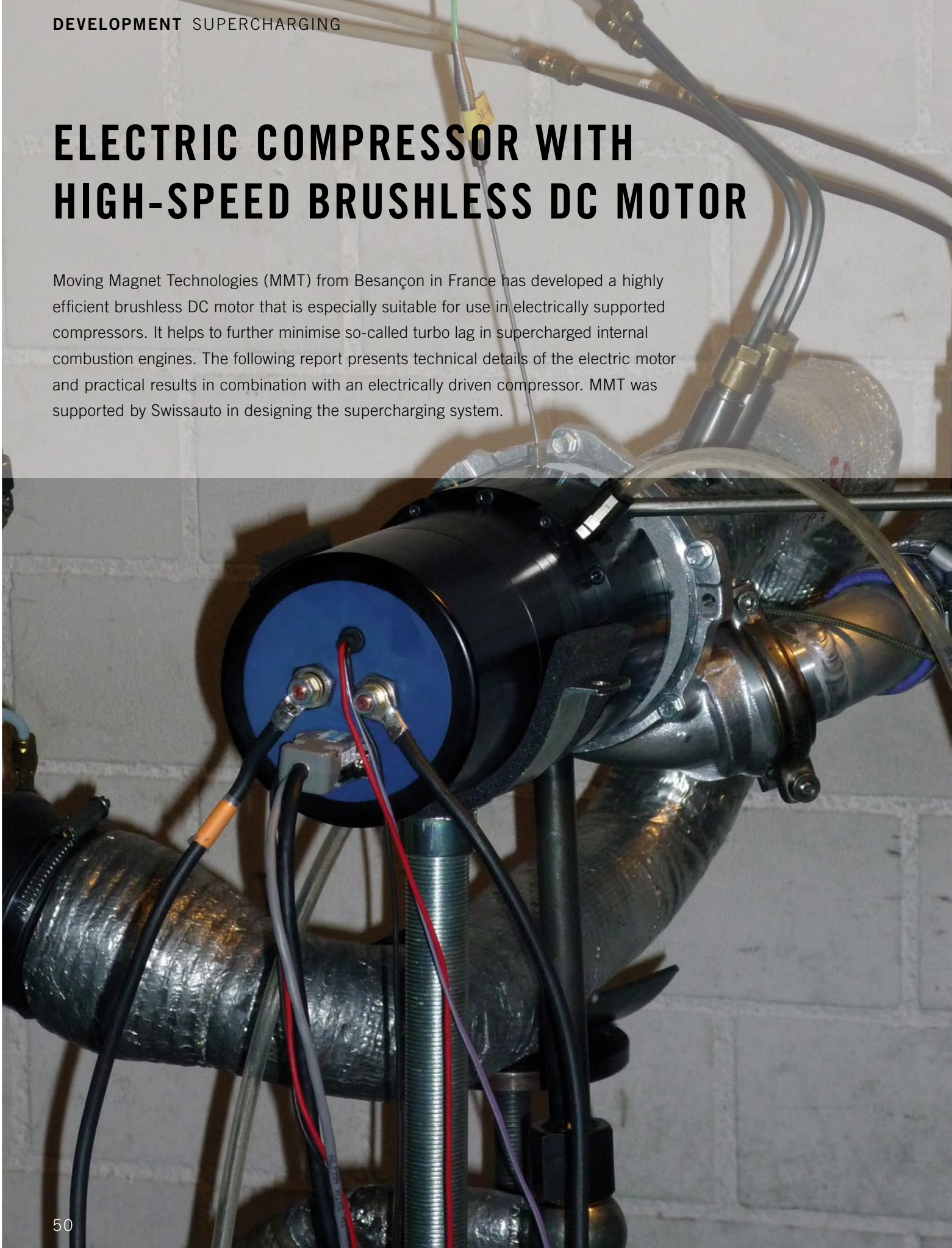


ELECTRIC COMPRESSOR WITH HIGH-SPEED BRUSHLESS DC MOTOR

Moving Magnet Technologies (MMT) from Besançon in France has developed a highly efficient brushless DC motor that is especially suitable for use in electrically supported compressors. It helps to further minimise so-called turbo lag in supercharged internal combustion engines. The following report presents technical details of the electric motor and practical results in combination with an electrically driven compressor. MMT was supported by Swissauto in designing the supercharging system.



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OBJECTIVE TARGET

Electrically driven compressors or turbochargers are one potential area of application for high-speed electric machines. In this particular case, the objective was to increase the limited transient boost pressure attainable by modern turbochargers during vehicle acceleration without having to compromise on the positive characteristics of this turbocharging technology [1]. Due to MMT's long experience in the development of brushless permanent-magnet motors and the simultaneous aptitude of such drive units for both high rotational speeds and high power densities, this technology can be used to drive a radial compressor. MMT, a subsidiary of Swiss company Sonceboz SA, then investigated integration options for this type of motor into

an automotive compressor for the first time [2]. However, they were only able to take basic measurements in their own laboratory owing to the need for more specific equipment in order to accurately simulate the overall system (including measurement of mass flow and compression ratio). In addition to this, the motor was not ideally suited to the type of compressor wheel in use.

In order to attain more realistic results, MMT decided to collaborate with Swissauto Wenko AG. The following steps were taken as part of this collaboration:

- : select a suitable compressor wheel of the type used in batch production and define the required compression ratio and acceleration rates in line with the performance levels of the MMT electric motor
- : development of the magnetic design of the motor and the mechanical design of the overall system, including integrated power electronics
- : creation of the motor prototype and electronics as well as validation of their basic performance levels
- : construction, including the compressor wheel, and testing of the overall system at Swissauto's test bench
- : validation of MMT's BLDC (brushless DC) motor technology and its decisive contribution to the project.

CHOOSING THE COMPRESSOR AND REFERENCE VALUES

Although the range of speeds that can be achieved by MMT-specific motor technologies is actually much higher (more than 200,000 rpm in the case of some developments), the intention here was to take advantage of the results from MMT's initial experiments involving an e-booster [2] where the motor output was 2 kW at 80,000 rpm. For this reason, the first step in the collaborative work with Swissauto was to specify a compressor wheel that could be taken from an existing turbocharger and would, therefore, provide several reference values for the compression ratio and acceleration time. This was the basis for selecting a Garrett compressor specification, which is used in batch production and offers a wheel diameter of 52 mm. The aim here was to produce a compression ratio of 1.3 over an acceleration time of 300 ms using the maximum output and rotational speed supplied by the electric motor. The motor

performance levels were defined at a mechanical output of 2 kW and 80,000 rpm. A supply voltage of 48 V was selected.

BRUSHLESS MOTOR TECHNOLOGY

Over the last 20 years, MMT has managed to fine-tune the electric motors it develops to create structures that not only offer excellent performance, but are also compatible with batch production methods. This work has allowed it to develop several families of motors based on a vast range of design guidelines [3, 4] as well as a significant level of expertise.

MMT's designs usually contain five pole pairs. This allows higher torques to be generated at low speeds, although it is not compatible with higher speeds (typically >20,000 rpm) due to the associated high retroactive generator voltage (back EMF) and electrical frequency.

However, when designing ultra-high-speed drives, the design criteria are to a large extent determined by a need to account for many additional effects (e.g. various magnetic losses, high-speed ventilation technology, friction loss and even the mechanical integrity of the rotor). MMT's major challenge was therefore to develop a magnetic design that was adapted for the requirements of high speeds while remaining highly compatible with conventional large-batch industrialisation processes.

Both in general and for the reasons referred to above, high-speed BLDC motors run using a single-pole-pair magnet, although a two-pole-pair configuration can also be a good compromise. The solution [5] that is instrumental in this case is based on a permanent-magnet drive that includes a six-toothed stator and a rotor with two pole pairs. The overall operating principle is shown in ❶.

The stator is characterised by teeth with a narrow, straight profile, one of the key features of MMT technologies. This design means that the coil windings can be wound automatically "off line", then picked up later and placed on the teeth. This structure can function with six or just three windings, but six are recommended for the stringent performance requirements associated with high-speed drives of this type. The rotor primarily consists of a two-pole-pair magnet, designed either as a ring or as a structure made from formed magnet segments.

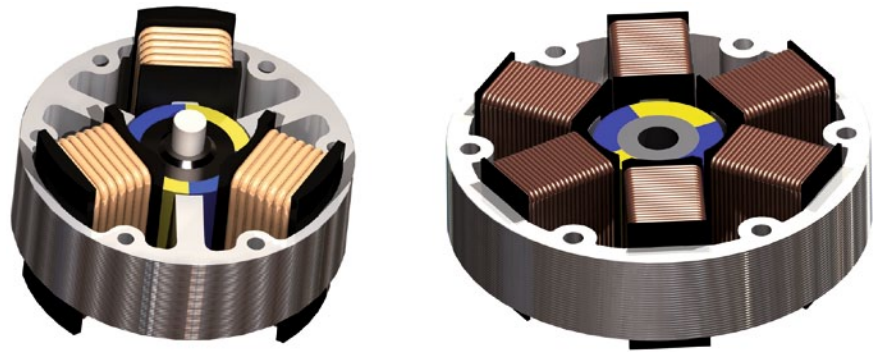
DEVELOPMENT SUPERCHARGING

Another important feature of this kind of motor is its extremely low cogging torque. The cogging torque (no-current torque) is characterised by several periods of torque fluctuation over an electric cycle and actually exhibits losses that become relevant at high speed. To compensate for this whilst also incorporating narrow teeth and large spaces between them, the proposed solution centres around a rotor design that results in sinusoidal flux alteration in the air gap (either the permanent-magnet ring demonstrates sinusoidal magnetisation or the magnet segments, which usually demonstrate unidirectional magnetisation, are shaped accordingly). The stator teeth are embossed slightly to compensate for residual harmonics, as the magnet itself and the magnetisation will never be able to do this sufficiently.

MAGNETIC AND ELECTROMAGNETIC DESIGN

Starting from the performance levels specified, the calculations relating to the magnetic circuit of the motor are made on the basis of an iterative design process. As part of this, all relevant loss factors (magnetic, mechanical, aerodynamic) and the mechanical limits of the rotor must be taken into account. A safety sleeve is used to safeguard the mechanical integrity of the rotor.

Once this first design stage is complete, attention must be turned to the integration of the motor with the compressor. The supporting system is a fundamental



❶ Three or six-coil BLDC motor structure

element of all high-speed drives. For practical reasons, the ability to use the turbocharger's existing hydrodynamic bearings was advantageous in designing an initial test model in this case. Additionally, a water cooling jacket was placed around the motor.

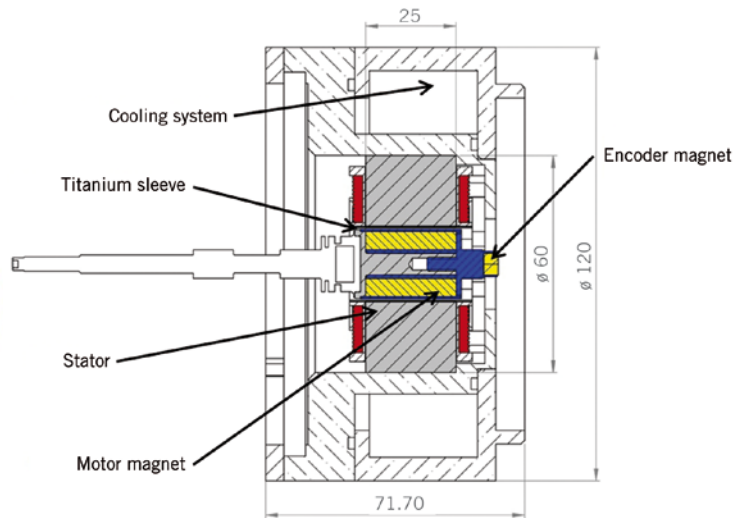
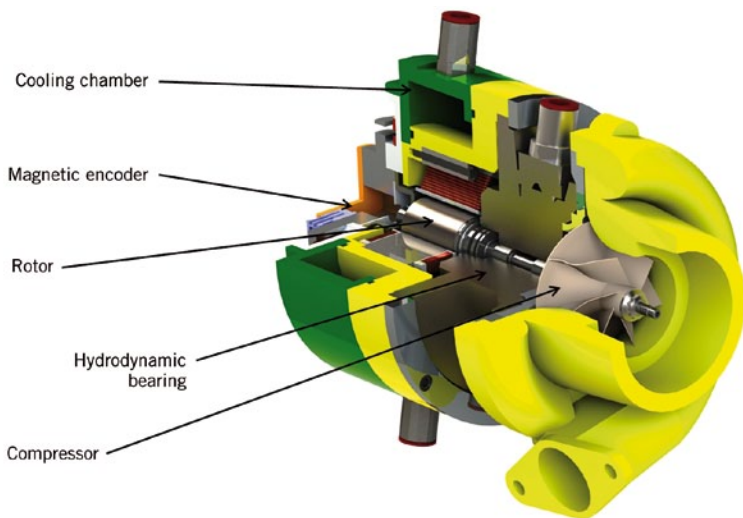
Another challenge of this development project was to integrate a complete power electronics system into the rear of the motor, making it possible to operate the motor separately as well as reducing power dissipation via cables to the greatest extent possible. This electronic control system, based on MOSFET modules, is capable of supplying more than 100 A at up to 48 V. To control the motor, a sensor was also required and a magnetic encoder was placed on the hollow rotor shaft. ❷ shows the motor integrated into the compressor, ❸ shows the complete structure. After assembly and validation of the basic performance levels of the

motor and power electronics, it was time to transfer the system to the Swissauto test bench.

TEST BENCH AND MEASUREMENT RESULTS

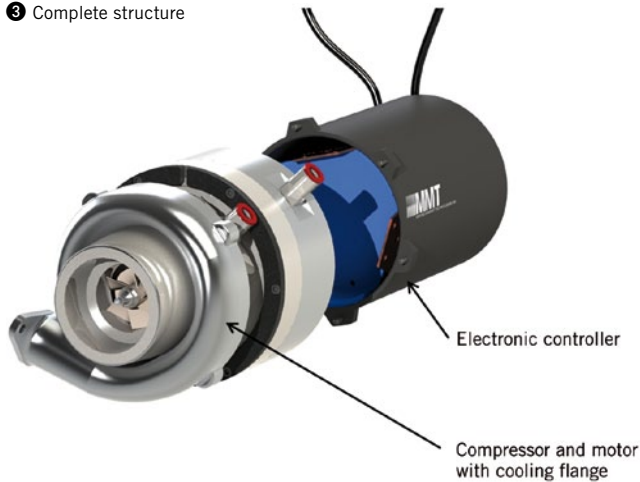
Swissauto specialises in the development and production of advanced turbocharging systems and therefore has suitable test equipment at its disposal. ❹ shows the compressor on the test bench. As shown in ❺, the test results clearly point out that it is possible to attain the target compression ratio at a rotational speed of approximately 80,000 rpm, with the expected acceleration time. The red lines correspond to the iso speed curves, while the blue line has been able to reach the compression ratio of 1.32 by pushing the electronic control unit to the limits of its performance.

This compressor characteristic diagram also plots transient run-ups. Each of



❷ Electric motor as 3D CAD view (left) and cross section (right) (dimensions in mm)

3 Complete structure



4 The compressor as set up on the test bench

these relates to acceleration from 0 to the maximum rotational speed that can be represented at the maximum output producible by the electric machine. In order to recreate the different “swallowing” effects that could be produced by a potential turbocharged combustion engine, appropriately dimensioned apertures were included on the delivery side of the compressor. This allowed the response of a turbocharged combustion engine to typical step change in load to be simulated. For example, the green run-up curve in 5 corresponds to a step change in load where the target combustion engine is running at a very low rotational speed, while the yellow curve corresponds to a

load connection around the torque vertex of the combustion engine.

CONCLUSION

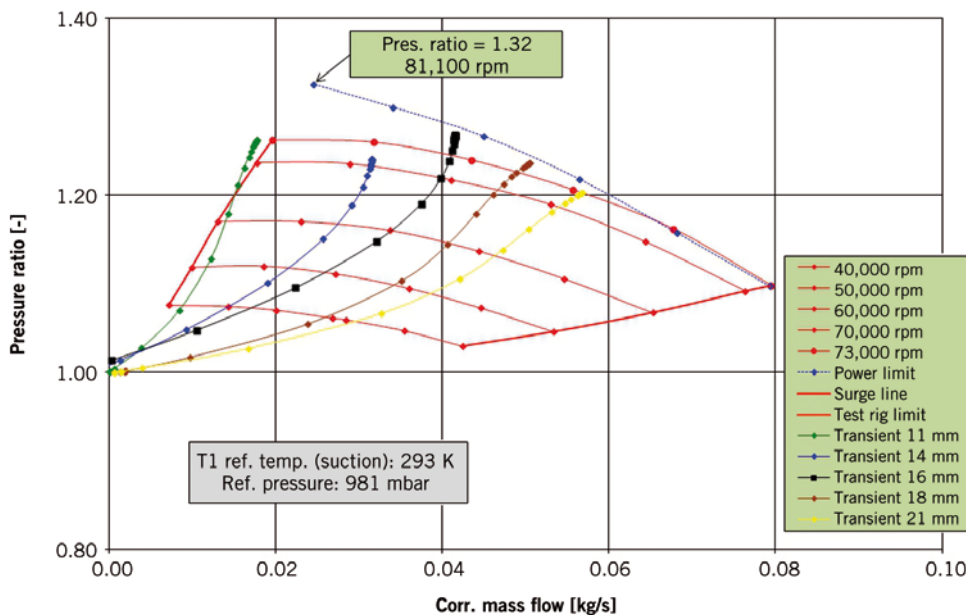
MMT develops high-speed motors, concentrating not only on optimum designs that take all the relevant physical parameters into account, but also on ensuring that this design can later be produced in large batches. This article has outlined a specific application of an MMT motor technology in an electric compressor and provided evidence of its ability to make a relevant improvement to transient boost pressure buildup. MMT’s competence in working with electronic control systems

and Swissauto’s expertise in the design and production of compressors have significantly contributed to this.

A further stage of development for this specific prototype will be to test it in a combustion engine in order to directly evaluate the advantages that the electric compressor brings to motor performance levels. Furthermore, MMT is currently involved in various projects associated with electrically assisted compressors, turbochargers and high-speed generators with mechanical outputs of a few kilowatts and rotational speeds ranging from tens of thousands to more than 200,000 rpm.

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- [3] European patent EP 0949747
- [4] US patent US 8,102,093
- [5] PCT patent Application WO 2010/130894



5 Compressor characteristics: constant speed and transient run-ups

THANKS

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