# Design of electrified turbomachinery for use in modern industrial hybrid powertrains

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**Abstract.** Whilst the automotive industry has made progress with electrified turbomachinery at the passenger vehicle scale, progress has been slower for heavy duty, on and off-highway, and industrial scale engines. But, the numbers of these engines, and their contribution to carbon emissions and general pollution, are still significant.
Through combining high speed electrical machines with turbocharger components to create electrified turbomachinery, it is possible for these users to gain responsiveness, reduce engine start times and reduce emissions. By recovering waste exhaust energy, the electrical power generated can be used to feed hybrid system batteries and motors leading to beneficial reductions in specific fuel consumption, $NO_x$ and $CO_2$ emissions. This paper will explore the development of two products that leverage this technology, the electric compressor and electric turbocharger.
**Keywords:** Electric compressor, turbocharger, waste heat recovery, electric boosting

## 1 Introduction

The rise of electrification is enabling a shift away from fossil fuels – at least at the point of use. Whilst key industries work towards this, they will continue to need the internal combustion engine and the fuels they burn in the near term. The continuing need to increase drivability whilst reducing emissions is enabling emerging technology to achieve these aims.

As regulations continue to push internal combustion engines to have both lower emissions and greater efficiency, the need to optimise the engine further at key running points increases. Many existing applications use a turbocharger, where the energy contained within exhaust gases is extracted via a turbine connected to a compressor to improve the thermal efficiency of an engine. Aerodynamic matching of the exhaust driven turbocharger turbine involves a compromise between transient response at low load and power targets at high load. Due to this trade off, the drive for ultimate efficiency at certain running points can in turn adversely impact running points at other engine running conditions, which is undesirable both from a driver satisfaction and an engine emissions viewpoint. One of the possible solutions to this problem is to use a separate electrical device to provide additional boost or an integrated motor generator within the turbocharger to accelerate turbocharger response times as well as harvesting electrical energy in certain engine modes [1]. These devices need significant power to operate, which can be seen as a barrier to entry due to the cost of a high voltage system. The trend for increased voltage of hybrid systems can be seen as an enabler to assist these systems to operate efficiently as the electrical losses and DC current requirements reduce with the increased voltage.

Fig. 1 summarizes the different concepts of electrical turbomachines that can be integrated to hybrid systems.

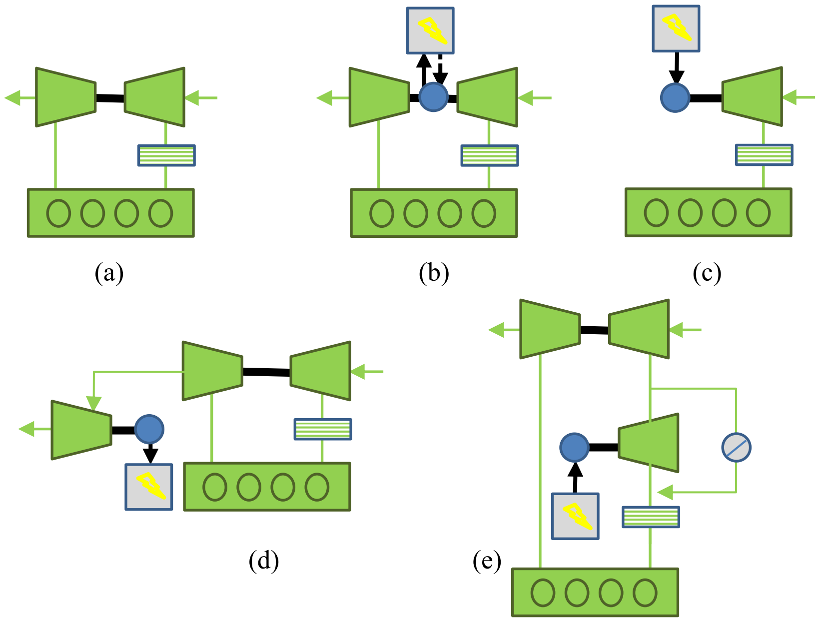


**Fig. 1.** Schematic layout of electric turbomachines: (a) Non-electrified turbocharger, (b) e-turbocharger, (c) e-compressor, (d) turbocharger with electric turbo compound (ETC), (e) turbocharger coupled with e-compressor

The electrical compressor (c), (e) can improve transient response of the engine by providing air on demand, whilst also potentially improving emissions by being able to control engine combustion via the air fuel ratio independently of engine/turbocharger speed [2]. An electrical turbocharger (b) can additionally harvest waste power at certain engine operating modes which can then be used for boosting later on or powering other engine ancillaries, helping to further reduce fuel consumption [3].

Lee et al [4] or Alshammari et al [5] summarise comprehensive comparisons of different electric turbomachines topologies characteristics.

This paper focuses on the electrical machine and power electronic development for an electric compressor and turbocharger, describing the key requirements and challenges associated with high speed machine design.

## 2 Commercial Applications

Passenger cars usually use electric turbomachines to gain performance, such as reducing the acceleration time from 0 to 60 mph with help of an electric compressor. On the other hand, commercial vehicles take advantage of electric turbomachines for reducing tailpipe emissions and reducing overall fuel usage. This is primarily done by matching the air-handling architecture to run at its most efficient points and using the compressor electric component of the turbocharger to mitigate any induced driveability problems. The introduction of these electric turbomachines is enabled by higher power electrical systems being introduced to power modern hybrid powertrains. The hybridisation improves the efficiency of the engine boosting system and its transient responses, while reducing fuel consumption and emissions, together with optimising low load operation and recovering the energy usually wasted during deceleration phases. In order to improve the efficiency of the engine, this paper is focused mainly on the development of two technologies: the electric compressor and the electric turbocharger.

### 2.1 Electric Compressors

Placed in series of the regular turbocharger, the electric compressor supplements the conventional turbocharging system by improving boost pressure and transient engine response at low engine speeds, eliminating turbo lag. The electric compressor has high potential to reduce emissions and improves fuel economy, while allowing further engine downsizing.

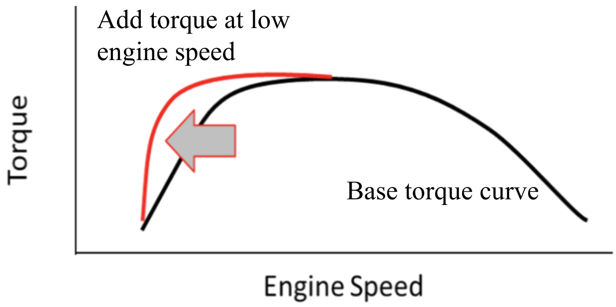


**Fig. 2.** e-compressor benefit on engine transient response

**Key Requirements**

The primary requirements are the aerodynamic performance of the compressor, the boost pressure and flow rates that are necessary. This informs the performance requirements, while the operating environment requirements further characterise the machine within this heavy-duty vehicle sector. In the case of the electric compressor, multiple frame sizes are considered to allow greater applicability of a base electrical machine design.

**Table 1.** Electric compressor requirements.

| | **Requirement** | **Value** |
|---|---|---|
| Performance | 'Steady State' Operating Speed | 66,000rpm Max |
| | Transient Operating Response | 250 - 450ms from zero to 90% maximum speed |
| Environmental | Operating Life | Min 30,000hrs |
| | System Voltage | 48V |
| | Power (Input) | 10-15kWe |
| | Max. Ambient Temperature | 150 °C |
| | Cooling System | Water based coolant integrated to the host engine / vehicle coolant system |
| | Coolant Temperature | >100 °C |
| | Lubrication System | Sealed for life bearings |
| | IP Rating | IP69k |

## 2.2 Electric Turbochargers

Equipped with a high speed electric motor, an electrically assisted turbocharger can improve turbocharger performance by adding torque to the turbine shaft or generate electrical energy from the exhaust gas flow. It combines the benefit of the e-compressor with the ability to recover additional energy from the exhaust flow. This allows additional downsizing without losing responsiveness from the engine.

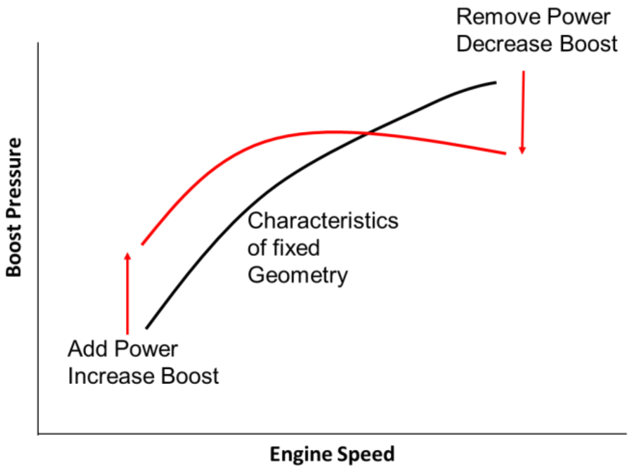


**Fig. 3.** Boost pressure characteristics comparison between e-turbocharger and conventional turbochargers

## Key Requirements

The requirements for the electric turbocharger are similar to those for the electric compressor. In this case, only one frame size is considered. These additions are for regenerating capability and the system is intended for steady state running at different speeds as opposed to a focus on a fast start transient in the case of the electric compressor.

**Table 2.** Electric turbocharger requirements.

| | Requirement | Value |
|---|---|---|
| Performance | Motoring Speeds (Steady State) | Up to 112,000rpm |
| | Generating Speeds | Up to 126,000rpm |
| Environmental | Operating Life | Min. 25,000hrs |
| | System Voltage | 48V |
| | Power (Input) | 10-20kWe |
| | Max. Ambient Temperature | 150 °C |
| | Cooling System | Water based coolant integrated to host engine / vehicle coolant system. |

| | |
|---|---|
| Coolant Temperature | > 100 °C |
| Lubrication System | Oil lubricated bearings |
| IP Rating | IP69k |

# 3 System Development

The following section describes the main design steps undertaken and highlights the key challenges and choices faced in the development of these high speed machines.

## 3.1 Summary of the Design Process

Cummins Turbo Technologies (CTT) and Bowman Power Group (Bowman) have collaborated to develop electrified turbomachinery; specifically, this paper describes the development of an electric compressor and an electric turbocharger.

Bowman has focused on the electrical machine design aspects whilst CTT focused on the turbomachinery and its applications. This combination has allowed targeted and achievable performance requirements to be defined, shown in **Error! Reference source not found.** and **Error! Reference source not found.**.

Typically for high speed electrical machines and their power electronics, the core components are pushed to their limits with respect to thermal (mechanical, power electronics, control), mechanical stress, rotordynamics, and electromagnetics; a balance is required to ensure the optimum solution is produced with respect to cost, size, and performance. This requires a holistic approach to design.

**Fig. 4** illustrates the key design actions, split between preliminary and secondary activities.

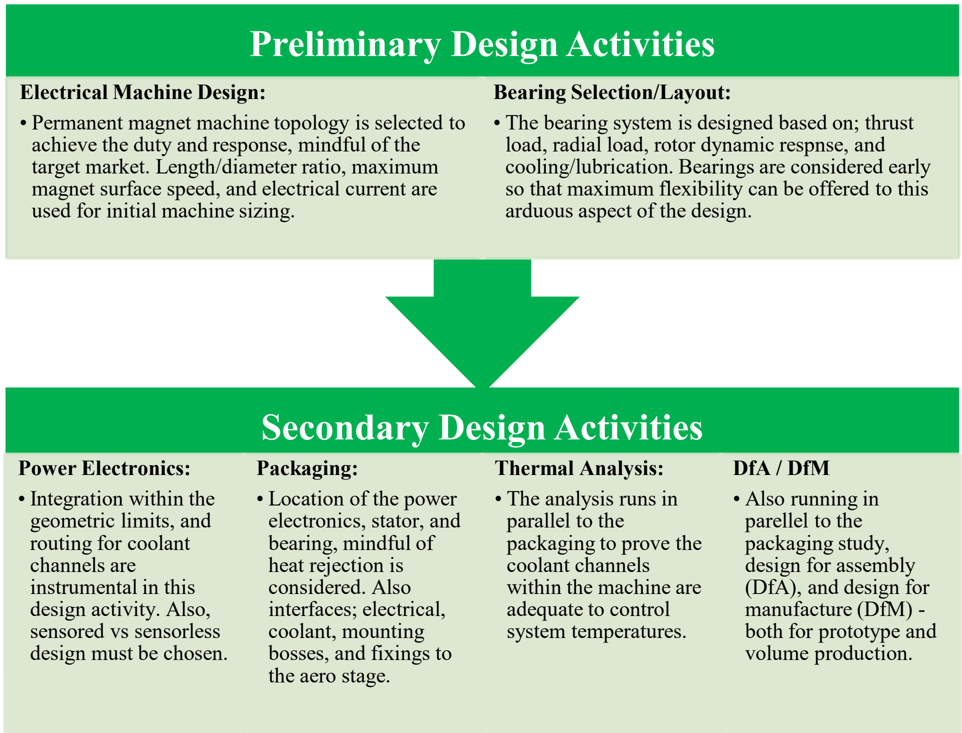


**Fig. 4.** Design activities flow

## 3.2 Key Challenges and Solutions

It is evident from the transient requirements that a key task is to minimise the rotating inertia in order to minimise the power draw from the vehicle power system. The two key component groups contributing to the inertia are the turbomachinery wheels and the electrical machine rotor. The aspect ratio of the electrical machine rotor and therefore its rotating inertia is a key optimisation parameter, where specifically for the electric compressor the design was steered to minimise the magnetic rotor diameter within the bounds of acceptable rotor dynamic behaviour. This results in the turbomachinery typically contributing over 75% of the rotating inertia of the system.

Knowing the rotating inertia and turbomachinery aerodynamic loading allows the current draw from the vehicle power system to be calculated. For heavy duty vehicles with 48V power systems, electric compressors and turbochargers at maximum assist will naturally want to be drawing close to the vehicle power system limits (200 – 500 Amps).

Harmonic losses within high speed machines are an important consideration, the sources of these losses come from the power electronic control strategy and the electrical machine winding. Depending on the power, voltage and speed requirements various options and topologies become more or less applicable as is discussed in the Power Electronics and Control section.

**Bearing Selection & Layout**

Rolling Element Bearings (REBs) provide a low friction, high stiffness solution, offering efficiency benefits to the turbomachinery as well as the electrical machine. REBs in a cartridge bearing mounted between the compressor and turbine wheel are favourable for control of critical factors such as bearing alignment, however for these machines a cartridge approach would require the electric machine to overhang the bearing span. In these cases, it is not possible to achieve the high power requirements with an overhung electric machine due to the rotordynamics and the packaging constraints. Two independent bearings spanning the electrical machine must therefore be used.

The challenge was to achieve a bearing bore of adequate size to manage the thrust load, but also have the speed capability to achieve the required operating points. Larger bearings carry higher loads and permit a stiffer shaft – enabling favourable rotordynamics – but generate more heat than their smaller counterparts and are limited by their attainable speeds.

Where the electric turbocharger made use of an active oil system for bearing cooling and lubrication, permitting oil damping to the bearings, for simplicity of integration and reduced maintenance, the electric compressor uses ‘sealed for life’, solidly mounted bearings. This defines the electric compressor as a sub-critical machine whilst the electric turbocharger has been designed to run super-critical.

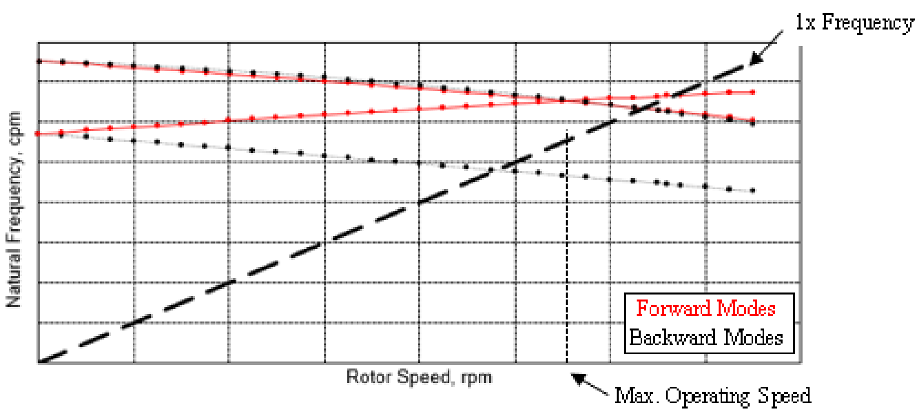


**Fig. 5.** Electric compressor Campbell plot

The critical mode for the electric compressor to run sub-critically is the compressor wheel first forward bending mode. To push this mode beyond the maximum operating speed (with margin), design effort was focused to reduce the rotating and overhung mass, and also tune the bearing span and electric machine length. **Fig. 5** shows the Campbell plot for the electric compressor demonstrating that the design has been successfully controlled to push the forward modes well above the maximum operating speed of the machine. Backward modes will not be excited by machine operation and are therefore not of concern.

**Packaging**

The initial electrical machine sizing work for both machines converged on a suitable length/diameter ratio to achieve – among other things – the acceleration requirements. Beyond this, consideration was given to the power electronics packaging. The chosen layout differed between the electric turbocharger and the electric compressor. The former uses a separate power electronic package, remote from the machine, largely as a result of the temperatures of the application from the turbine aero stage, and packaging constraints. On the latter, the power electronics were fully integrated onto the electric compressor housing. Further discussion on this integration is provided in this section.

The power electronics comprises both power and control PCB, mindful of inter-connectivity and cooling requirements to reject heat from the board's capacitors, transistors and low power components, requiring a heat sink due to the high ambient temperature requirement (150 °C). The layout options explored are shown in **Fig. 6**.

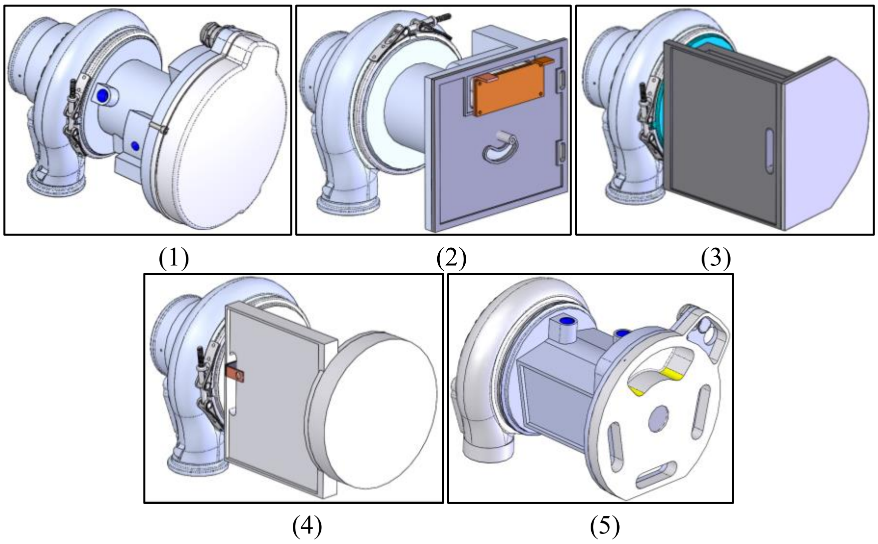


**Fig. 6.** Electric Compressor Packaging Options. (1) Circular PE on the end of the electric compressor. (2) Square PE on the end of the electric compressor. (3) Single power board on the outside of the electric machine, control boards also mounted in the outside. (4) Single power board on the outside of the electric machine, control boards on the end of the electric compressor. (5) Split power boards on the outside of the electric machine, control boards on the end of the electric compressor.

The main question raised by these design options was whether to package the electronics at one end of the machine, or around the body. **Table 3** summarises the main benefits and disadvantages of this key design point.

**Table 3.** Electric compressor packaging trade-off.

| Power Electronics Location | Advantages | Disadvantages |
|---|---|---|
| On the end of the electrical machine. | - Simple stator cable exit to connect to power boards.<br>- Components could be machined. | - Results in a longer overall machine length.<br>- Poor use of available radial package space.<br>- More extensive coolant channels required. |
| Wrapped around the electrical machine. | - Smaller box package.<br>- Reduced machine length.<br>- Reduced maximum diameter.<br>- Dual use of the stator cooling jacket to also cool the transistors.<br>- More usable electronic board area.<br>- Compact design, fewer internal channels so low total mass. | - Need for complex busbars to connect the power boards to the control board.<br>- Higher complexity of housing machining operations – drives a necessity to casting production techniques. |

**Power Electronic Motor Control**

Permanent magnet synchronous motors can be classified in different ways, but if the back-EMF (electromotive force) profiles are considered, we can classify them as brushless direct current (BLDC) motor and permanent magnet synchronous motor (PMSM). This terminology defines the shape of the back-EMF: for BLDC is trapezoidal, for PMSM is sinusoidal.

The table below shows a comparison of the two types of permanent magnet synchronous machine.

**Table 4.** BLDC and PMSM machine

| BLDC | PMSM |
|---|---|
| - Fed with direct currents | - Fed with sinusoidal currents |
| - Trapezoidal back-EMF | - Sinusoidal back-EMF |
| - Stator Flux position commutation each 60° | - Continuous stator flux position variation |
| - Torque ripple at commutations | - No torque ripple at commutations |

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|---|---|
| - Low order current harmonics in the audible range<br>- Higher core losses due to harmonic content<br>- Less switching losses<br>- Control algorithms are relatively simple | - Less harmonics due to sinusoidal excitation<br>- Lower core loss<br>- Higher switching losses<br>- Control algorithms are mathematically intensive |

The control schemes that can be used are mainly 6-Step Switching, Direct Torque Control (DTC) and Field Oriented Control (FOC).

In the table below a comparison between the modes is presented, but it can be said that vector control methods (DTC and FOC) provide a high performance response with quicker torque dynamics in the case of DTC and better steady-state behaviour for FOC.

**Table 5.** Comparison between the different control methods

| **6-step Advantages** | **DTC Advantages** | **FOC Advantages** |
|---|---|---|
| - Cheap hardware<br>- Low frequency switching<br>- Low computational capability required<br>- No need of motor parameters<br>- When in current mode the amplitude of the motor current can be controlled, allowing the motor torque to be regulated | - Minimal torque response time<br>- No PID controller for flux and torque<br>- The step response has no overshoot<br>- No coordinate transformation<br>- | - Good dynamic performance<br>- Great accuracy both in speed and in torque<br>- Full motor torque capability at low speed<br>- Higher efficiency for each operation point in a wide speed range |
| **6-step Disadvantages** | **DTC Disadvantages** | **FOC Disadvantages** |
| - Not an ideal dynamic behaviour<br>- Torque ripples<br>- Low efficiency<br>- Possible vibration<br>- No direct current controls (with voltage source hardware) | - Possible problem during starting<br>- Inherent torque and flux ripples<br>- No direct current controls<br>- High noise level due to the variable switching frequency | - High switching frequency<br>- High computational capability required<br>- Need accurate information on the position |

With consideration of the requirements, FOC control was the chosen strategy for these machines as it has good dynamic performance and low speed torque, albeit this strategy is a compromise between having less current harmonics and core losses in exchange for having higher switching frequency and switching losses. This is specifically important to limit the eddy current heating of the electrical machine rotor as cooling is limited with ‘sealed for life’ bearings. FOC is also able to control directly the current in case the engine control unit (ECU) requests a reduction on the capability of the battery.

One of the most mature methods is the FOC back-EMF estimator, it has good performance in medium and high speed range. The magnitude of the back-EMF voltage is proportional to the speed, when the rotor rotates at low speed the magnitude of the voltage is very small or zero. The challenge is for the electric compressor starting at zero speed or in a low speed region where the voltage is too low to have good position information. This low speed region is expected to be in the range of 10% of the back-EMF. This is not the case for the electric turbocharger where the system will continue to rotate due to the power from the turbine at sufficient speed to provide a good voltage signal to estimate the rotor position.

Both a sensor and sensorless approach can be used to start the machine from zero speed. The sensored approach offers the fastest start-up times, as the position of the rotor is always known. The downside is that it adds further components to the system. The sensorless approach is reliable as there are no sensors to provide false readings but at the expense of slower start up times.

**Fig. 7.** illustrates the delay in reaching the setpoint speed of the sensorless approach compared to the sensored approach, caused by not knowing the position of the rotor. This is mainly due to the fact that at low speed the estimator is not reliable because there is not enough voltage and an open loop control is needed to start the rotation. When a suitable speed is reached the estimator takes control of the rotor position. Different starting conditions have been simulated, considering the rotor at different unknown positions as well at a different low speed point where control is not able to appreciate that the rotor is spinning using the back-EMF when the system is not motoring; this uncertainty adds a variable delay in reaching the target speed that lays in the region of 0.05-0.15s.

Experimental tests will be performed in early 2020 to tune the above methods on the physical machines.

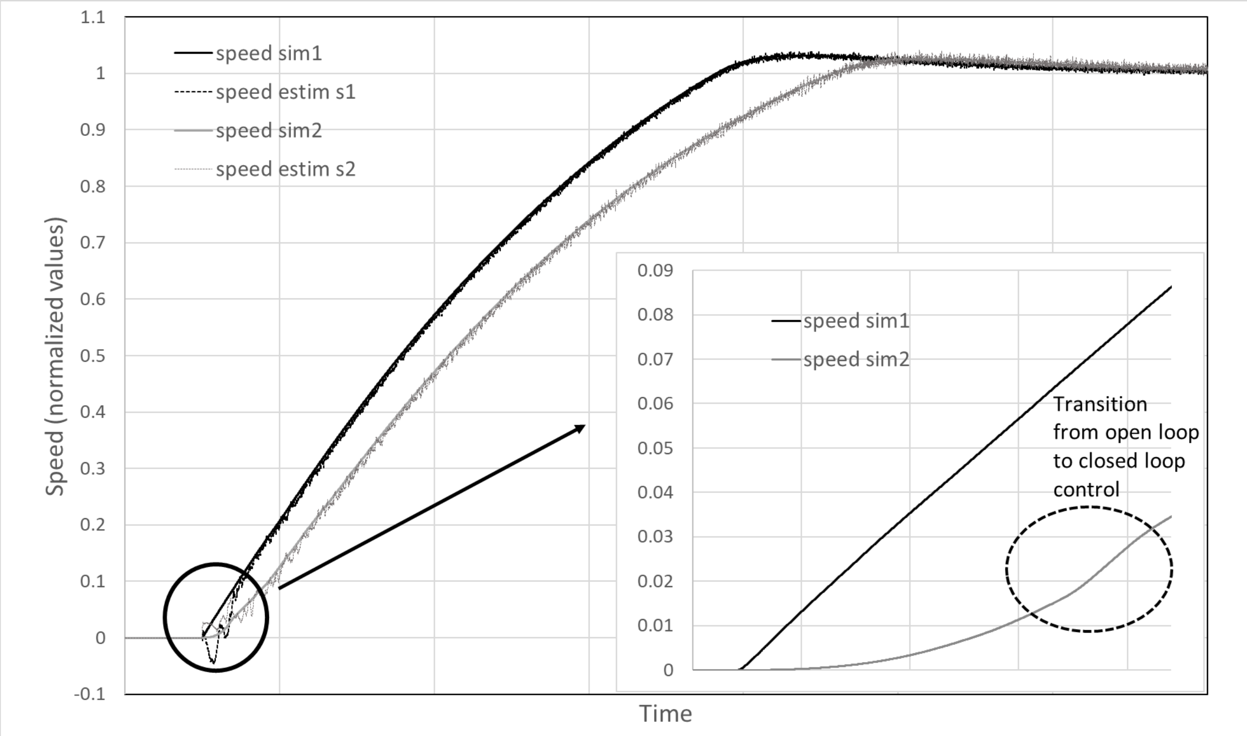


**Fig. 7.** Comparison between the response time of the electric compressor with sensor (simulation1) and sensorless (simulation2) control, with a zoom at starting point where the rotor is at zero speed.

### 3.3 Final Design

**Fig. 8** and **Fig. 9** illustrate the key features of the machines. On **Fig. 8**, note the external locations of the carefully packaged interfaces for power, coolant, and oil. **Fig. 9** shows how the electronics have been integrated to the housing of the electric compressor with appropriate coolant and power cable sites to suit a range of installations.

**Fig. 8.** Electric Turbocharger. Blue: coolant ports, yellow: power connections, orange and green: oil ports

**Fig. 9.** Electric Compressor design option

## 4 Conclusions

The development of electrified turbomachinery has significant challenges associated with their design. Their high-power density means that it is necessary to balance the limits of an increased range of different disciplines, from thermal (mechanical, power electronics, control), mechanical stress, rotordynamics, electromagnetics and from an application perspective, the packaging. From examples of key challenges, it has been demonstrated that these challenges can be overcome, opening the door to the benefits of greater control of the turbomachinery to ultimately improve drivability and reduce emissions.

For an electric compressor, it has been shown that 'sealed for life' bearings can meet the strenuous duty requirements of heavy duty vehicles and can be designed to operate sub-critically, thereby simplifying the overall design. The electrical turbocharger requires a more complex design to meet the requirements as it needs oil fed bearings and will operate super-critically.

For an electric compressor, the use of a sensor has been shown by simulation to achieve the lower targets for acceleration rates from zero to full speed, whilst the sensorless approach is expected to achieve the higher targets with an increase in acceleration time of between 0.05 and 0.15 seconds; an optimised solution may use both approaches. In this instance the electric turbocharger has a simpler requirement as it does not require a zero speed start thereby allowing the sensorless approach to be used exclusively.

For both machines it is necessary to liquid cool the power electronics and electrical machine but at standard vehicle coolant system temperatures of greater than 100 degC.

A prototype electric turbo machine suitable for heavy duty vehicles will be in test during the first half of 2020.

## References

1. Tavcar, G.; Bizjan, F.; Katras, T. Methods for improving transient response of diesel engines—influences of different electrically assisted turbocharging topologies. J. Automob. Eng. 2011, 225, 1167–1185
2. Zhao,D.; Stobart, R.; Mason, B. Optimising the Energy Efficiency and Transient Response of Diesel Engines through an Electric Turbocharger. American Control Conference (ACC), Philadelphia, 2019.
3. Ricardo, M.B.; Apostolos, P.; Yang, M.Y. Overview of boosting options for future downsized engines. Sci.China Technol. Sci. 2011, 54, 318–331.
4. Lee,W.; Schubert, E.; Li, Y.; Li, S.; Bobba, D.; Sarlioglu, B. Overview of Electric Turbocharger and Supercharger for Downsized Internal Combustion Engines. IEEE Trans. Transp. Electrif. 2017, 3, 36–47.
5. Alshammari,M.; Alshammari, F.; Pesyridis, A. Electric Boosting and Energy Recovery System for Engine Downsizing. Energies 12(24):4636, 2019.