Development and Validation of a 2-stage Electric Compressor System to Overcome Turbocharger Lag on High-Speed Internal Combustion Engines

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Abstract:

Bowman eTurbo Systems set about developing a solution which can be easily integrated to high-speed natural gas, biogas, and hydrogen internal combustion engine powered generator sets (gensets) to eradicate turbocharger lag and allow their use in transient applications without negatively impacting the steady state performance of the engine.

This paper details the definition and development of an engine and fuel agnostic, easily retrofitted, oil free, coolant free, 2-stage electric compressor, with a 55kW Power Electronics (PE) control system capable of accelerating the eCompressor from rest to target speed in less than 1 second, to support engines during transient load acceptances.

Validation of the solution on a customer's 20MWe gas peaking site supporting the UK national electricity grid with 10 x 2MWe natural gas gensets is presented. Results show cold engine load ramp rates could be increased by approximately ten times, enabling transient performance only achievable with today's diesel gensets, and much faster response times for the operator's site to meet the increasingly stringent balancing demands of UK national electricity grid resulting from unsteady and intermittent renewable power generation.

Key Words: eCompressor; turbocharger lag; transient

1 Introduction

Over recent decades OEM's have developed and iterated high-speed lean burn spark ignited engine designs to provide the highest possible power densities and efficiencies when running natural gas, biogas and more recently hydrogen. This evolution has led to the implementation of high lambdas with elevated levels of Miller cycling, and the requirement for high efficiency and high boost pressure capable turbocharger systems that are increasingly required to function with lower and lower exhaust gas temperatures.

These requirements on the turbocharger system are typically achieved by matching large frame sized turbochargers with vaned compressor diffusers and turbine nozzle guide vanes to achieve optimal full load engine performance. This results in turbochargers with high thermal mass and inertia, and poor efficiency at low engine loads, leading to significant challenges when trying to increase engine load due to turbocharger lag, which is more exaggerated when the engine is cold.

In 2020, Bowman eTurbo Systems presented a paper at ATK2020 'Electric Turbocharging – A Path to Increased Lean Burn Gas Genset Efficiency Together with Diesel like Transients '[1]. This 1D simulation study looked at the possibility of using different electrified turbocharging solutions to reduce turbocharger lag in modern high-speed engines. Chapter 4.2 looked specifically at different eCompressor layouts, Figure 1, each of which was predicted to decrease the load ramp time of a cold, pre-heated 1MWe lean burn natural gas engine genset from 90seconds to less than 10seconds. Table 1 shows the selection matrix from this paper, highlighting that plumbing an eCompressor to flow air into an engine's exhaust manifold, upstream of the engine turbocharger turbine, offered the best compromise between performance, electric machine size, cost, complexity and retrofitability.

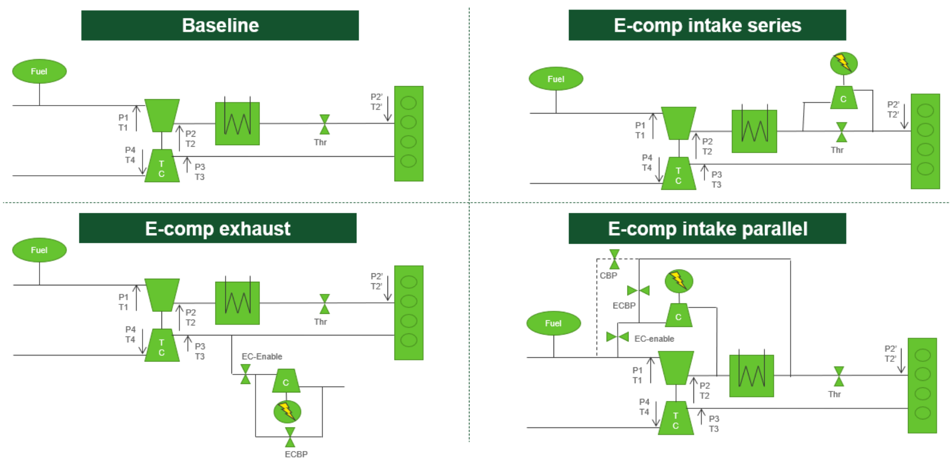

Figure 1: eCompressor layouts investigated on 1MWe gas genset [1]

Table 1: E-Compressor layout selection matrix for 1MWe gas genset [1]

+ / - Indicative relative to each other	E-Comp intake parallel (~4Nm / 30kWe)	E-Comp intake parallel (~20Nm / 100kWe)	E-Comp intake series (~20Nm / 100kWe)	E-Comp exhaust (~3Nm / 20kWe)
Start-up impact	-	-	+	+
Size / Cost	0	-	-	+
Integration complexity	0	0	-	+
Controls complexity	-	-	+	0
Exhaust scavenging potential	-	-	-	+
Applicability to multiple genset platforms	0	0	-	+
Total	**- 3**	**- 4**	**- 2**	**+ 5**

The approach to flow air into the exhaust upstream of an engines turbine stage to accelerate the turbocharger is not novel. As far back as 1964, MAN [5] performed on-engine tests flowing air directly into the turbine housing of marine diesel turbochargers to accelerate the turbocharger during transients, systems were subsequently implemented in the field. More recently Volvo [3] have implemented their "PowerPulse" system to eliminate turbo lag by injecting stored compressed air upstream of the turbocharger turbine. VE Commercial Vehicles Ltd [2] and JCB [4] have similarly used compressed air to inject directly into the exhaust manifold of the engine to reduce turbocharger lag. In all cases, the papers cite the preference to inject air on the exhaust side of the engine upstream of the turbine, rather than on the intake side downstream of the compressor stage. The reason being that, although the intake side air mass can be directly consumed by the cylinders to increase engine torque, it momentarily creates an adverse pressure ratio across the compressor stage which due to the turbocharger compressor surge line, limits the mass of air that can be injected and limits the reduction in turbocharger lag achievable.

With the success of the above compressed air injection systems operating in the field and the conclusions from Bowman eTurbo Systems' 2020 eCompressor simulation study [1], the decision to develop an eCompressor solution (Referred to as StartIQ™ throughout this report) to flow air into the exhaust of high-speed combustion engine gensets was made in 2021.

The three main aims for the StartIQ™ product development were to

- eradicate turbocharger lag for high-speed engine cold starts
- be simple to apply to existing high-speed gensets of any fuel type in the 0.5 to 5.0MWe range
- have no impact on steady state engine efficiency, emissions, or durability

2 Product Definition and Requirements

A power generation customer in the UK operating approximately 500Mwe of gas peaking gensets agreed to trial the technology, with the longer-term goal to roll out the technology to their genset fleet to meet expected future market requirements.

Much of the early focus in defining the StartIQ™ product were based on applying the technology to the customer's specific genset and meeting their requirements.

Customer genset data

- Rating: 2MWe / BMEP 18bar
- Fuelling: Pre-mixed natural gas
- Combustion: High turbulence piston bowl with J-gap spark plug
- Camshaft: Moderate miller cycle
- Turbocharger: Single ABB TPS57
- NOx rating: Sites range from 250 - 500mg/Nm3 @ 5%O2 depending on local legislative requirements

Customer requirements for StartIQ™ system

1. Load ramp from breaker closed to 100% load < 15seconds
2. Power draw from local low voltage 3-phase supply not to exceed that available during the genset load ramp (estimated at 50kW for the short duration operations intended)
3. Easy integration, <1 day downtime for single genset integration
4. Product life = genset life (15 years)
5. Fully unmanned / automated operation
6. Support up to 15 starts per day
7. No detrimental impact on genset emissions control, fuel efficiency or maintenance schedule
8. Cost target as agreed with customer

To design the StartIQ™ system to meet the requirement of a sub 15seconds load ramp, the amount of air required to be flowed into the exhaust manifold needed to be assessed. To do this cold engine starts (where the engine had been shut down for a minimum of 4 hours) were performed using one of the customers gensets. From this data a 1D simulation model of the engine was created and correlated, Figure 2. Figure 3 shows the simulated baseline genset power and predicted load ramps with different air mass flow rates flowed into the exhaust manifold at an assumed compression temperature of 150degC.

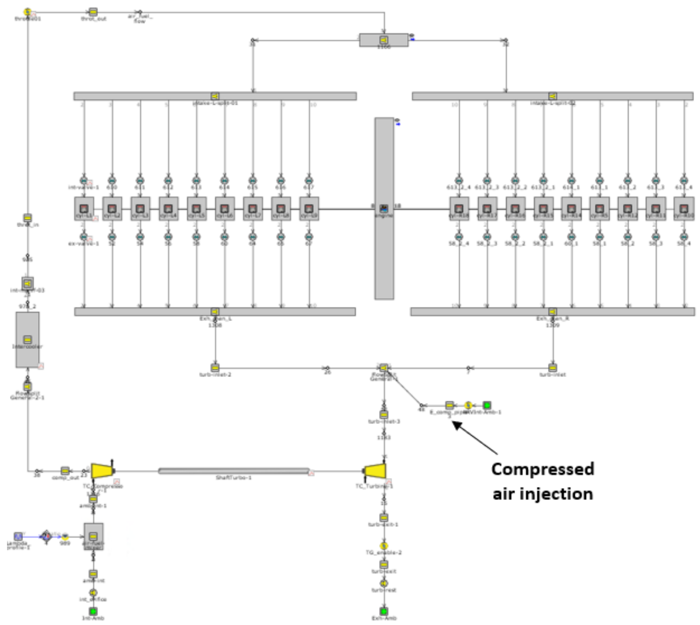

Figure 2: 1D simulation model of customer engine with compressed air injection

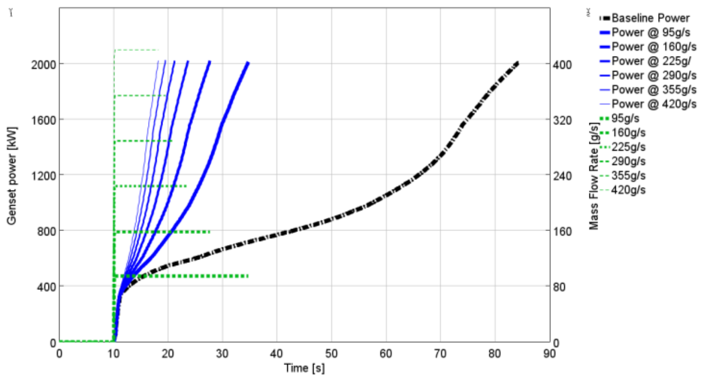

Figure 3: Simulation of injected air flow versus genset load response (Note: breaker closes at 10seconds / start of load ramp)

From these predictions and allowing for inaccuracies in the simulation model, a minimum requirement of achieving greater than 300g/s air flow on average over the load ramp was set.

For the StartIQ™ system to be applicable to other spark ignited high speed engines, it needed to overcome higher exhaust pressures than measured on the customer engine. Inferring from Bowman eTurbo Systems customer engine database, a Pressure Ratio (PR) was set for the eCompressor to be able to overcome the exhaust pressures expected at 22bar BMEP and with miller cycling levels seen in today's most advanced single stage turbocharged production gensets.

Simulations of five different radial compressors ranging from approximately 70 to 100mm diameter were performed to understand the potential speed and power required to achieve both the target compressor PR and greater than 0.3kg/s air flow at lower PR through the genset's load ramp. Additionally, a simulation was performed of a 2-stage eCompressor using two of the same compressors in the middle of the size range for comparison.

The simulations were performed in two steps, Step 1, targeting the maximum PR with 20% surge margin, and Step 2 targeting 2.5PR with the same speed attained in the first step, illustrated in Figure 4.

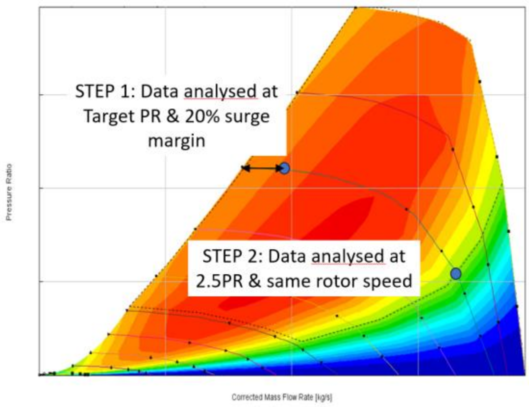

Figure 4: Analysis points to determine eCompressor speed and power requirement.

Figure 5 shows the predicted speed and power versus air mass flow rate for each of the eCompressors simulated. The requirements could be met with approximately 60kW electrical power and 165krpm using a single stage compressor system with the smallest diameter wheel simulated. With the 2-stage compression system, a similar power is needed but with significantly lower rotor speeds, ~92.5krpm

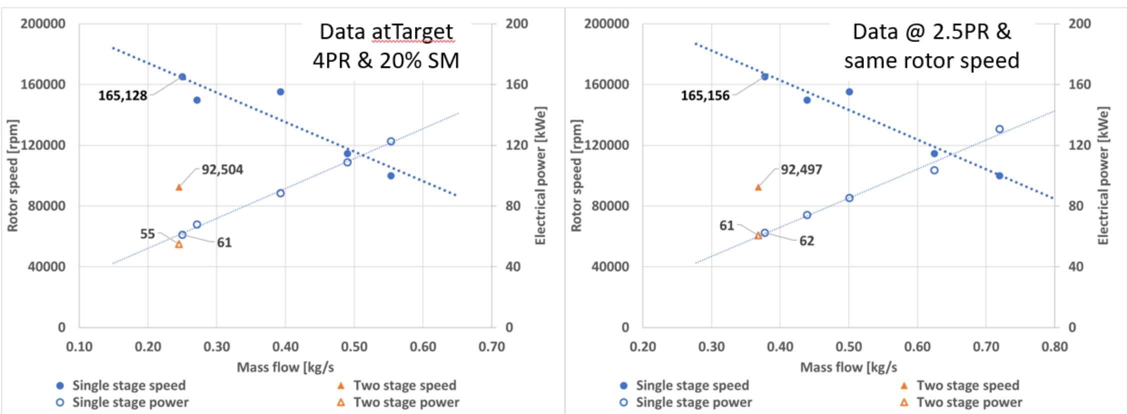

Figure 5: Comparison of eCompressor speed and power for single and 2-stage eCompressor layouts.

Taking Bowman eTurbo Systems' experience with surface mounted permanent magnet (SPM) eTurbomachinery into account, Figure 6, the proposed StartIQ™ system with single compression stage was seen to sit significantly beyond the existing design envelope. It was therefore concluded that the requirements should be met using a 2-stage eCompressor.

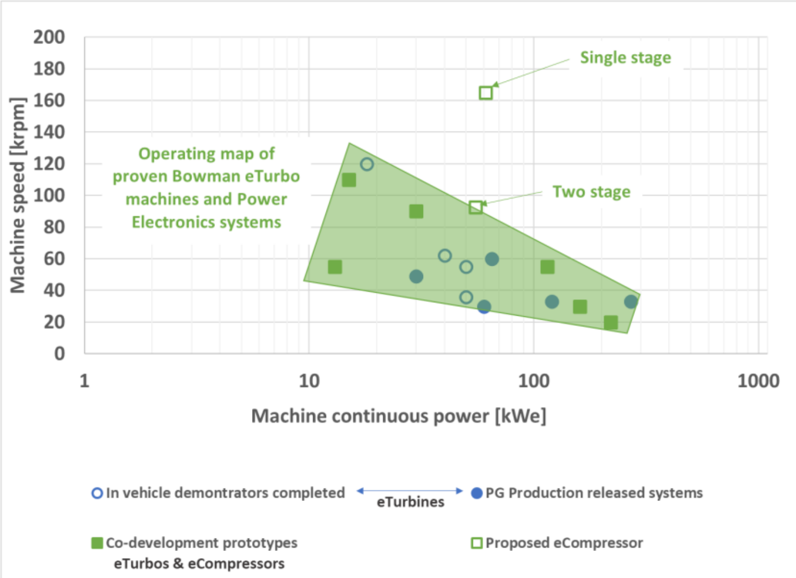

Figure 6: Comparison of speed and power for single and 2-stage eCompressor systems versus Bowman eTurbo Systems experience.

The StartIQ™ system and high-level product requirements were then fixed so a detailed design and build of a prototype could be progressed.

- 2-stage StartIQ™ system
  - Capable of target pressure ratio for modern 22bar BMEP engine
  - Capable of > 0.3kg/s at low pressure ratios
  - <1sec acceleration from rest to 90% of target speed
- Easy integration
  - No cooling system
  - No lubrication system
- Duty cycle and life
  - Capable of 3 x 20second full power runs per hour
  - Capable of 15 starts per day for the life of product
- No surge events during operation / Automatic surge protection
- No reverse flow of exhaust gases to StartIQ™ system
- Electrical integration and operation
  - Use local 3-Phase Low Voltage supply (local auxiliary grid)

- Use own signals and/or existing genset signals to achieve full automation

3 Product Design

3.1 System Aerodynamic Performance

Bowman eTurbo Systems worked with a Tier 1 turbocharger supplier to assess the aerodynamic suitability of their compressor stages to meet the product requirements. Four different compressor sizes were analysed in three different combinations, labelled small, medium, and large frame size for comparison purposes.

Each frame size combination was paired such that the surge margin on each compressor was similar when the maximum pressure ratio was achieved (See Figure 13 for further understanding). The speed and power requirement to achieve target PR for each 2-stage combination equated to

- Small – 41kWe @ 96krpm
- Medium – 55kWe @ 90krpm
- Large – 68kWe @ 85krpm

Figure 7 shows the predicted genset load ramp performance for each frame size with the speed limited to that required to achieve target PR or by limiting the torque to that required to achieve target PR, throughout the genset load ramp. It was predicted that the medium frame size 2-stage eCompressor could exceed the 300g/s air flow requirement.

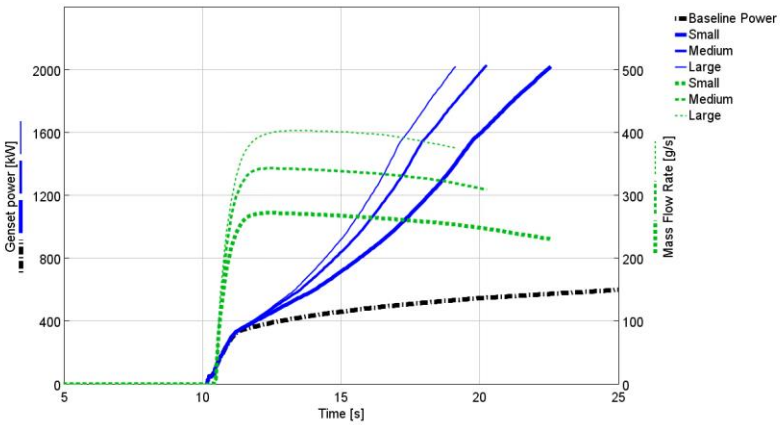

Figure 7: Simulation of different sized 2-stage eCompressor effect on genset load response (Note: breaker closes at 10seconds / start of load ramp)

A design power and speed of 55kWe and 90krpm, together with the medium sized 2-stage aerodynamic hardware, were chosen as the basis for the design of the StartIQ™ eCompressor and PE.

3.2 eCompressor

It is clear from >20 years of development of high-speed machines at Bowman eTurbo Systems that SPM machines offer the best power densities. With the 55kWe and 90krpm requirements for StartIQ being at the challenging end of Bowman eTurbo Systems experience (Figure 6), the 2-stage eCompressor required a bespoke SPM design to ensure acceptable rotordynamic behaviour could be achieved.

By concurrently iterating CAD, FEA, electromagnetic and rotordynamic model,s an optimal SPM design was determined. The resultant machine core consists of a 2-pole permanent magnet rotor using a high strength Carbon Fibre reinforcement band to provide the radial strength required to operate the eCompressor with the highest possible magnet surface speeds. The use of Carbon Fibre allowed approximately 1.3x increase in magnet rotational speed compared to using a metallic sleeve in a material such as Titanium, unlocking the possibility to increase shaft diameter and meet the same power capability with approximately 40% reduction in magnet length. This approach reduced the shaft length significantly versus that achievable with a metallic retention sleeve, permitting the 55kWe power requirement to be achieved, whilst maintaining acceptable rotor dynamic behaviour.

Due to the transient requirements of this application, the heat generation within the machine is relatively minor compared to continuous running machines and, through careful design of the bearing carriers and housings, two key simplifications to the machine were achieved.

1) it was not necessary to actively cool the machine as the temperatures remain within acceptable levels for all key components when simulating the 3 x 20 second full power cycles with only 40second cool down period between. Figure 8 illustrates the simulated temperature rise over the 3 x 20 second full power cycles.

2) it was not necessary to actively lubricate the bearings for cooling, and together with the operational profile and product life requirements, allowed greased for life bearings to be implemented.

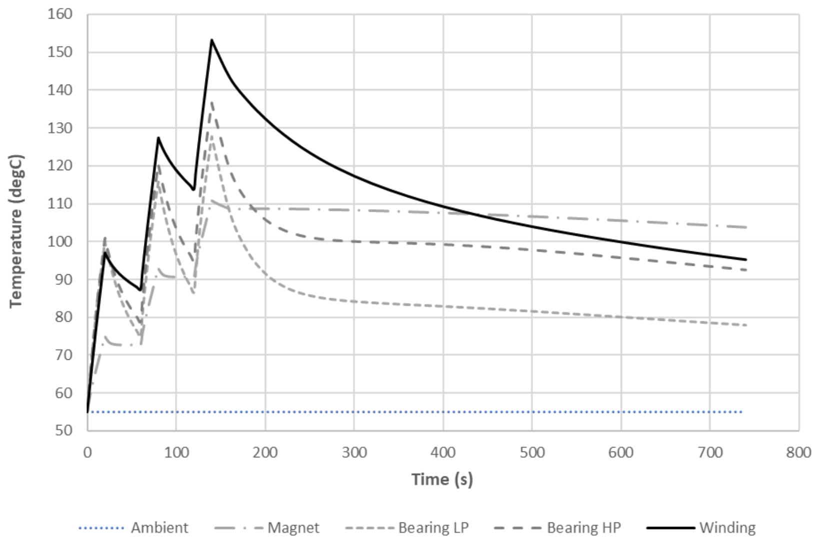

Figure 8: Simulation of key electrical machine temperatures (3x20s full power cycles)

The final StartIQ™ eCompressor design achieves the product life requirements with 55kWe at 90krpm without an active cooling system or active lubrication system while achieving an impressive power density of 4.6kWe/kg, Figure 9.

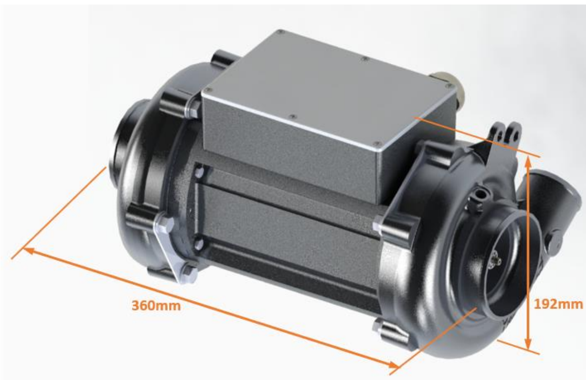

Figure 9: StartIQ™ eCompressor: 55kW, 90krpm, 12.05kg, 192mm height, 360mm length

3.3 Power Electronics - Inverter

The PE inverter is a key component of the StartIQ™ eCompressor system, it converts the typical 400Vac, 50/60 Hz grid voltage and frequency into a variable voltage and frequency which can accurately control the eCompressor speed.

Typical industrial off-the-shelf inverters are limited in peak output frequency to approximately 600 Hz (36,000 rpm Max) and therefore are not suitable to operate this turbomachinery based eCompressors which, require frequencies more than 1,500 Hz (90,000 rpm 2-pole machine).

Bowman eTurbo Systems has been developing high-frequency PE for the past 20 years and since 2021 we have been developing our 6th generation PE module, targeted for this application (motoring) as well as eTurbocharger applications which require bi-directional operation i.e., able to both motor and to generate back to the grid.

The basic specifications for this module are given by Table 1.

Table 1: Bowman eTurbo Systems bi-directional Silicon Carbide PE module specifications

Parameter	Value
Functionality	Motoring and generating grid-tied
Type	Multilevel Silicon Carbide MOSFET
Electrical Power	+/-55kW continuous (55kVA)
Efficiency	>97%
Input voltage line-line /frequency range	360 to 510 Vac , 50/60Hz
Output voltage line-line /frequency range	0 to 600 Vac, 0 to >2,500 Hz
Maximum speed	150,000 rpm (2-pole machine)
Transient response	10ms (switching from motoring to generating)
Cooling type	Air cooled

It is essential that the quality of the voltage/current waveform used to control the eCompressor is of high quality (low harmonic content), as any high frequency harmonics will generate heat within the eCompressor rotor which, as already described is not actively cooled. As such, it is necessary for the inverter to operate at frequencies in the region of 30 to 45kHz (20 to 30 times faster than the eCompressor), to create the high-quality waveforms.

To enable such high switching frequencies, Bowman eTurbo Systems has developed the drive based on advanced multilevel Silicon Carbide MOSFET technology, which additionally results in a highly efficient and power dense PE design, requiring air cooling only, for continuous operation at the maximum power level.

Figure 10 illustrates the quality of the waveform reconstruction from the inverter at 1,500 Hz (90,000 rpm 2-pole).

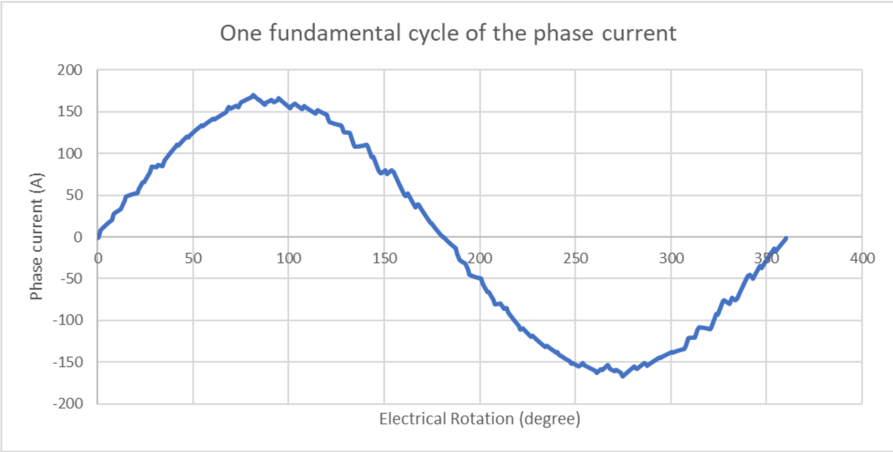

Figure 10: 1,500 Hz, 90,000 rpm, 55kW current waveform with 2.4% Total Harmonic Distortion

3.4 Air Handling System

The requirement for no reverse flow of exhaust gases to the StartIQ™ system was achieved by adding a high temperature, high pressure capable, spring-loaded Non-Return Valve (NRV) in the pipework running between the eCompressor and the engine exhaust manifold, Figure 11.

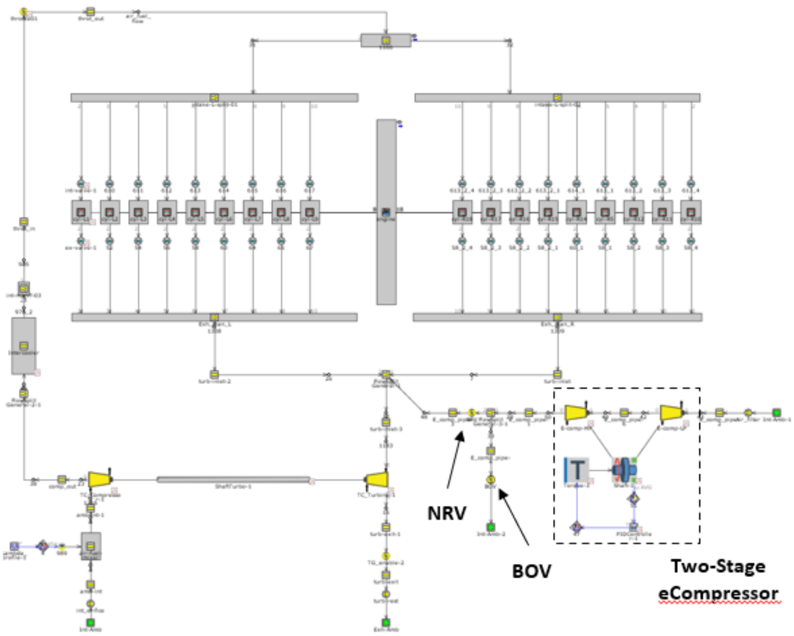

Figure 11: 1D simulation model of customer engine with StartIQ™ system

The addition of the NRV presents challenges to the operation of the eCompressor under three scenarios.

1. Accelerating the eCompressor when exhaust pressures are > 1bara.
2. When the eCompressor approaches the maximum PR achievable at any eCompressor speed (surge line)
3. Stopping the eCompressor when the genset is at target load.

To overcome these challenges a pressure sensor and electronically controlled Blow Off Valve (BOV) were added to the pipework between the eCompressor and the NRV (Figure 11). Control logic was implemented to operate the BOV and modulate the eCompressor speed so that surge could be avoided during each of the three scenarios.

Figure 12 shows the simulated eCompressor Low Pressure (LP) and high Pressure (HP) operating points during an eCompressor acceleration from 0 to 90,000 rpm with the genset on load and the exhaust pressure already at ~2bar absolute. Without the BOV, both LP and HP are driven into surge, however with the BOV surge is avoided by holding it open at the start of the eCompressor speed ramp. Provided the eCompressor speed is sufficiently high when the BOV is electronically closed, the NRV valve seamlessly opens, diverting the air flow from the BOV into the exhaust manifold.

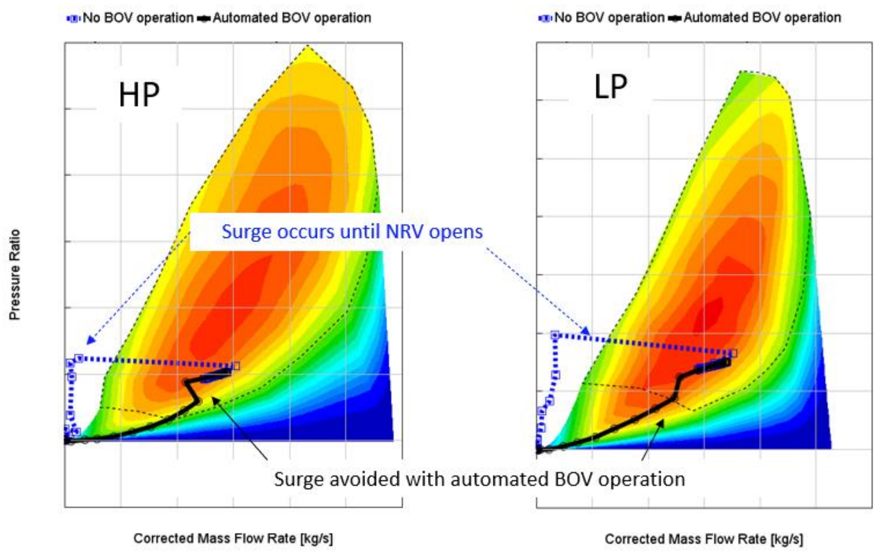

Figure 12: Simulated StartIQ^{TM} system speed up from 0rpm with 2bar exhaust back pressure.

Figure 13 shows the simulated eCompressor LP and HP operating points during an eCompressor acceleration from 0 to 90,000 rpm from breaker closed (0% genset load) and subsequently during a genset load ramp up to and beyond the maximum exhaust back pressure the StartIQ^{TM} system was designed for. Without the BOV, both LP and HP compressors are driven into surge when the maximum exhaust pressure is reached and exceeded. However, by opening the BOV based on the eCompressor speed and HP outlet pressure values, surge is avoided as the air flow vents to atmosphere while the NRV shuts as the delta pressure across it suddenly decreases. The eCompressor speed can then be safely decelerated to 0rpm and the engine load can self-sustain.

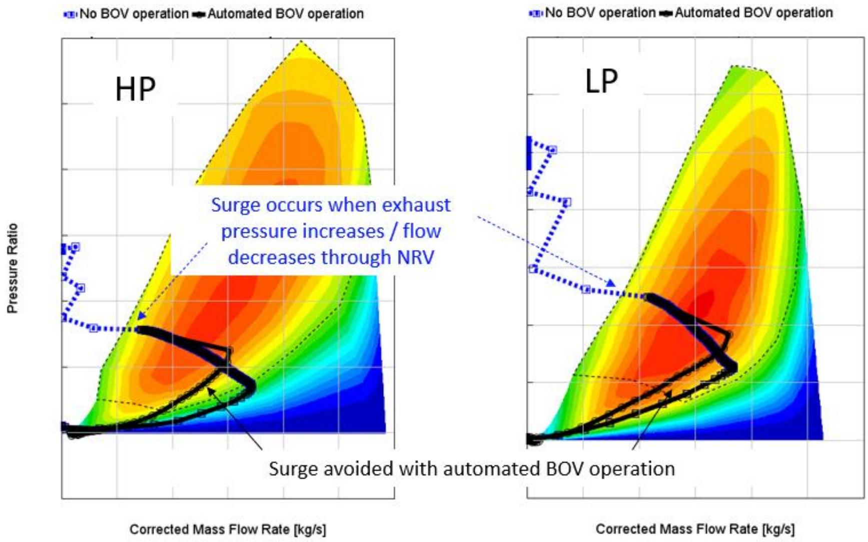

Figure 13: Simulated StartIQ™ system during normal startup against raising exhaust pressure with auto disconnect to avoid surge.

The StartIQ™ system disconnect logic when the genset load is achieved is functionally the same as that for surge avoidance, however the BOV opening and eCompressor deceleration are triggered using customer signals.

4 StartIQ™ Testing

4.1 Bench Testing at Bowman eTurbo Systems

In Q1 2022 the first prototype 2-stage eCompressor was built, Figure 14, and bench tested to confirm rotor dynamic, thermal, and electrical behaviour and aerodynamic and dynamic performance were sufficient to meet the product requirements.

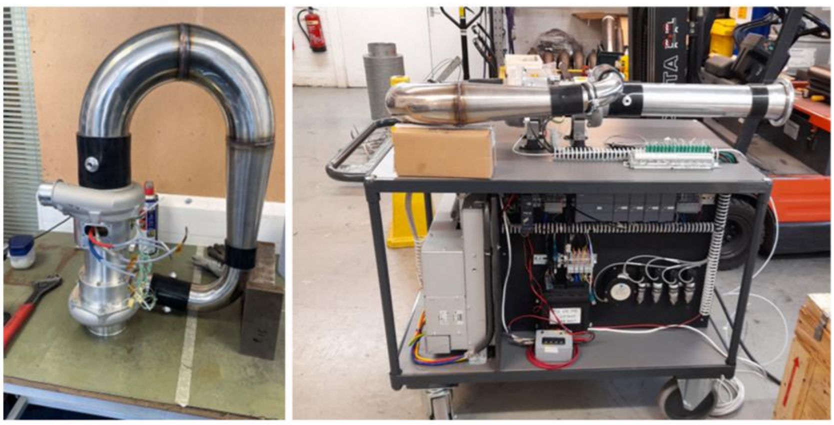

Figure 14: StartIQ™ TRL4 prototype system

The learnings from the TRL4 testing were used to update and calibrate simulation models, and a TRL7 production intent eCompressor design progressed. In parallel all components required to operate and integrate the system to the genset including valves, sensors, mounting method, new cast exhaust manifold section, controller, etc were defined, designed, and sourced, Figures 15 and 16.

The full TRL7 system acceleration and deceleration performance was proven on the test bench with the correct pipework, valve arrangement and back pressure applied downstream of the NRV to represent the engine exhaust pressure. Cyclic testing to prove operational repeatability without risk of surging events and to prove component reliability was completed before signing of the TRL7 StartIQ™ system for in-application testing.

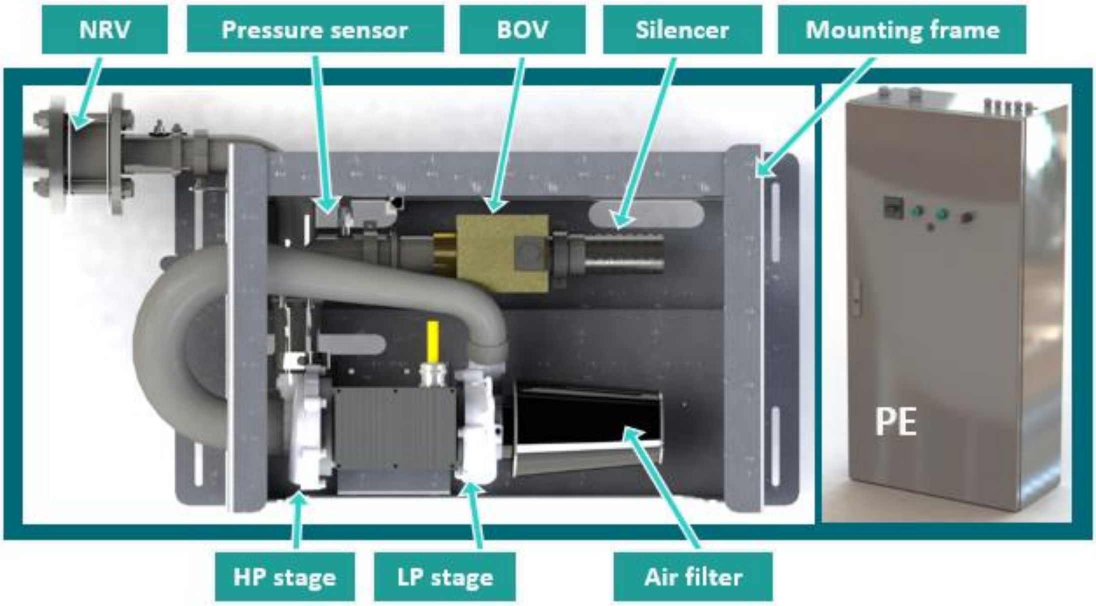

Figure 15: StartIQ™ TRL7 system design

4.2 Integration to Customer Genset

Integration into the customer genset focused on three principal areas, mechanical, electrical and controls, Figure 16.

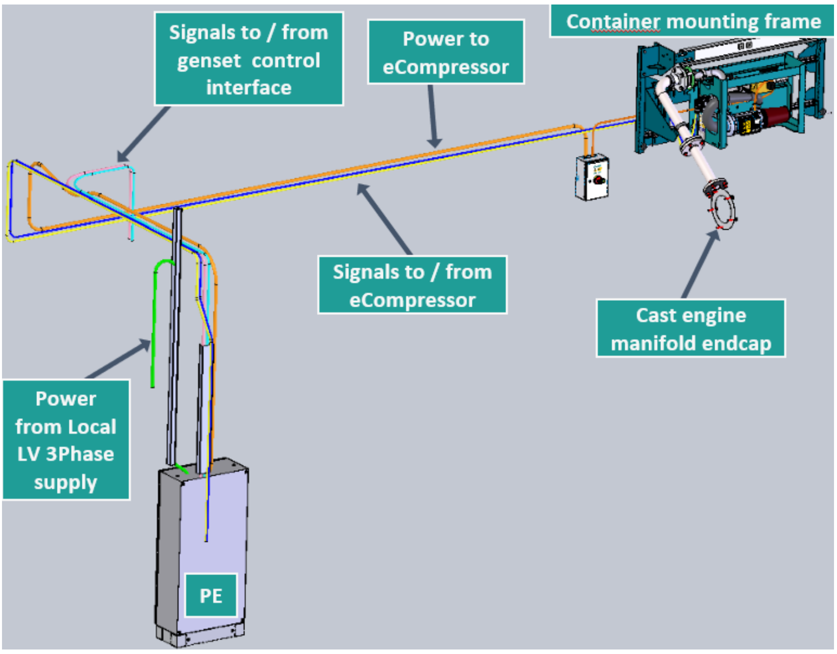

Figure 16: Genset interface design for StartIQ™ system

4.2.1 Mechanical Integration

To rule out any risks of high cycle fatigue on the engine turbocharger turbine blades, the StartIQ™ system was connected to the exhaust manifold at the opposite end to engine turbocharger, i.e., the closed end of the exhaust manifold. A new exhaust manifold endcap was designed, cast, and fitted to the engine with an additional port for the StartIQ™ system connection.

The StartIQ™ eCompressor frame was mounted off-engine to the genset container in a location which would not interfere with regular maintenance of the genset. A survey of different customer sites highlighted differences in container manufacturer engine position relative to the containers. Flexibility in the frame mounting approach was required to ensure all container-to-container variations could easily accounted for in the x, y, and z directions while mounting the system. The system was then connected to the exhaust manifold by means of a flexible, high-temperature bellows designed to allow for thermal growth as well as some level of misalignment due to container-to-container variability.

4.2.2 Electrical Integration

3Phase Low Voltage power for the StartIQ™ PE was taken from the customers' existing local LV Power Distribution Panel. The PE were positioned at the air inlet side of the container within close proximity to the Genset Control Interface Panel.

4.2.3 Controls Integration

The controls interface with the customer genset was to be as simple as possible with as few signals as required to successfully and safely operate the StartIQ™ system.

Existing signals within the Genset Interface Panel, three digital and one analogue were used for StartIQ™ system control purposes.

- Digital: Genset fast start requested (Removal of request signal disengages StartIQ™ system)
- Digital: Run StartIQ™ system (Removal of run signal disengages StartIQ™ system)
- Digital: Genset stopped (Used to cycle StartIQ™ system at low speed to clear NRV and exhaust manifold of condensation and contaminants after each genset shutdown)
- Analogue: Genset kW load

Three digital outputs were sent from the StartIQ™ system to the Genset.

- Digital: Healthy / Not healthy (Switch Genset to slow load ramp)
- Digital: StartIQ™ system trip (Switch Genset to slow load ramp)
- Digital: Run signal for customer to log start count and run hours of StartIQ™ system

Additionally, the StartIQ™ system was hardwired to the Genset Emergency shutdown safety wire loop if any StartIQ™ system faults are detected that indicate the pipework to the exhaust manifold or valve operation may be compromised.

Figure 17 shows the eCompressor system components mounted on a frame and its installation within the genset container.

Figure 17: eCompressor system installation in Genset container

4.3 StartIQ™ System and Genset Performance

Approximately 40 StartIQ™ system assisted genset starts were performed to tune the StartIQ™ system together with the Genset to assist the engine to achieve 100% load as quickly as possible.

The main challenge to overcome was that the Genset load ramp was never intended by the OEM to be so aggressive, so neither the engine throttle nor fuelling were tuned to perform such a manoeuvre. Or, in simpler terms, the genset and engine controllers could not take full advantage of the technology as they could not keep up with the StartIQ™ system accelerating the engine turbocharger so quickly. To overcome this the genset load controller was adjusted so that upon the breaker closing, a 2MWe block load command was set. The result, the throttle and fuelling PID controllers would saturate within 1 second allowing the maximum genset load rate to be realised. Note: This method also presented with challenges upon achieving 100% genset load, discussed in section 4.5.

Figure 18 shows the StartIQ™ system behaviour achieved. Upon receiving the signal that the breaker was closed, the eCompressor accelerates to its target speed in approximately 1.2 seconds (78krpm was targeted for this application as the StartIQ™ system power is comfortably below the 50kW deemed safe to use the customers local 3phase supply without modification). The StartIQ™ system holds the target speed steady until the Genset achieves 2MWe, at which point the eCompressor disengages as described in Chapter 3.4. Within 200ms of eCompressor disengaging, the HP outlet pressure decreases by approximately 40%, eliminating the opportunity for the eCompressor to surge as the NRV closes. The HP outlet pressure is seen to drop quickly and smoothly to 0barg, showing no signs of surging or back flow from the exhaust system to the StartIQ™ system.

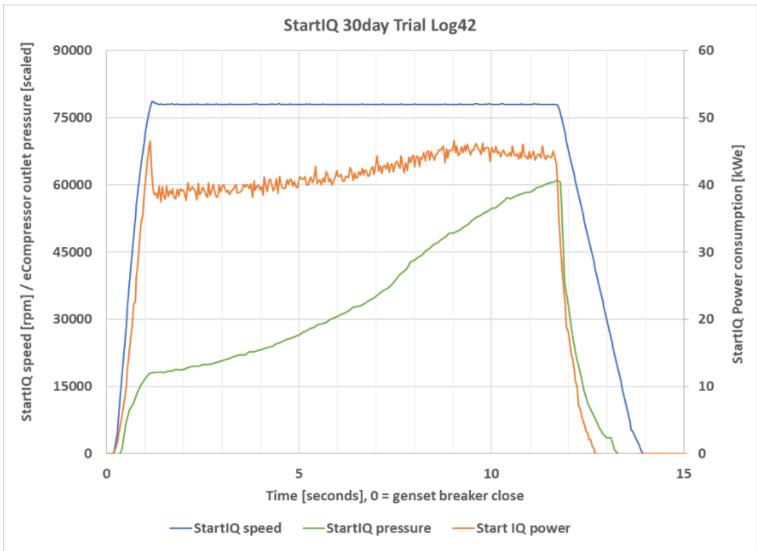

Figure 18: StartIQ™ log taken following commissioning and tuning of system and genset performance (StartIQ™ log42 from Figure 10)

4.4 Genset performance and 30-day trial

Following the system tuning work, potential StartIQ™ system and genset failure modes were investigated and modifications to the control logic made to ensure both StartIQ™ system and genset were suitable to be left unmanned and running automated for a 30-day trial.

During the trial more than 160 successful starts were completed with example genset load and eCompressor out pressure profiles taken during the trial illustrated in Figure 19. Observing the eCompressor out pressure traces confirmed the StartIQ™ system was disconnecting from the genset without surge events or reverse flow from the exhaust toward the eCompressor throughout the trial. The genset load profiles showed variation in the breaker closed to 100% genset load time from 9 to 16 seconds. Despite this broad range it was concluded that the genset load profiles were in fact extremely repeatable when taking account of the length of time the Genset had been shut down since its previous run i.e., how hot, or cold the engine block, exhaust manifold and turbocharger turbine were at the time of starting. The traces in Figure 19 are colour coded with varying thickness (red / thick for hot engine through to blue / thin for cold engine) to highlight this effect.

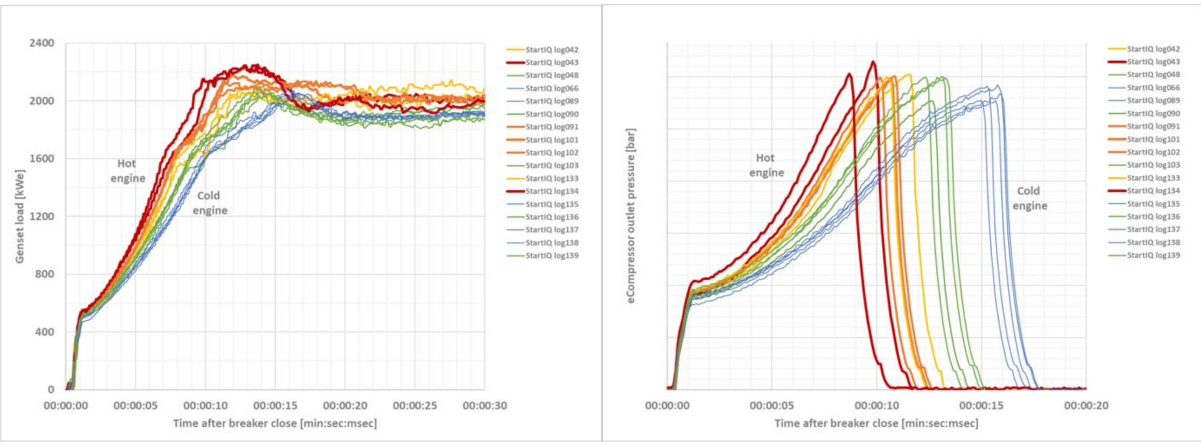

Figure 19: StartIQ™ logs recorded during 30day field trial on customer genset.

The test data highlighted the need for further optimisation of the system and genset. Cold genset starts were not always achieving the target 15seconds load ramp, and there was insufficient enthalpy in the exhaust to maintain 100% load until approximately 30 seconds had passed after the StartIQ™ system had disconnected. Hot starts were seeing up to a 12.5% genset load overshoot and although the genset was not shutting down for overload protection, this was deemed undesirable.

4.5 Genset and StartIQ™ system optimisation

To improve the cold and hot genset load ramp performance the genset, engine and StartIQ™ system calibrations were adjusted.

To improve the cold start genset load ramp time, the engine transient lambda enrichment was adjusted to avoid the inflection in the load ramp rate which can be seen at 1600kW / 10seconds in Figure 15. Further adjustment reduced the rapid load acceleration occurring when the engine is in hot condition and the StartIQ™ system disengages at 2000kWe / 9 seconds in Figure 15.

During the 30 seconds phase after the StartIQ™ system disengages at 2MWe with cold engine, the engine spark timing was retarded to increase the turbine inlet gas temperatures by an amount appropriate to limit the genset load dip to less than 5% of that at which the StartIQ™ system disengages.

Both hot and cold genset start performance were further improved by performing real-time analysis of the StartIQ™ system data through the initial stages of the genset load ramp. It could be determined within seconds of the breaker closing if the engine is starting from a hot or cold condition and the timing of disengaging the StartIQ™ system adjusted accordingly.

The hot engine load overshoot was fundamentally a result of the constant 2MWe target load profile imposed from when the breaker closes through to when full load is achieved, described in Section 4.3. During the genset load ramp phase, the genset load controller PID loop saturates, and once 2MWE genset load is achieved takes time to unwind. The settings of the genset load controller were adjusted to successfully decrease the load overshoot. However, this was achieved at the expense of sacrificing Genset load ramp performance, as it was no longer possible to fully saturate the fuelling and throttle until some seconds after the genset breaker opened. This is evident when comparing the time take to achieve 800kW after the breaker closes in the Figure 20 (the collective sum of all optimisation adjustments) which is approximately one second slower than in Figure 19.

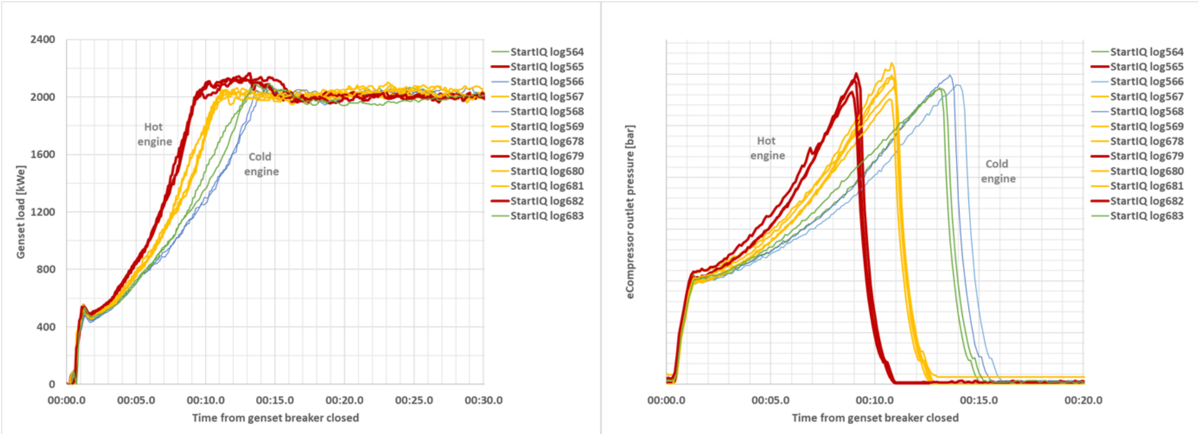

Figure 20: StartIQ™ logs recorded following optimisation of genset, engine and StartIQ™ system.

To date, the lead system at the customer site has now accumulated >1160 successful genset load ramps assisted by StartIQ™. The >600 starts since the system optimisation above was performed have all achieved less than 15 second load ramp time and less than 5% load undershoot when the genset was cold, or less than 10% overshoot when hot following the StartIQ™ system disengaging.

4.6 Full 20MWe site test

At the time of authoring this paper, ten production StartIQ™ systems have been installed, commissioned and are in their first month of running automated at a customer's 20MWe gas peaking site in the UK.

Although there has not been time to analyse this data in depth for this publication, commissioning on the customer site highlighted engine to engine performance variabilities that additionally need to be accounted for. Taking this variability into account, the eCompressor target speed was increased to 80krpm, ensuring the all ten StartIQ™ installations were achieving < 13second from breaker closed to 100% genset load, providing enough margin to meet the customers 15second requirement throughout the calendar year.

5 Summary and Outlook

Bowman eTurbo systems have successfully developed a 55kWe eCompressor system (StartIQ™) which can be installed to the exhaust manifold of high-speed generating sets to eliminate turbocharger lag. The system has been developed without the need for cooling or lubrication, making it simple to integrate to existing gensets of any fuel type in the 0.5 to

5.0MWe range (Depending on load ramp requirements 2 x StartIQ™ systems would be recommended for engines > 2.5MWe).

Testing on a 2MWe spark ignited gas peaking genset has demonstrated that the system reliably eliminates turbocharger lag on cold engine starts without impacting the genset steady state efficiency, emissions, or boundary conditions (durability). This allows for easy integration to existing OEM genset portfolios with minimal development time or investment.

To further enable spark ignited gas and hydrogen genset to meet the transient demands of other applications today suited to diesel gensets, consideration on how to adapt the technology to off-grid island mode applications and micro grids, emergency standby and datacentre applications is ongoing.

References

[1] Douglas, K., 2020, Electric turbocharging – A path to increased lean burn gas genset efficiency together with diesel like transients / 25. Aufladetechnische Konferenz

[2] Barman, J., Patchappalam, K., and Gambhir, H., 2019, "Compressed Air in Engine Exhaust Manifold to Improve Engine Performance and Fuel Economy," SAE Symposium on International Automotive Technology, Technical Paper 2019-26-0043

[3] Fleiss, M., Burenius, R., Almkvist, G., Björkholtz, J., 2015, The New Volvo 235hp Diesel Engine with Extreme Take-Off Performance / 24th Aachen Colloquium Automobile and Engine Technology.

[4] Skittery, A. Cornwell, R. & King, R., 2021, Boosting the JCB Fastrac "World's fastest tractor" / IMECHE 14th International Conference on Turbochargers and Turbocharging.

[5] Smalley, R., 1963 "Jet Assist for Turbocharged Marine Diesels," SAE Technical Paper 630164