM)</td>
</tr>
<tr>
<td>Nominal speed</td>
</tr>
<tr>
<td>Nominal output power</td>
</tr>
<tr>
<td>Power supply voltage</td>
</tr>
<tr>
<td>Peak current</td>
</tr>
</tbody>
</table>

Figure 1. Example of a typical MM132 structure.

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 $5.5 \times 10^{-6}$ 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 $P_{\text{hydro}}$ lost in this type of bearing.
All these parameters are sufficient to characterize the external load applied to the motor and allow the dynamic calculation of the system.

c. Rotor Mechanical Model

Due to the high mechanical stress resulting from the centrifugal force, a retaining sleeve must be added onto the magnet to ensure its integrity. As far as the sleeve material is concerned, 3 materials could be considered: titanium, Inconel and carbon fiber. Titanium has finally been selected for its easy machining capability for prototyping. The sleeve thickness is determined using a two layer model (magnet and sleeve). The mechanical stresses ($\sigma_r$ and $\sigma_\theta$) are calculated using the equilibrium equation:

$$\text{div} \bar{\sigma} + \bar{F} = 0$$

(1)

with $\bar{\sigma}$ being the stress tensor and $\bar{F}$ the force density.

Using the different symmetry, this equation can be simplified:

$$\frac{\partial \sigma_r}{\partial r} + \frac{\sigma_r - \sigma_\theta}{r} + Fr = 0$$

(2)

with ($\sigma_r$, $\sigma_\theta$) being the mechanical stresses and $Fr$ the radial force density. The development of this equation can be found in the article [4] and resolving this equation allows us to plot the curve Figure 4 representing the minimum rotor sleeve thickness to withstand the centrifugal force at 100kRPM.

Using the equation of the sleeve thickness versus the magnet diameter, it was possible to obtain the inertia model $J_{\text{rotor}}$ of the rotor which links the inertia of the rotor to the magnet diameter and the magnet length. This relation is represented in Figure 5. The aluminum compressor wheel inertia as well as the 6mm bearing axle have been taken into account into this calculation.

d. Motor Model

MMT has developed an analytical tool that allows to quickly calculate the 3 main parameters of the motor (torque constant, electric resistance and inductance). This computation is done using an excel sheet and is based on the structural definition of the MM132 technology (see section II). This software also provides additional parameter such as the mean induction in the stator, the magnet mass, the copper mass, etc. The stator iron losses $P_{\text{iron}}$ are calculated using equation (3) given in [5]. The stator is made of ArcelorMittal NO20 iron sheet. This material is a high frequency grade steel and $Cp$ has been estimated around 1.25W/kg at 50Hz and 1T during a previous study. Rotor iron losses and windage power losses are neglected since they are assumed to be really low compared to the hydrodynamic losses.

$$P_{\text{iron}} = Cp \cdot m \left( \frac{L}{50} \right)^k \hat{B}^2$$

(3)
with \( C_p \) iron losses coefficient, \( m \) the iron mass, \( f \) the induction frequency and \( B \) the stator mean induction.

e. Acceleration Model

This calculation is based on Newton's second law (4). This equation can be expressed (5) with \( T_{em} \) being the electromagnetic torque of the motor

\[
\frac{d\omega}{dt} = \sum \text{Torque}
\]

(4)

\[
(f + j_{\text{compressor}}) \frac{d\omega}{dt} = T_{em}(\omega) - \frac{P_{\text{compressor}}}{\omega} - \frac{P_{\text{iron}}}{\omega} - \frac{P_{\text{hydro}}}{\omega}
\]

(5)

V. OPTIMIZATION METHOD AND RESULTS

This optimization was a 2-step optimization: first step is the calculation of the acceleration time, the energy required to accelerate and the losses at the rated speed of 80kRPM. These computations were done for each simulated motor. Table 2 resumes the main parameters of the motor and the boundary constraints used for the optimization process as well as the step size used for each parameter. As seen in the previous section, models are analytical providing fast and accurate calculations. The total number of iteration (or simulated motor) is approximately 10000.

Table 2. Optimization boundary constraints

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Minimum value</th>
<th>Maximum value</th>
<th>Step size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor diameter</td>
<td>55 mm</td>
<td>62.5 mm</td>
<td>2.5 mm</td>
</tr>
<tr>
<td>Magnet diameter</td>
<td>15 mm</td>
<td>23 mm</td>
<td>1 mm</td>
</tr>
<tr>
<td>Airgap</td>
<td>1.25 mm</td>
<td>2.25 mm</td>
<td>0.25 mm</td>
</tr>
<tr>
<td>Magnet thickness</td>
<td>3 mm</td>
<td>5 mm</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Magnet length</td>
<td>10 mm</td>
<td>30 mm</td>
<td>2 mm</td>
</tr>
</tbody>
</table>

To post-process these results, the self-organizing maps (SOMs) have been used. These are a type of artificial neural network useful for visualizing low-dimensional views of high-dimensional data. SOMs computations were done using MATLAB and the public SOM TOOLBOX [http://www.cis.hut.fi/somtoolbox/]. SOMs are not typical 2D function plots in the sense that there is no up, down, left and right, nor x or y axes. For instance if we were to make the SOM again, even if we use the same settings, where each group of neuron or node up could be different due to randomization in the organization process. Figure 6 shows the results of the optimization process using SOMs/KOHONEN maps. To read those maps, it has to be understood that the spatial location of an output “node or neuron” in these 8 maps corresponds to the exact same calculated solution.

These SOMs maps allow us to make the best choice in terms of compromise between energy, acceleration time and losses. These maps show us that if the optimization target is the acceleration time, the magnet diameter and the motor diameter should be medium, the airgap should be small (relative to the data set defined in Table 2). On the contrary, the magnet thickness and the magnet length should be large and long. The result of the analysis of these maps is the Table 3 containing all the typical parameters of the prototyped motor. The magnet used for this prototype is a grade 28 Samarium-Cobalt magnet (minimum remanence equal to 1.03T).

Table 3. Prototype main dimensions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor diameter</td>
<td>60 mm</td>
</tr>
<tr>
<td>Magnet diameter</td>
<td>18 mm</td>
</tr>
<tr>
<td>Magnet length</td>
<td>25 mm</td>
</tr>
<tr>
<td>Magnet thickness</td>
<td>5 mm</td>
</tr>
<tr>
<td>Airgap</td>
<td>1.25 mm</td>
</tr>
<tr>
<td>Magnet mass</td>
<td>42 g</td>
</tr>
<tr>
<td>Magnet remanence</td>
<td>1.03T</td>
</tr>
</tbody>
</table>

VI. PROTOTYPE AND MEASUREMENTS

Figure 7, Figure 8 show two overviews of the complete system (electronics, electric motor and compressor). The electric motor replaces the turbine on a conventional turbocharger (Figure 7). A 48V electronic controller able to withstand 170A peak is mounted directly on the back end of the electric motor to limit the overall electric resistance of the system. The complete system can be seen in Figure 8. Thanks to SWISSAUTO test bench, measurements of the prototype were possible. The E-booster map is represented in Figure 9. Iso-speed curves are plotted for speed going from 40kRPM to 73kRPM. An electronic limitation didn't allow to complete
the measurements at 80krpm however one measurement was made at this speed reaching an overpressure of 1.32 (initial objective of this project). Different transient behaviors are shown corresponding to different openings made in a closing cap. Typically these curves correspond to the ones that can be observed during a compressor acceleration starting from different initial engine speed.

This 1.3 overpressure specification is mostly linked to the compressor but our goal to develop a BLDC motor delivering 2kW at 80kRPM has been reached. Figure 10 reports the pressure ratio versus time during the acceleration of the system. Transient curves are plotted and are similar to the ones presented in Figure 9. The pressure rise lasts almost one second so clearly more than 0.3s. This is mostly due to the volume of the bench tubing (approximately 3L) to be filled during these transients and this explains why the time required for the pressure to be established is increased. We can assume that this time could be decreased on a real engine as the volume to be filled will be lower. The blue solid line represents the speed of the rotor versus time. The difference between the rotor speed and the tubing pressure is obvious. The acceleration time is approximately 350ms so the initial specification is almost fulfilled on the electric motor side.

**Figure 7. Motor & compressor assembly**

**Figure 8. Global system overview**

**Figure 9. E-booster mapping**

**Figure 10. Pressure versus time evolution & rotor rotation speed**

**VII. CONCLUSION**

The design of a high speed electric motor dedicated to operate under transient behavior is complex. Moreover in this study, a lot of numerous tasks had to be done to obtain an operational prototype. The motor had to be integrated on a compressor with a cooling system and an integrated electronic controller had to be developed and built. In this paper, the optimization process was detailed. As a data post-processing method, SOMs are powerful and greatly help in the selection of a solution (not only the optimal solution but also an intermediate solution that might be the best compromise).

These calculations that involved multiple physical models (mechanic, electromagnetic) were successful and the E-booster measurements done are in agreement with our initial
objectives. Additional work still needs to be done to assess the thermal behavior in continuous operation as well as the impact of such a system on a real engine.

REFERENCES

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DEFINITIONS/ABBREVIATIONS
BLDC - Brushless direct current
Cp - Iron losses coefficient(in W/kg) for a given frequency and induction
SOMs - Self-organizing maps