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Development of eCompressor system to improve high-speed engine transient load acceptance

Turbochargers & Air/Exhaust Management

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ABSTRACT

OEM's have developed and iterated high-speed spark ignited internal combustion engines to provide the highest possible power densities and efficiencies. This evolution has led to technology choices that require lean mixtures and high charging pressures, typically with low exhaust gas temperatures.

To accommodate this, turbochargers have trended towards achieving the highest possible pressure ratios with efficiency optimised at 100% engine load, resulting in solutions with high inertia, high thermal mass and poor efficiency at low engine loads. The result? High BMEP, high-speed lean burn spark ignited gas engines are not suitable to be used in highly transient applications serviced by todays diesel variants, particularly when the engine is cold.

This paper details the definition and development of an engine and fuel agnostic 2-stage electric compressor, with a 55kW power electronics control system capable of delivering pressure ratios greater 4 in less than 1 second, to support engines during transient load acceptances.

Validation of the solution on a 20MWe on grid gas peaking site supporting new 'Quick Reserve' requirements of the UK national electricity grid is presented, showing cold pre-heated engine load ramp rates could be increased by approximately 10 times. Further iterations of the system to enable the technology to be used in off-grid, emergency standby and datacentre, as well as two-staged turbocharging applications are presented.

1 INTRODUCTION

Over recent decades OEM's have developed and iterated high-speed lean burn spark ignited (SI) Internal Combustion Engine (ICE) 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 ICE performance. This results in turbochargers with high thermal mass and inertia, and poor efficiency at low ICE loads, leading to significant challenges when trying to increase ICE load due to turbocharger lag, which is more exaggerated when the ICE is cold.

In 2020, Bowman [1] performed a study looking at the possibility of using different electrified turbocharging solutions to reduce turbocharger lag in modern high-speed ICE's. 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 ICE genset from 90s to less than 10s. It was concluded that integrating an eCompressor to flow air into an ICE's exhaust manifold, upstream of the ICE turbocharger turbine, offered the best compromise between performance, electric machine size, cost, complexity and ease of retrofit.

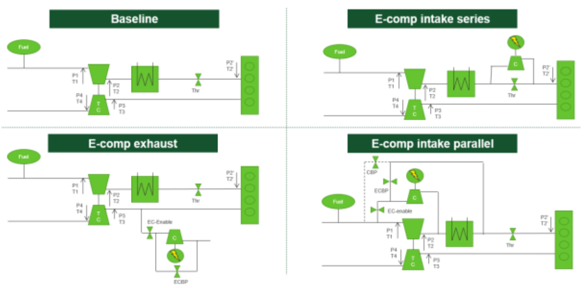

Figure 1. eCompressor layouts investigated on 1MWe gas genset [1]

The approach to flow air into the exhaust upstream of an ICE's turbine stage to accelerate the turbocharger is not novel. As far back as 1964, MAN [3] 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 [4] have implemented their "PowerPulse" system to eliminate turbo lag by injecting stored compressed air upstream of the turbocharger turbine. VE Commercial Vehicles Ltd [5] and JCB [6] have similarly used compressed air injected directly into the exhaust manifold of the ICE to reduce turbocharger lag. In all cases, the papers cite the preference to inject air on the exhaust side of the ICE 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 ICE 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 ICE was made in 2021.

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

- eradicate turbocharger lag for high-speed ICE 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 ICE efficiency, emissions, or durability.

2 PRODUCT DEFINITION AND REQUIREMENTS

A power generation customer in the UK operating approximately 500MWe of 2MWe gas peaking gensets (Field Engine 1) 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 focused on meeting Field engine 1's requirements, but also to ensure the system would be applicable to other high Brake Mean Effective Pressure (BMEP) spark ignited high speed ICE's in the market. Details of how the StartIQ™ system requirements were developed can be found in Bowman [2].

The StartIQ™ system and high-level product requirements:

- Capable Pressure Ratio (PR) expected for modern 22bar BMEP ICE's
- Achieve < 15s breaker close to 100% load with Field engine 1 in cold pre-heated condition
- No cooling system
- No lubrication system
- 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 when applied in a 2-stage layout. Four different compressor frame (wheel) sizes were analyzed in three different combinations, labelled small, medium, and large for comparison purposes.

The speed and power requirement to achieve target PR expected for 22bar BMEP ICE's, for each 2-stage combination equated to

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

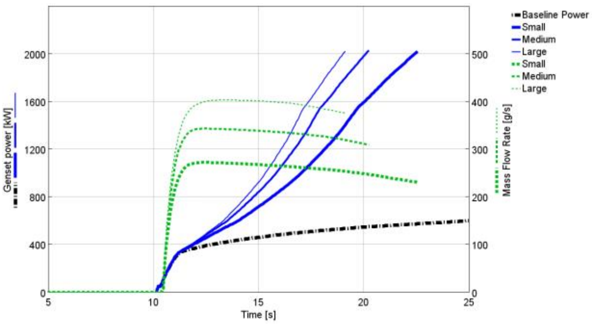

Figure 2. Simulation of different sized 2-stage eCompressors applied to Field Engine 1 (Note: breaker closes at 10s / start of load ramp)

When applied to Field Engine 1, it was predicted that the medium frame size would comfortably meet the customers 15second requirement, Figure 2. A design power and speed of 55kWe and 90krpm, were chosen as the basis for the design of the StartIQ™ eCompressor and its Power Electronics (PE).

3.2 eCompressor

By concurrently iterating Computer Aided Design (CAD), Finite Element Analysis (FEA), electromagnetic and rotor-dynamic models, an optimal Surface Mounted Permanent Magnet (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 behavior.

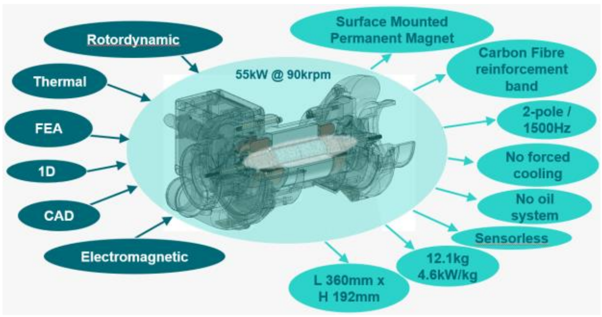

Figure 3. Design tools and resultant prototype design.

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 remained 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 4.
2. It was not necessary to actively lubricate the bearings for cooling which, together with the operational profile and product life requirements, allowed greased-for-life ceramic ball bearings to be implemented. Note: the thrust loads for the LP and HP being close to

balanced through the operating speed range also played a significant role in meeting the bearing life requirements.

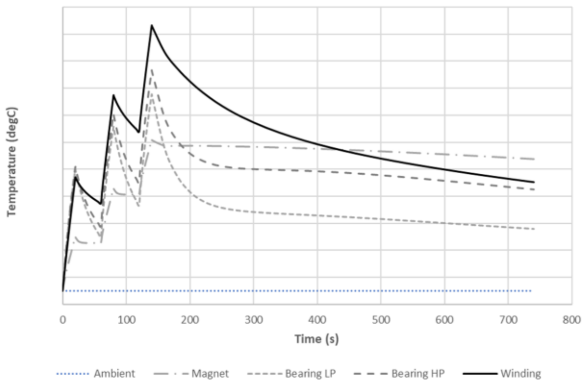

Figure 4. Simulation of key electrical machine temperatures (3x20s full power cycles)

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 5.

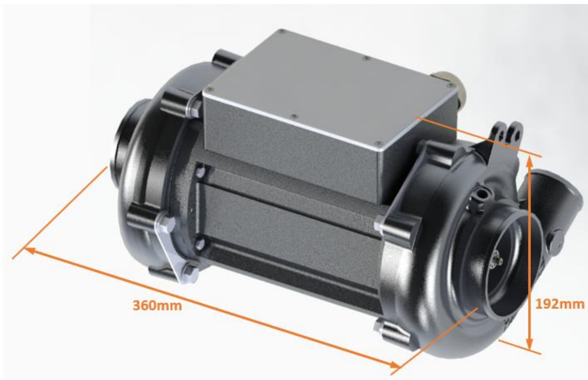

Figure 5. StartIQ™ eCompressor: 55kW, 90krpm, 12.05kg, 192mm height, 360mm length

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 turbomachinery based eCompressors which require frequencies more than 1,500 Hz (90,000 rpm 2-pole machine).

A new (Bowman 6th generation) PE module development was undertaken to meet the new requirements 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 in 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, Figure 6.

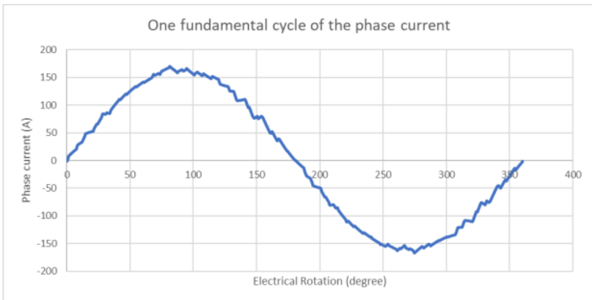

Figure 6. 1,500 Hz, 90,000 rpm, 55kW current waveform reconstruction with 2.4% Total Harmonic Distortion

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, also requiring air cooling only, for continuous operation at the maximum power level.

3.4 Air Handling System

The connection to the ICE was achieved by adding a high temperature, high pressure capable, spring-loaded Non-Return Valve (NRV) in the pipework between the Compressor and the ICE exhaust manifold, Figure 7.

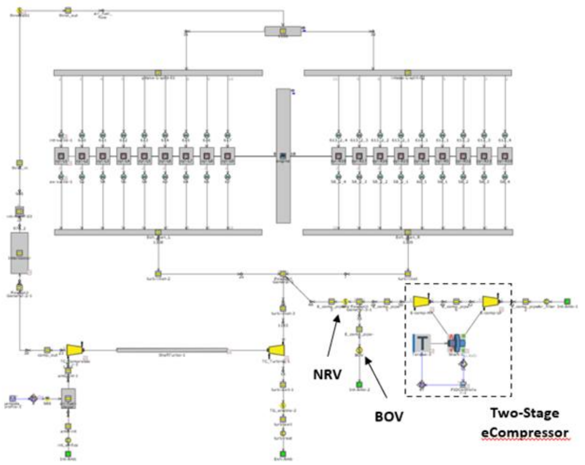

Figure 7. 1D simulation model of Field engine 1 with StartIQ™ system

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

1 Accelerating the eCompressor when exhaust pressures are > 1bar absolute - relevant when wanting to operate the eCompressor when the ICE is already on load.

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 scenario.

Figure 8 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 beyond the surge line, 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 line, into the exhaust manifold.

Figure 9 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™ system was designed for. Without the BOV, both LP and HP compressors are driven beyond the surge line 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 pressure delta across it suddenly decreases. The eCompressor speed can then be safely decelerated to 0rpm and the ICE load can self sustain.

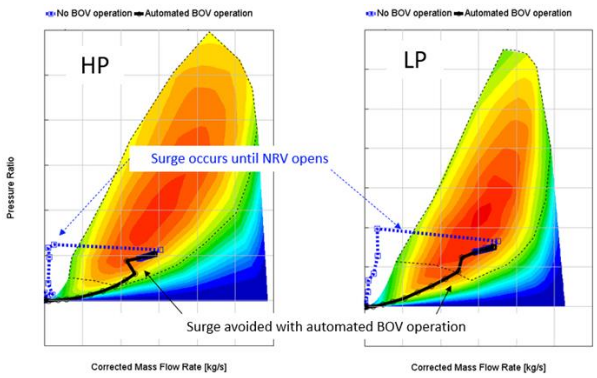

Figure 8. Simulated StartIQ™ system speed up from 0rpm with 2bar absolute exhaust back pressure.

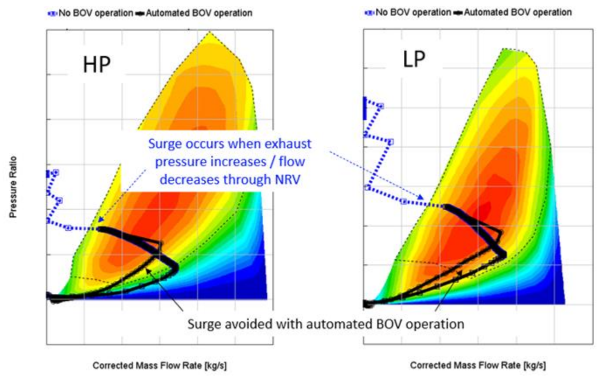

Figure 9. Simulated StartIQ™ system during normal startup against rising exhaust pressure with auto disconnect to avoid surge.

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 as input to the StartIQ™ system.

4 STARTIQ™ TESTING

4.1 Bench Testing at Bowman eTurbo Systems

In Q1 2022 the first prototype 2-stage eCompressor was built, Figure 10, and bench tested to confirm rotor dynamic, thermal, electrical, aerodynamic and dynamic performance were sufficient to meet the product requirements.

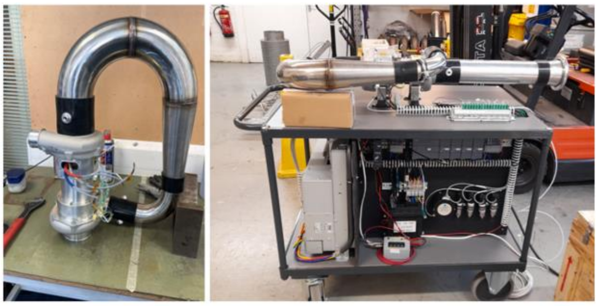

Figure 10. StartIQ™ TRL4 prototype system

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 Field engine 1 including valves, sensors, mounting method, controller, etc., were defined, designed, and sourced, Figure 11.

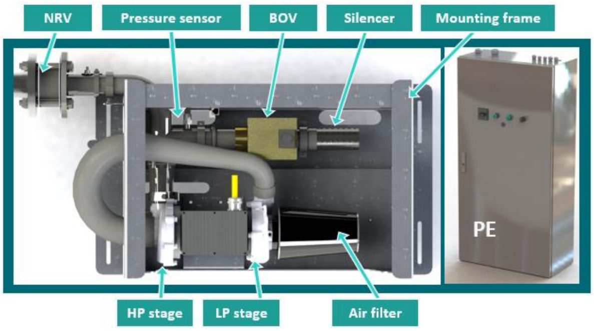

Figure 11. StartIQ™ TRL7 system design

Mapping the TRL7 StartIQ™ eCompressor at constant speed, and with fixed back pressure valve area, indicated higher air flow, pressure ratios and thus PE power consumption than simulated (Figure 2) for the initial seconds of running. After some time at steady state the flow and pressure ratio were seen to drop back closer to that expected as the machine reached more stable operating temperatures. As the LP and HP maps provided by the Tier 1 turbocharger supplier are measured at steady state conditions (as would be the case when applied to an ICE), it was concluded they do not provide a good match to the performance when the eCompressor LP and HP wheels and housings, and thus the outlet air temperatures, are low.

Therefore, the eCompressor simulation model was recalibrated to the measurements by scaling the compressor maps to better match the measured data in the first seconds after the eCompressor spin up, as expected when used in application.

Figure 12 show steady state operating points from the corelated model targeting fixed operating speeds with the back pressure applied to the system varied from 1.05bar (assumed exhaust pressure at 0% ICE load) up to a maximum exhaust pressure and with the Power Electronics current limited.

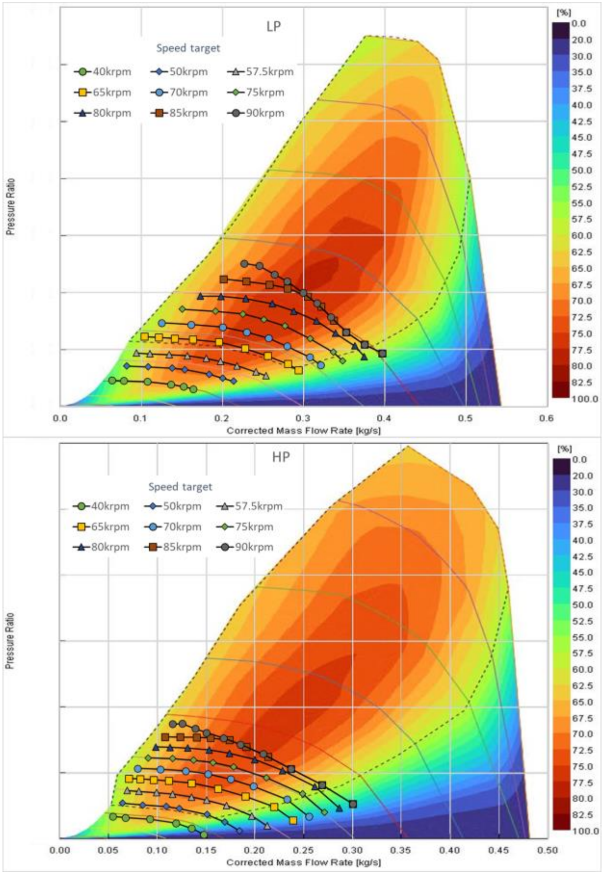

Figure 12. StartIQ™ LP and HP operating maps based on potential in application boundary conditions

With the PE current limited, the maximum eCompressor speed achieved varied between 82,000rpm and 90,000rpm dependant on the back pressure applied to the eCompressor, Figure 13.

This ‘PE current limiting’ operating strategy, referred to as ‘Torque limited’ through this paper, is not only beneficial to limiting the maximum powers and temperatures for the eCompressor and PE throughout the outlet pressure operating range (Figure 13), but this strategy also unlocks the possibility to provide a more repeatable air mass flow delivery to the ICE during transients, regardless of ambient temperatures, pressure (altitude) or eCompressor start temperature. E.g. if the atmospheric air density decreases, the power/torque required for compression at any given operating speed decreases. In this case the eCompressor controller will automatically increase the eCompressor speed to keep to the torque limit, thus increasing the air mass flow delivered to the ICE. Or, in other words, by riding the eCompressor torque limit, the eCompressor speed is free to float up and down, helping to maintain more consistent air mass flow rate versus pressure ratio, ensuring the impact of changes in ambient conditions on transient benefit provided to the ICE is minimised.

As an example, operating the eCompressor at 35°C ambient temperature versus 25°C ambient temperature, with a system back pressure of 2bar, would result in approximately 4% reduction in mass flow delivered at constant shaft speed. With constant torque, the eCompressor speed at the higher temperature would increase by approximately 1300rpm limiting the reduction in mass flow delivered to approximately 1.5% versus at 25°C ambient.

This effect can be observed comparing Figures 28 and 30 which were operated in torque limiting mode. Due there being approximately 500m altitude difference between the test sites, StartIQ™ with Field Engine 3 achieved approximately 3krpm higher eCompressor speeds through the genset load ramp compared to field Engine 2.

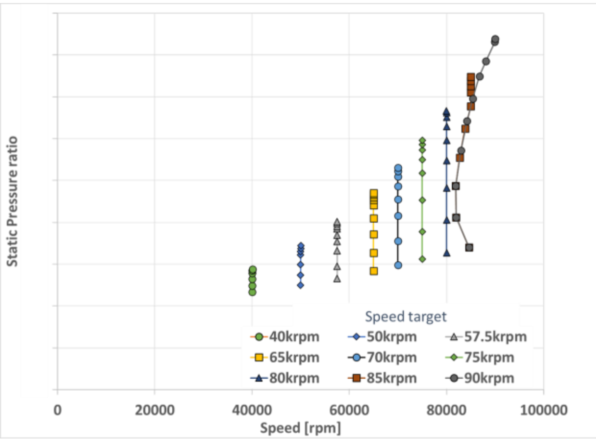

Figure 13. StartIQ™ steady state speed versus overall pressure ratio operating map simulated at ISO conditions.

Figure 14 additionally highlights the possibility to modulate the air mass delivery to the ICE depending on how the eCompressor target speed is set versus ICE exhaust back pressure during any transient event. In the plot, the right side of the speed lines represent the flow at low exhaust back pressure of ~1.05bar, and the left-hand side of the speed lines the flow at higher back pressures when the operating point is close to the surge line.

As an example, with the ICE at a starting load of 0% (1.05bar exhaust pressure) and operating in torque limiting mode, the eCompressor will accelerate to the maximum speed to deliver ~0.4kg/s (operating within the choke region on both LP and HP stages) within approximately 1 second from command. As the ICE load and exhaust pressure increase, the mass flow will reduce as the operating point moves up and to the left across the LP and HP compressor maps. In this example should the ICE have the maximum possible exhaust pressure achievable with the eCompressor at 100% load, the eCompressor would then deliver approximately 0.22kg/s.

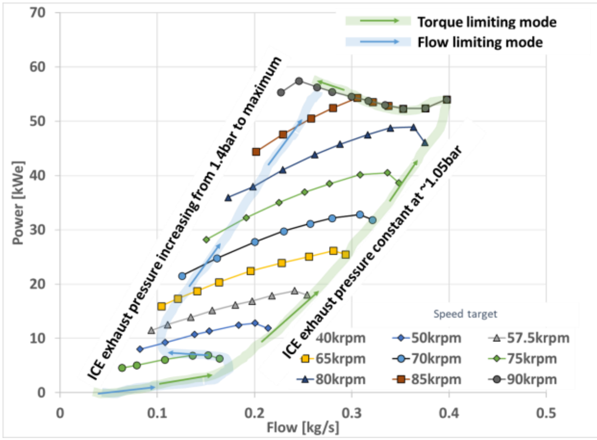

Figure 14. StartIQ™ power draw versus air mass flows simulated at ISO

Alternatively, the eCompressor speed could be varied as the ICE load rises, offering the possibility to deliver approximately 0.16kg/s if the eCompressor target speed is initially 40krpm when the genset breaker closes. The flow would then drop to approximately 0.1kg/s as the ICE exhaust back pressure increases with the eCompressor held in the first seconds at 40krpm. The eCompressor speed would need to be steadily increased as the ICE load and exhaust pressure increase, further minimising the air flow delivered to the ICE while maintaining surge margin until full load is achieved. This method, referred to as 'Flow Limiting' mode through this paper, offers the possibility to approximately halve the air flow delivered to the ICE by the StartIQ™ system, versus operating in torque limiting mode.

The result of running with the NRV line exit blocked off and BOV in the open position, i.e. 100% of the eCompressor outlet flow through the BOV and silencer line, can be seen in Figure 15. The surge margin calculated on both the LP and HP stages are more than 100% throughout the operating speed range of the eCompressor, demonstrating that operational safety of the StartIQ™ system can be guaranteed at any time, regardless of the eCompressor speed, ICE operating conditions or ambient conditions, by simply opening the BOV.

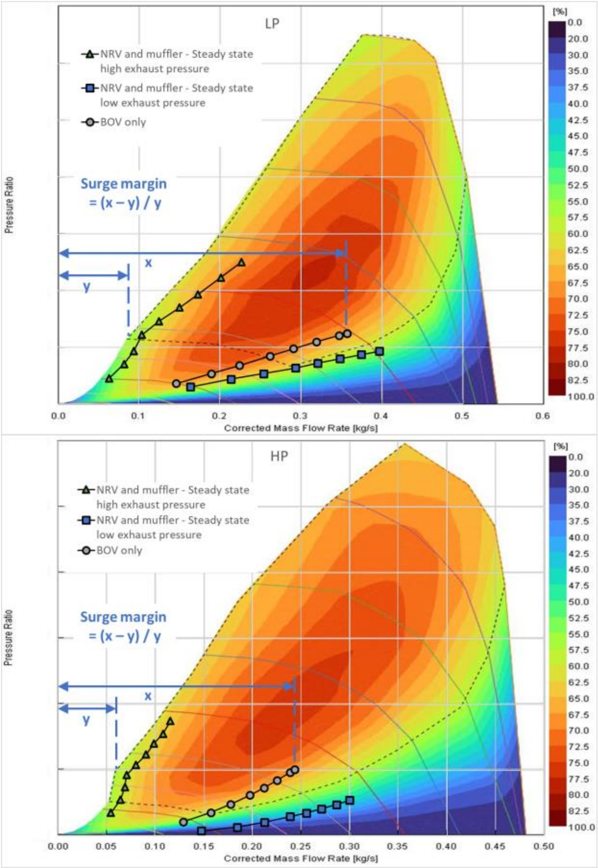

Figure 15. Demonstration of surge margin with 100% eCompressor flow through the BOV line targeting between 40 and 90krpm

The onset of surge was tested when targeting speeds between 80 and 90krpm using an electronically controlled butterfly valve to slowly increase eCompressor outlet pressure until instabilities of greater than 0.05bar peak to peak (±0.025bar) could be seen on the pressure trace (Note: not audible). Additional endurance testing was performed using a fixed orifice to induce a backpressure on the eCompressor system as the eCompressor speed was cycled up and down while maintaining margin to thermal limits. Figure 16 shows the results of these tests plotted on the operating map of the eCompressor system, from which a surge line was derived for field testing Exceeding this ‘surge line’ will trigger the BOV to immediately open and eCompressor to reduce speed to 0 rpm (and along the ‘BOV only’ operating line plotted in Figure 15).

Figure 17 shows the bearing temperatures measured when cycling the eCompressor targeting its maximum speed for 12s, stopping until 8 minutes had passed from the start of the run, and repeating continuously until the system temperatures stabilised. From this a field limit with 30°C margin to the bearing manufacturer’s limit was applied to allow for variations around thermocouple location and measurement inaccuracies between units, uncertainties around heat soak effects and ambient variations in the field. The in field bearing limit is applied only while the eCompressor is running. Considering approximately 6°C heat soak occurs to the HP bearing after the StartIQ™ system is shutdown, there is approximately 9°C margin to in field bearing limit as plotted.

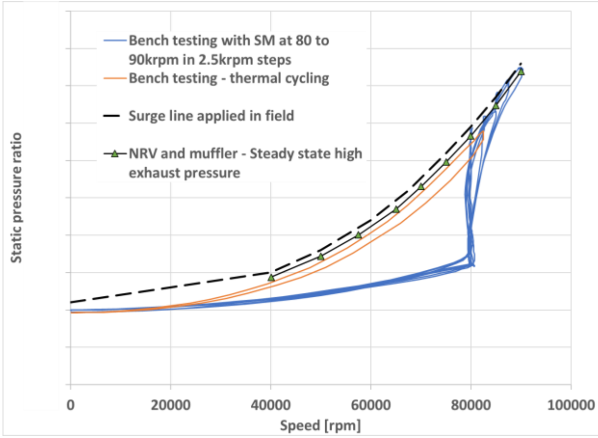

Figure 16. Derivation of StartIQ™ operating map surge line for field testing

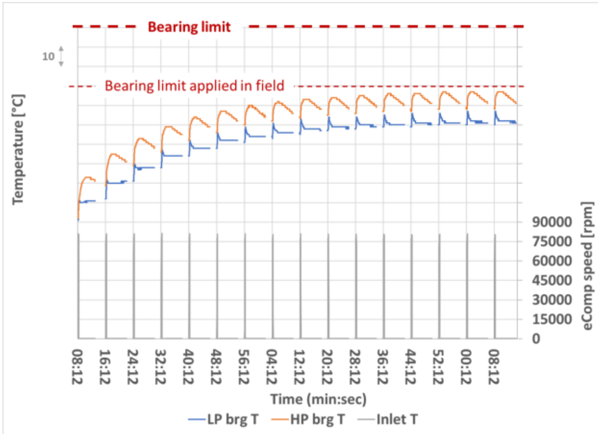

Figure 17. Thermal limit testing performed with 22°C ambient temperature

4.2 Field testing

To date three gensets with varied ICE specifications have been tested with StartIQ™ applied to assess on grid load ramp capability.

Table 2. ICE specifications tested with StartIQ™ assisted load ramp.

		Spark ignitied Pre-mixed NG engine		
		Field engine		
		1	2	3
Rating	MW	2	2	1.25
BMEP	bar	18	18	22
Miller cycle		Light	Light	Medium
Est turbo inertia	kgm3	0.045	0.002	0.024
Number of turbos		1	4	1

4.2.1 Field engine 1

4.2.1.1 Integration to Customer Genset – Integration into the customer genset in Q4 2022 focused on three principal areas, mechanical, electrical and controls, Figure 18.

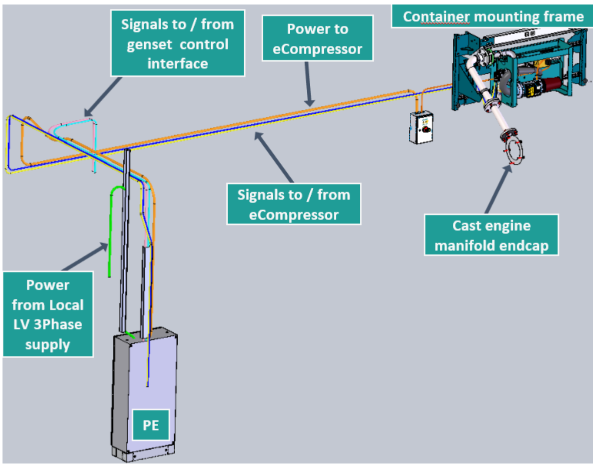

Figure 18. Genset interface design for StartIQ™ system

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

Figure 19. TRL 7 eCompressor system installation in Genset container.

The StartIQ™ eCompressor frame was mounted off engine to the genset container, Figure 19, in a location which would not interfere with regular maintenance of the genset and connected to the exhaust manifold by means of flexible, high temperature bellows.

Electrical Integration – 3Phase Low Voltage power for the StartIQ™ PE was taken from the customer's 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.

Controls Integration – The controls interface with the customer genset was to be as simple as possible. Therefore, existing signals within the Genset Interface Panel, three digital and one analogue were used for StartIQ™ system control purposes. Three digital outputs from the StartIQ™ state machine were sent to the Genset with the purpose of the genset either targeting a fast or slow load ramp. 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.

4.2.1.1 StartIQ™ System and Genset Performance - Figure 20 shows the StartIQ™ system behaviour achieved using speed limited mode.

Upon receiving the signal that the breaker was closed, the eCompressor accelerates to its target speed in approximately 1.2s (78krpm was targeted for this application as the StartIQ™ system power is comfortably below the 50kW deemed safe to use the customer's 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. Figure 21 shows the operation with margin to the surge line during the disengaging process.

Figure 20. StartIQ™ log taken following commissioning and tuning of system and genset performance (StartIQ™ log42 from Figure 22)

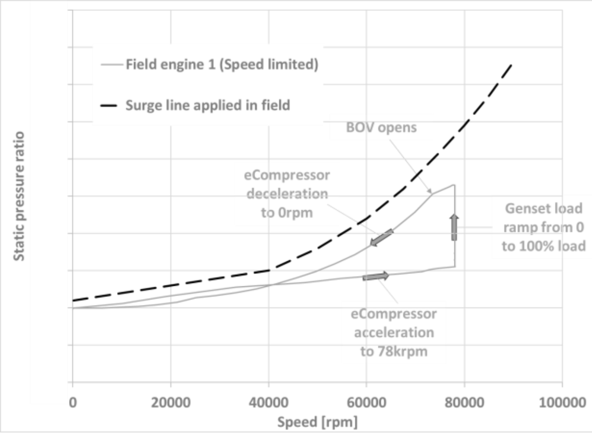

Figure 21. StartIQ™ operating map for Field engine 1 with 78krpm speed limited control

Genset performance and 30-day trial

Following the system tuning work, both StartIQ™ system and genset were left unmanned and running automated for a 30-day trial.

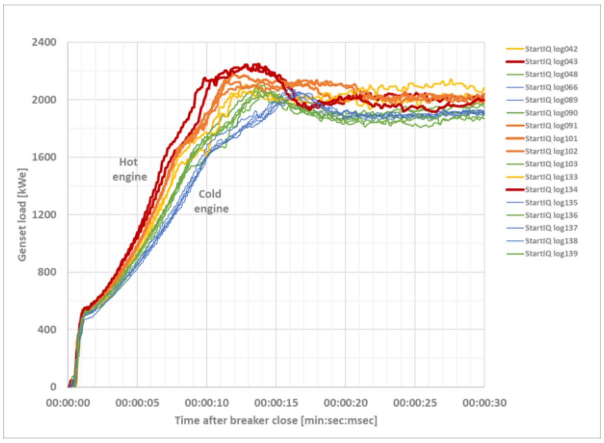

Figure 22. StartIQ™ logs recorded during 30day field trial on customer genset.

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 22. 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 are colour coded, red for hot engine through to blue for cold engine) to highlight this effect.

The test data highlighted the need for further optimisation of the system and genset. Cold genset starts were not always achieving the target 15s load ramp, and there was insufficient enthalpy in the exhaust to maintain 100% load until approximately 30s 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.

Genset and StartIQ™ system optimisation

To improve the cold and hot genset load ramp performance the genset, ICE and StartIQ™ system calibrations were adjusted, results can be seen in Figure 23.

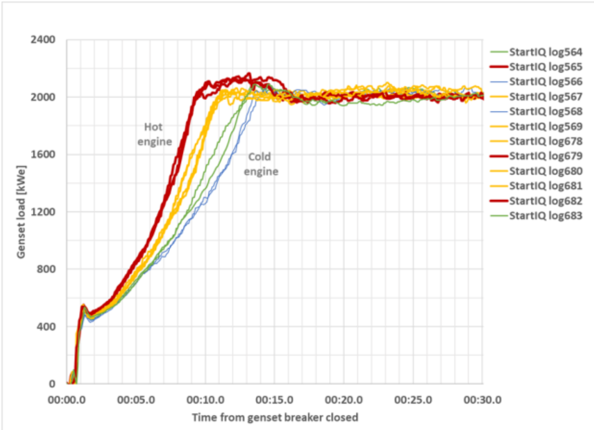

Figure 23. StartIQ™ logs recorded following optimisation of genset, ICE and StartIQ™ system.

During the 30s phase after the StartIQ™ system disengages at 2MWe with cold ICE, the ICE 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 ICE is starting from a hot or cold condition and the timing of disengaging the StartIQ™ system adjusted accordingly.

The hot ICE load overshoot was fundamentally a result of the genset controller PID loop saturating during the load ramp, and once 2MWe genset load is achieved taking some seconds to unwind the integral part. The settings of the genset load controller were adjusted to successfully decrease the load overshoot.

This lead TRL7 system accumulated more than 1600 successful genset load ramps assisted by StartIQ™ before upgrading the system on this genset in Q2 2024 with a production intent, system to match the other 9 gensets on site.

Full 20MWe site test against grid requirements

Nine production StartIQ™ systems were installed and commissioned on the remaining Gensets at the customer's 20MWe gas peaking site in the UK with automated site level 20MWe starts commencing in November 2023. The aim was to track and improve the site level performance as measured against the UK's National Energy System Operator (NESO) upcoming Quick Reserve (QR) service [7]. At the time of authoring this paper, over 10,000 automated starts with StartIQ™ assisting the genset load ramps to full load (i.e. equivalent to ~1000 site level starts) have been accumulated.

Quick Reserve is aimed primarily for reacting to pre fault disturbances to restore the energy imbalance quickly and return the frequency close to 50.0 Hz. It is intended to be operated by units for short periods, before handing over to other slower reacting units to be brought online within 15minutes to replace the QR units (this 15-minute balancing will be serviced by units operating in the upcoming Slow Reserve (SR) market, Figure 24).

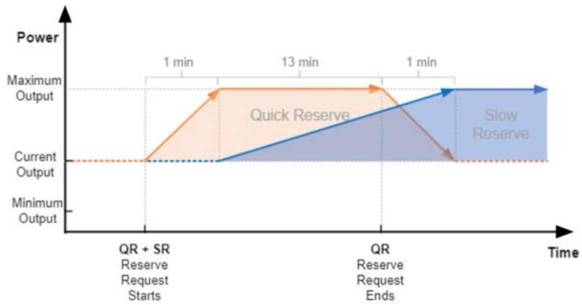

Figure 24. NESO [7] QR and SR explanation

QR is separated into Positive Quick Reserve (PQR), (where units are requested to increase generation) and Negative Quick Reserve (NQR) (where units are requested to increase demand, or consumers to reduce demand). Figure 25 shows how the PQR market is designed using the following parameters

- Time to full delivery – Less than 60s after the 'Reserve Request Starts'
- Time at full delivery – Minimum 3 minutes, maximum 13 minutes.
- Cease time – Maximum 60s after the reserve request ends
- Activation Period – Equal to 'Time to delivery' plus 'Time at full delivery' plus 'Cease time', minimum 5 minutes, maximum 15 minutes
- Recovery period – Minimum 3 minutes

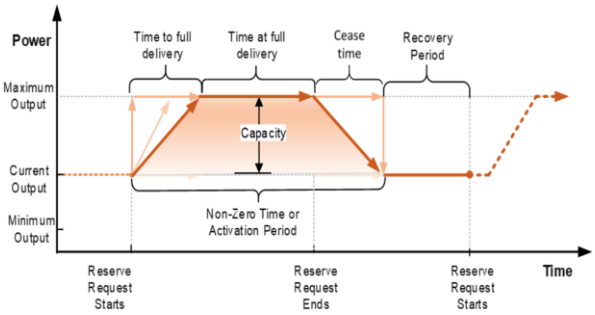

Figure 25. NESO [7] PQR explanation

Taking the PQR minimum Activation period and minimum recovery periods into account it is feasible that the StartIQ™ system could be called upon with only 8 minutes rest between load ramps. Hence, bench testing (Figure 17) was performed under this operating mode.

Figure 26 similarly shows the result of back-to-back engine starts performed by the customer, the first start being with cold pre-heated genset and subsequent starts with the genset hot. Despite having considerably higher ambient temperatures (approximately 25°C hotter than during bench testing) the high volumetric airflow within the ICE room, together with the shorter duration runs needed with the ICE in hot condition, resulted in the bearing temperatures stabilising at lower final temperature than measured during bench testing (Figure 17).

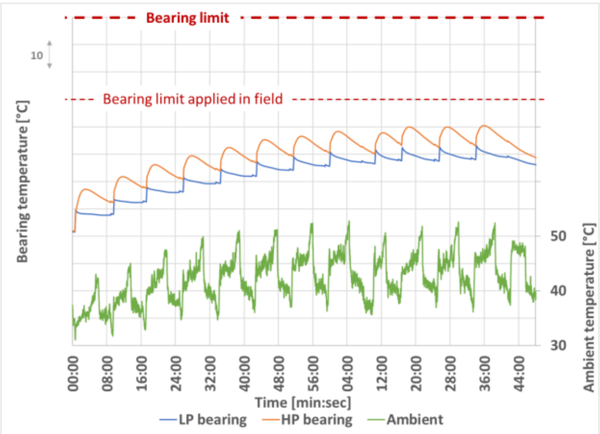

Figure 26. Customer back-to-back start testing to prove worst case PQR requirements can continuously be met by StartIQ™.

Approximately 15°C margin is maintained to the field bearing limit applied while the eCompressor is running (Note approximately 6°C heat soak occurs after the StartIQ™ system is shutdown) giving confidence that the Genset and StartIQ™ system could meet the most aggressive load profile possible within PQR.

Figure 27 shows the most recent snapshot from the customer site of the 'Time to full delivery' performance (Start command to 2MWe) of approximately 2100 individual Genset starts as measured at the genset. With the most recent improvements (made together with the genset OEM) to reduce the time for the Genset to synchronise to the grid, the PQR Time to Full Delivery has significant margin to the 60s requirement.

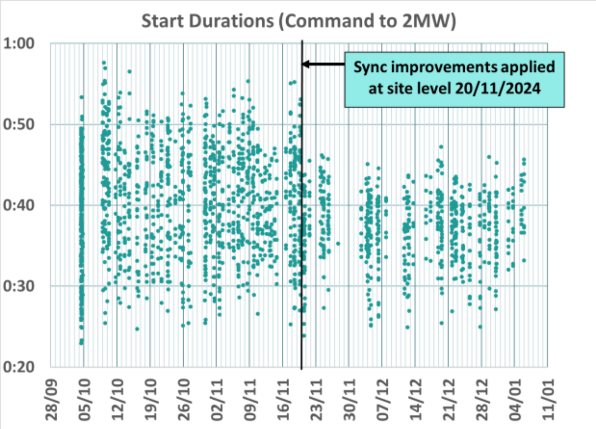

Figure 27. Genset level 'Time to full delivery' performance (Start command to 2MWe)

The UK NESO QR market went live on the 3rd of December 2024.

4.2.2 Field Engine 2

Similarly, the StartIQ™ system was integrated into another Customer spark ignited natural gas genset to demonstrate achievable start performance. The OEM design strategy for Field Engine 2 was very different versus Field Engine 1, with 4 less efficient low inertia turbochargers applied to the ICE. Together with a turbo match allowing for 100% load operation at extreme ambient temperatures, much higher exhaust back pressures versus those observed with Field Engine 1 were apparent and therefore the eCompressor system would need to target the highest achievable speed to maintain margin to surge as the genset approaches 100% load.

Figure 28 shows the operating map with StartIQ™ operating in Torque limiting mode (with the maximum 90krpm speed targeted while applying the maximum current limit throughout the genset load ramp). An impressive, controllable cold pre-heated genset load ramp of 6s could be achieved. However, when the genset was hot, control of the ICE turbocharger acceleration and genset load control as it approached 2MWe in less than 4s proved challenging.

With turbos having ~20 times less inertia versus the Field Engine 1, and without access to the ICE or Genset governing controllers to improve the load genset control, a different operating strategy for the StartIQ™ system was required. The eCompressor flow was reduced considerably during the early part of the genset load ramp by reverting to a flow limited control strategy. This was achieved by initially targeting 45krpm speed when the genset breaker closed and then increasing the target speed as the eCompressor outlet pressure increased, Figure 29.

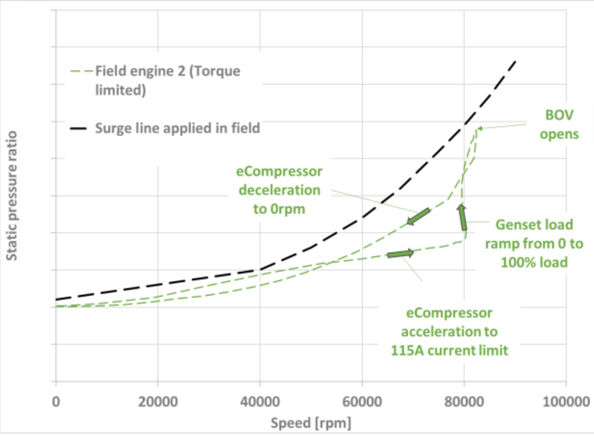

Figure 28. StartIQ™ operating map for Field Engine 2 with Torque limited control

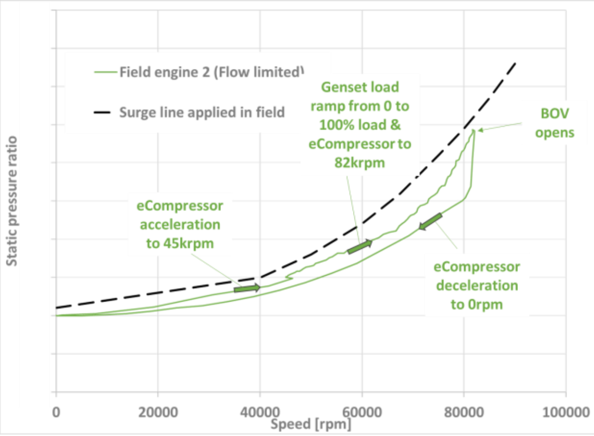

Figure 29. StartIQ™ operating map for Field Engine 2 with Flow limited control

Additionally with the operating line closer to the Surge line on Field Engine 2, the eCompressor was delayed from decelerating at the time of disconnecting from the Genset. This meant the BOV would open ensuring the eCompressor pressure ratio reduced before the eCompressor speed reduced ensuring the surge margin of the eCompressor was maximised throughout the disconnection process. (This effect can be observed when comparing Figure 21, with the operating line for Field Engine 1 moving towards the surge line as the eCompressor speed decelerates before the BOV physically opens)

With this new strategy together with early disconnection of the StartIQ™ system when the ICE was hot (at ~75% load), it was possible to achieve a hot genset load ramp time of 6s to 100% load, reliably without load overshoot. This compromise resulted in the cold preheated load ramp time increasing to 9s (versus 6s achieved with torque limited control).

4.2.3 Field Engine 3

Similarly, the StartIQ™ system was integrated into an OEM spark ignited natural gas genset, again with a different baseline ICE design strategy. The ICE with a single high efficiency turbocharger, had much higher levels of Miller Cycle together with 22bar BMEP resulting in an even higher exhaust pressure requirement. Using Torque limited control (Figure 30), an impressive 10 second and 6 second load ramp to 100% load could be achieved for cold pre-heated and hot ICE conditions respectively.

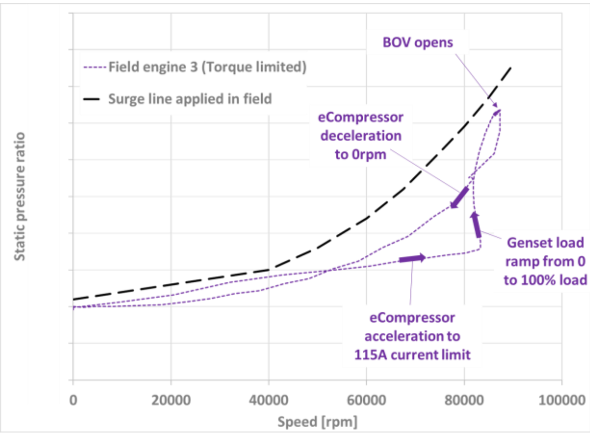

Figure 30. StartIQ™ operating map for Field Engine 3 with Torque limited control

Unlike Field Engines 1 and 2, spark timing retard alone was not sufficient to overcome the lack of temperature within the exhaust gas once 100% was achieved, with a 15 to 20% load dip occurring upon disconnecting with cold pre-heated starts. To overcome this, the eCompressor was maintained running at maximum torque until the ICE governing reserve was high enough to maintain 100% load, approximately 15 additional seconds after 100% load was achieved (i.e. when the exhaust manifold and turbocharger turbine were sufficiently hot / the exhaust enthalpy driving the turbine was high enough for the turbocharger to achieve the ICE boost pressure requirement at 100% load).

More importantly, the ability to keep the eCompressor on after full load was achieved, enabled the possibility to perform the genset load ramp without any fueling enrichment, and still achieve 100% load genset load and hold it steady afterwards while achieving steady state emissions. Without StartIQ™, the baseline ICE starting from cold pre-heated condition, was using fueling enrichment for approximately 40s, with NOx emissions so high they were outside the measurable range of the emissions equipment. With StartIQ™, the genset starting from cold pre-heated condition, the NOx emissions could be controlled, with the average over the load ramp below 500mg/Nm3 at 5%O2. Only 2s increase in the load ramp was observed during the no enrichment StartIQ™ runs versus the equivalent runs with fueling enrichment (2500mg/Nm3 peak, with average exceeding 1500mg/Nm3).

The ability to start quickly without the need to enrich or increase NOx emissions, is particularly useful in applications where the emissions of Gensets are continuously monitored, as is increasingly becoming the case in Europe.

4.3 Simulation of further applications and ICE layouts

4.3.1 Off grid - Simulated engine 4

A 1MW 22bar BMEP gas engine simulation model correlated to island mode load steps and emergency standby testing for project work carried out by Bowman investigating eTurbocharging benefits in 2020 [1], was adapted to incorporate StartIQ™.

For reference, for grid balancing this model with StartIQ™ applied in Torque limiting mode, results in a predicted 6 second cold preheated load ramp from breaker closed to 100% load. With the inertia of the turbo increased to that of Field Engine 3, an 11 second cold preheated load ramp is simulated.

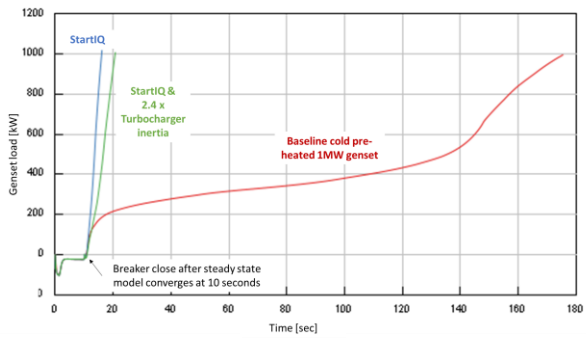

Figure 31. Simulated engine 4 - Predicted on grid load ramp time with StartIQ™ applied firstly with the baseline ICE Turbocharger and with secondly a larger frame sized turbocharger (2.4 x inertia) applied.

Island mode

For island mode operation it is beneficial that the StartIQ™ system eCompressor idle at a low rpm with the BOV open all the time the genset is running. Under this condition the eCompressor temperatures, bearing temperatures and power consumption are low as little work is done by the compressor stages. For example, idling at 10krpm, the power draw from the eCompressor is approximately 300W.

In the event of an Island mode load step, the eCompressor will accelerate much faster from 10krpm to its maximum speed, ~0.7s, versus 1.2s if started from 0rpm. The timing of closing the BOV would then be dependant on the genset starting load / exhaust pressure, as described in section 3.4, Figure 8.

Several basic assumptions were made within the model to ensure a fair comparison for the simulations with and without StartIQ™ applied.

- 80ms to detect the load step, regardless of magnitude.
    - A further 80ms ramp for throttle, compressor bypass, and fuel control valve to saturate once the load step detected.
    - A further 20ms for the eCompressor motoring torque to reach 115A limit once load step detected. (Totalling 100ms delay between load step application and eCompressor acceleration)
- The BOV is commanded open when the eCompressor has accelerated to a speed high enough (taking the BOV opening delay time into account) to overcome the exhaust back pressure without risk of surging.
    - The BOV is assumed to have a delay of 100ms from command to opening.
- The commands were saturated through the transient with no consideration for smooth genset load or speed recovery.
- Fuelling enrichment used the same lambda limit curve based on intake manifold pressure.
- The same Automatic Voltage Regulator (AVR) settings were used to reduce generator voltage as frequency decreases to aid with the genset load recovery.
- The eCompressor system kW was not taken into account as it is assumed the PE would be modified to remove the grid connection and replace it with a suitable battery and battery management system.

Table 4 shows a summary of load steps conducted from 25% starting load (Worst case starting condition for load acceptances for the ICE as found previously [1]), with the genset responses assessed against ISO 8528 pt5 spark ignited gas engine class G1, G2 and G3 for frequency deviation and response time requirements [8]. The colour coding assigned, shows if the individual requirement has been passed, blue for G3, green for G2, Orange for G1. If no class could be assigned, grey and finally if the genset did not recover at all within the simulation, grey with comment 'Not Applicable' (NA).

Table 3. Simulated Engine 4 – Predicted genset response from 25% load, with block load steps applied in 5% increments.

Block load applied		Baseline		StartIQ	
Start load	End load	Speed deviation	Recovery time	Speed deviation	Recovery time
%	%	rpm	s	rpm	s
25	35	1468	1.7	1472	1
25	40	1425	3.3	1442	1.3
25	45	1363	4.9	1406	1.6
25	50	1287	7.3	1367	1.8
25	55	1202	10.7	1326	2
25	60	1113	19	1284	2.3
25	65	NA	NA	1241	2.5
25	70	NA	NA	1199	2.7
25	75	NA	NA	1157	2.8
25	80	NA	NA	1115	3
25	85	NA	NA	1074	3.2
25	90	NA	NA	1037	3.4
25	95	NA	NA	NA	NA

Genset parameters	SI gas engine ISO 8528-pt compliance			
	Class	G1	G2	G3
Freq deviation	%	-25	-20	-15
Speed at deviation	rpm	1125	1200	1275
Recovery time	s	10	5	3

Summary of findings (interpolated from Table 4)

- Taking speed deviation and recovery time into account, load step compliance from 25% starting load can be increased
    - from 14% to 35% for G3
    - from 20% to 44% for G3
    - from 28% to 54% for G3
- Taking frequency deviation only into account, load step compliance from 25% starting load can be increased
    - from 25% to 35% for G3
    - from 30% to 44% for G3
    - from 34% to 54% for G3

Figure 32 shows an example of how the results in Table 4 were generated, a 25 to 50% load step, with and without StartIQ™ applied. As the exhaust pressures are relatively low at the beginning of the transient, ~ 1.4bar, the BOV can be commanded closed after the eCompressor speed exceeds 30krpm (approximately 0.3s after the load step is applied) with the valve then actually opening as the eCompressor speeds through 45krpm (approximately 0.4s after the load step is applied) and onward to its maximum speed. The extra acceleration given to the ICE turbocharger by StartIQ™, has a strong influence on reducing the genset speed deviation and a dramatic recovery time following the load step, particularly if the load step applied is large. For this example, with StartIQ™ applied the ICE can now achieve class G3 compliance for both frequency deviation (<15%) and recovery time (<3s), Table 4.

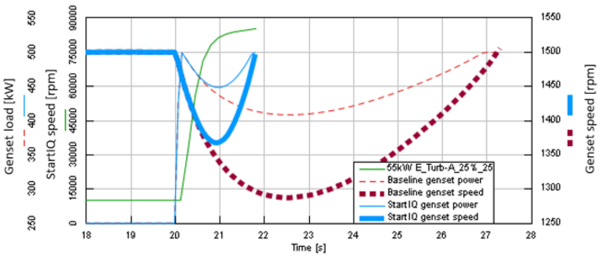

Figure 32. Simulated Engine 4 – Predicted Island mode 25 to 50% load step with StartIQ™ applied. Note: Load step is applied after convergence is achieved at 20s.

Note: the low-speed idling method with BOV open post eCompressor run, has been proven on bench test to rapidly cool the eCompressor machine and bearings, enabling the possibility to achieve duty cycles considerably more aggressive than that described in Figure 17.

Emergency standby

For emergency standby scenarios, the StartIQ™ eCompressor can be used to great effect. By accelerating from rest in Torque limiting mode as soon as the ICE starts firing during its start sequence (at approximately 200rpm), until the end of the load step significant benefits can be realised, Figure 33.

This is possible as the ICE turbocharger is accelerated during the ICE speed ramp, and when the ICE reaches target speed, 1500rpm, the turbocharger is close to 3 times faster than without StartIQ™ applied. This enables a 100% block load to be immediately applied to the ICE while achieving ISO 8528 spark ignited gas engine G1 [8]. Only a 32% load step is possible without StartIQ™ applied.

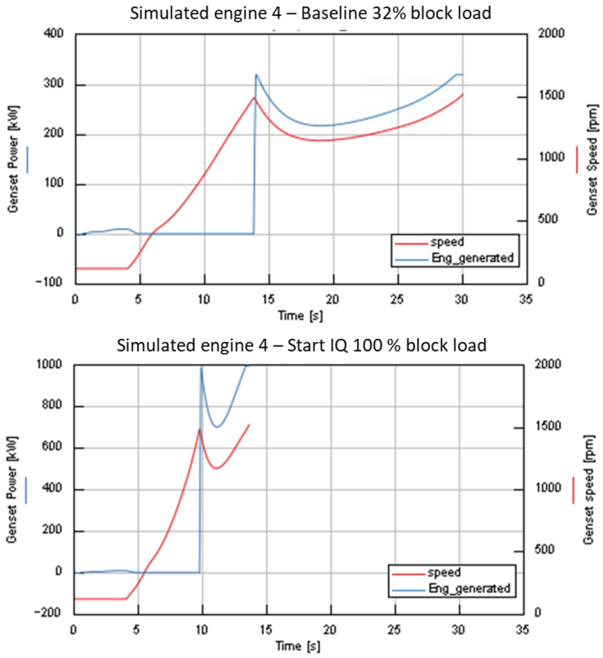

Figure 33. Simulated Engine 4 - Predicted Emergency standby performance with StartIQ™ applied.

Note: For reference replacing the Simulated Engine 4 turbocharger with the next frame size up (by increasing the inertia by 2.4 times, equivalent to Field Engine 3 turbocharger inertia), a maximum 60% block load step is simulated while achieving ISO 8528 spark ignited gas engine G1 [8] compliance.

4.3.2 Two stage turbocharging - Simulated Engine 5

Applicability of the StartIQ™ system can be extended to also cover two staged turbocharged ICEs. By applying the system to inject air between the outlet of the ICE HP turbine stage and the inlet of the ICE LP turbine stage transient improvements from 0 to 100% load can be provided. This gives a good benefit in terms of reducing turbocharger lag, but is far from optimal, as the increase in ICE HP turbine outlet pressure during the transient phase limits the HP turbocharger acceleration.

By alternatively connecting the outlet of the StartIQ™ eCompressor to both the ICE exhaust manifold before the ICE HP turbine, and between the ICE HP turbine outlet and ICE LP turbine inlet, the possibility to provide maximum acceleration at the beginning of a genset load ramp, as well as transient assistance up to 100% genset load can be realised. This requires two mechanical NRV's, one between the StartIQ™ system and the ICE HP turbine (ICE HP NRV), a second between the StartIQ™ system and the ICE LP turbine (ICE LP NRV), and an additional electronically controlled

Admission Valve (ADV) placed before the ICE LP NRV, Figure 34.

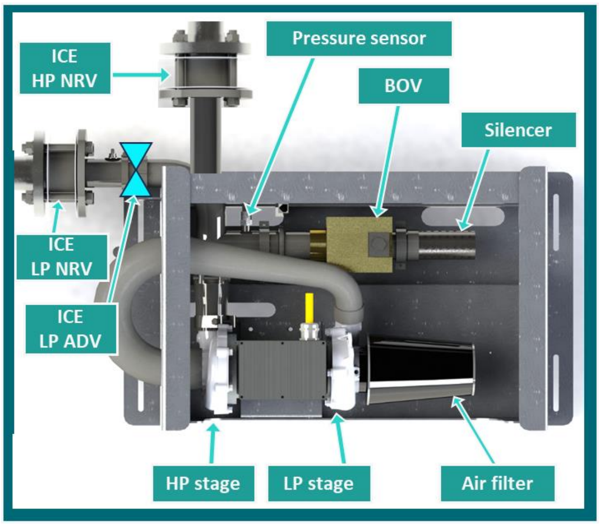

Figure 34. Recommended StartIQ™ eCompressor system layout for two stage turbocharged ICE.

With this layout the operation of the system is as described previously, with only the additional ICE LP ADV actuation to be considered.

At the beginning of the load ramp the ICE LP ADV is in its closed position, ensuring the air flow is delivered to, expanded through the ICE HP turbine and then the LP turbine stages, accelerating both. Later, as the genset load increases and before the StartIQ™ eCompressor approaches its surge limit the ICE LP ADV is opened and the StartIQ™ eCompressor flow diverts to the lower pressure ICE LP turbine stage only (the ICE HP NRV closes due the reverse in pressure drop across it). The ICE LP ADV remains opened until after 100% genset load is achieved and the system is disconnected from the ICE as previously described (BOV opens and eCompressor decelerates to 0rpm).

A 4.5MW 25bar BMEP two stage turbocharged spark ignited natural gas ICE was simulated with two StartIQ™ systems (one per bank) incorporated into the model to analyse the benefits, Figure 35. With the StartIQ™ systems connected to the LP stages only, a 0 – 100% load ramp time for cold pre-heated genset of 41s was predicted versus 173s for the baseline ICE. With the StartIQ™ systems connected to both HP and LP stages, as described above, 0 – 100% load ramp time for cold pre-heated genset of 26s was predicted.

Note: Simulated Engine 5 is port injected, therefore, although not simulated, the opportunity to use StartIQ™ on the ICE’s intake side would exist, either to only inject air between the LP and HP compressor stages or alternatively to inject post the HP compressor stage then switch to between then LP and HP compressor stages as the genset load increases.

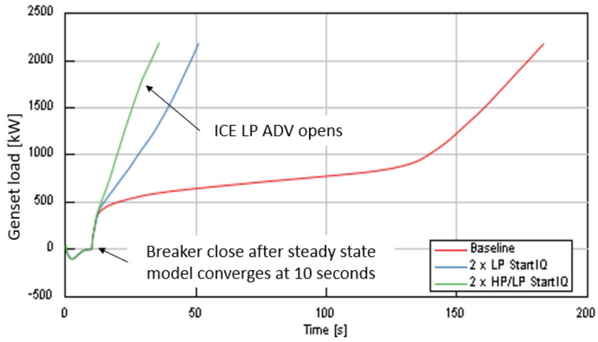

Figure 35. Simulated Engine 5 - Predicted on grid load ramp time with StartIQ™ applied. Note: only half the ICE / 1 bank was simulated.

5 SUMMARY AND OUTLOOK

Bowman eTurbo systems have successfully developed a 55kWe, 2-stage eCompressor system (StartIQ™) which can be installed to 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 ICEs > 2.5MWe). This allows for easy integration to existing OEM genset portfolios with minimal development time or investment.

Table 4. on-grid load ramp benefit with StartIQ™ applied to various SI ICE specifications

		Spark ignitied Pre-mixed NG engine						NG PI
		Field engine tested				Engine simulated		
		1	2	3		4		5
Rating	MW	2	2	1.25		1		2
BMEP	bar	18	18	22		22		25
Miller cycle		Light	Light	Medium		Strong		Strong
Est turbo inertia	kgm3	0.045	0.002	0.024		0.01	0.024	0.07 & 0.015
Number of turbos		1	4	1		1		2 x 2 stage
Number of Start IQ		1	1	1		1		2
		On grid 0 - 100% load ramp time						
Cold / pre-heated engine - baseline	s	85	60	55	NA	165	NA	173
Cold / pre-heated - StartIQ	s	13	9	10	12	6	11	26
Hot engine - StartIQ	s	9	6	6	8	-	-	-
StartIQ control limiting		Speed	Flow	Torque	Torque	Torque	Torque	Torque
Genset enrichement		Less	same	same	none	same	same	same

Field tests, and simulations (through chapters 4.2 and 4.3) show, that it is possible to entirely decouple the transient requirements of high-speed SI ICEs from the conflicting design philosophy of trying to achieve highest fuel efficiencies and power densities. The addition of the StartIQ™ eCompressor system to the exhaust system upstream of high-speed ICE turbocharger turbines, allows for fast load ramping to be reliably and repeatably achieved regardless of the engine type, fuel, condition (hot or cold/pre-heated), ambient condition or even the level of fueling enrichment utilised, Table 4.

The use of the StartIQ™ eCompressor has also been shown to be adaptable to off grid applications unlocking the possibility to perform

- 100% block load steps with high-speed SI gensets in emergency standby or backup power applications.
- Significantly reduced island mode load steps recovery times together with larger loading capability.

6 ACKNOWLEDGMENTS

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[7] NESO, https://www.neso.energy/industry-information/balancing-services/reserve-services/quick-reserve#Technical-requirements

[8] ISO 8528 pt5, 2005, Reciprocating Internal Combustion Engine Driven Alternating Current Generating Sets – Table 4 – Performance class operating limit values