New Generation of Electric-Turbo-Compounding (ETC) for Reciprocating Engine Generator Sets

Dr S Szymko

Bowman Power Group Ltd, Southampton, UK

Synopsis

Electric Turbo-Compounding (ETC) is a waste heat recovery system which has proven application in the recovery of energy from the exhaust of reciprocating engine generator sets. The ETC system converts a portion of the waste energy into grid quality electricity which can be exported or used locally and therefore increases the electrical efficiency and power density of the host generator set.

This paper reports on the output from an Innovate UK project as well as a Department of Energy and Climate Change (UK) project which supported the development of a new 'clean sheet' generation of ETC systems, robust enough for use in both Land and Sea applications.

The development of a 'clean sheet' design requires a clear project framework and design methodologies to be in place in order for the project to be successful. An overview of the main stages, methodologies and key design decisions are discussed. These include key early stage decisions such as defining the rated power of the machine as well as defining the innovations which has resulted in a 40% reduction in system cost. The paper concludes with a case study illustrating the real world efficiency and power density gains which can be attained.

Keywords: Electric Turbo-Compounding; waste heat recovery

1. Introduction

Diesel and gas reciprocating generator sets are globally used to produce electrical power. Applications range from the support of both large (national) and small (e.g. remote community or island) grids, through to industrial sites, factories, mines etc. and as a backup power source for critical operations such as data centres and hospitals. Generator set power output can range from less than 100 kWe to greater than 20 MWe.

The benefits of reciprocating engines are clear, examples include, low capital cost (particularly for diesel), simple to deploy and maintain, and their mobility is high (sets up to 2MWe can be containerised) with fast demand response times.

Cost of operation however is more challenging and the fuelling of these gensets can far exceed the capital expenditure of purchasing these systems in a single year. As an example, a 1 MWe generator set can combust in the region of 1,600,000 litres of fuel per year if running continuously at high load, which at a cost of $0.8/lt is a cost of $1.3m per year which is between 5 and 10 times the initial generator set cost.

There is a clear commercial drive to reducing fuel usage for the same power output (increase in system efficiency). There is also an environmental drive to decrease both pollutants and greenhouse gas emissions.

A range of potential methods can be employed to increase system efficiency to reduce fuel usage. Examples of methods to increase efficiency have centred on the following categories: 1) core engine improvements 2) air system improvements 3) waste heat recovery 4) site efficiency and power usage optimisation.

This paper focuses on the development of a waste heat recovery method called Electric Turbo-Compounding (ETC). This method utilises a high speed turbo generator to recover a proportion of the engine's exhaust energy which is converted directly to grid quality electricity.

Examples of industrial use of ETC use can be found in the following references [1] - [4].

Commercially, it is understood that the cost of fuel has a large influence on the return on investment of any power system including an ETC system. Bowman Power Group has delivered over 700 such ETC systems with over 18 million running hours accumulated. In 2014, the commercial cost driver instigated a development project with a key focus on reducing the capital cost of an ETC system. Enabling support from both the Department of Energy and Climate Change (UK) and Innovate UK has assisted a 'clean sheet' next generation ETC system development incorporating the function and reliability learnings from earlier products.

This paper focuses on the land based application of these products and outlines the development process, highlighting the key decision points and design decisions before discussing the validation process. Finally a case study is presented with an overall conclusion.

2. Electric Turbo-Compounding (ETC)

Electric Turbo-Compounding (ETC) is a technology which can be employed to recover energy from the waste heat of a reciprocating combustion engine, whether it is diesel or gas fuelled.

Figure 2 illustrates an electrically turbo-compounded generator set where a turbo generator (TG) is placed downstream of the engine's turbocharger in order to recover further exhaust gas energy. The electricity output from the turbo generator is typically > 1, 000 Hz and is therefore converted to grid quality electricity (or DC) by using a power electronics (PE) converter.

To maintain engine performance the turbocharger (TC) must be re-matched due to the change in backpressure it sees from the TG. The PE converts the TG output into grid-quality 50 or 60Hz 3-phase power or simply regulated DC.

An alternative configuration can be seen by Figure 2 where the TG is placed in the wastegate flow of the engine. In this configuration the TC does not need to be re-matched as the TG does not change engine performance. This configuration is described in reference [1].

The power generated can be used for: site ancillary loads, remote community power, industrial loads, grid export or even for offsetting the engine parasitic (ancillary plant) losses.

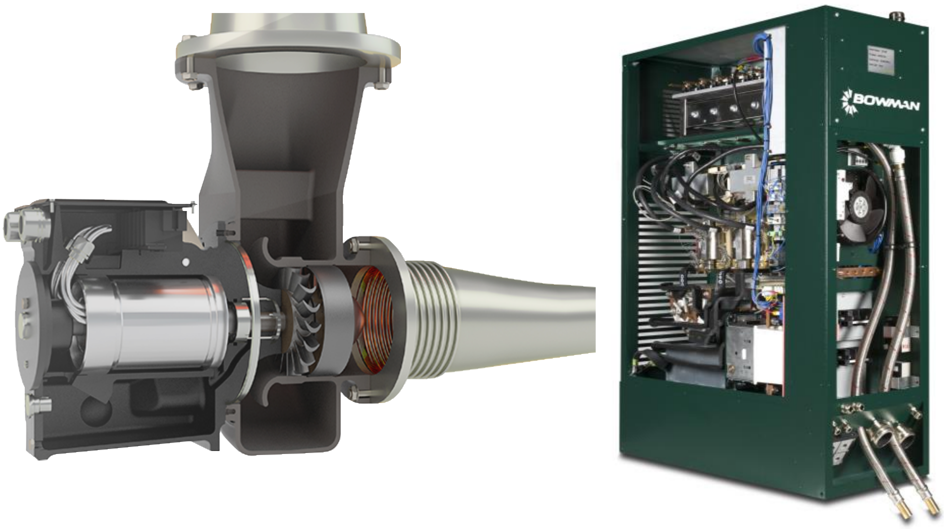

Figure 1: Cutaway of ETC turbo generator and power electronics module

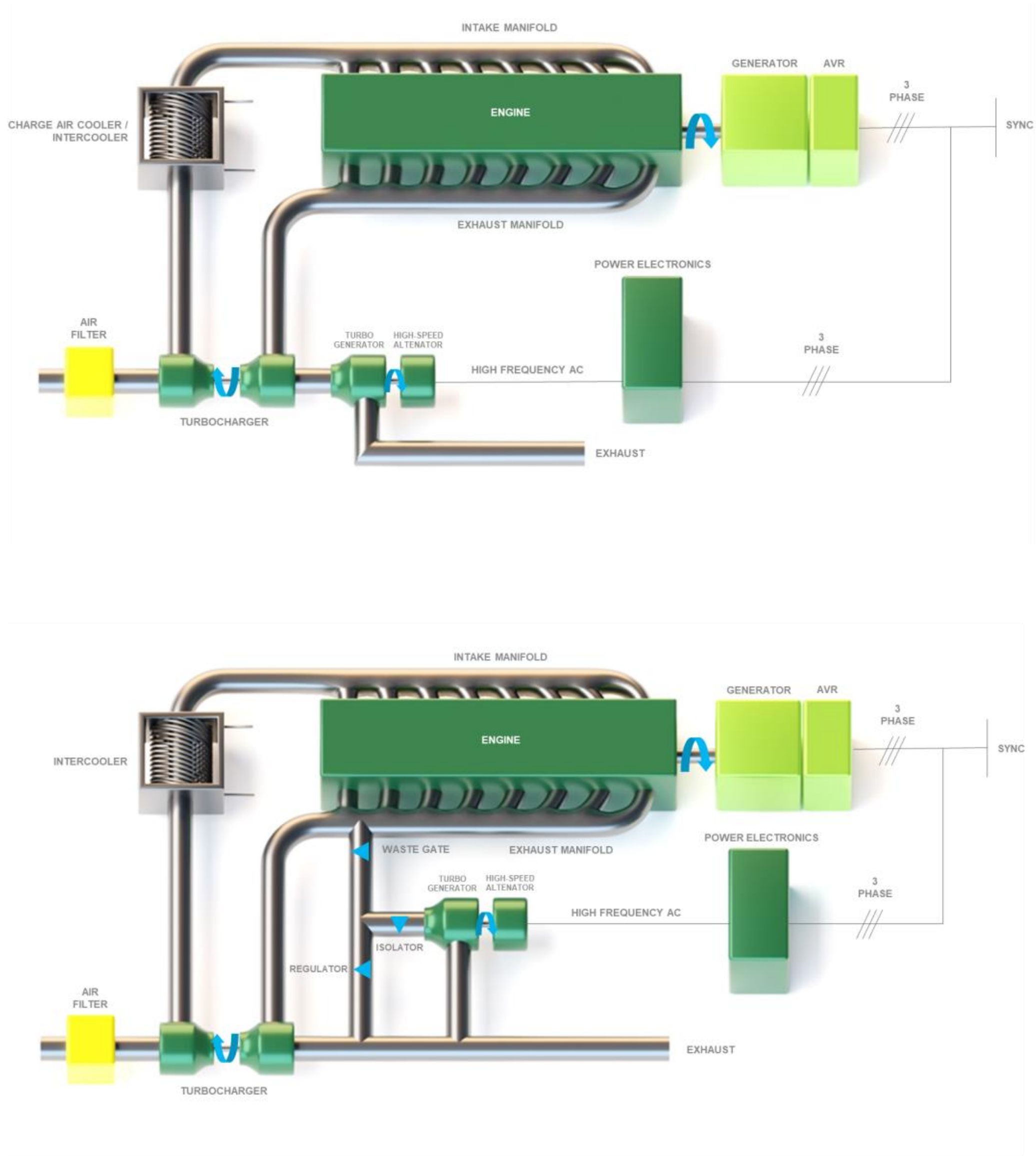

Figure 2: Electric Turbo-Compounded (ETC) engine: series (top) and parallel (bottom) configuration

3. ETC system development

A new clean sheet product development is a major undertaking. This type of development is conducted when a step change in technology, function, application and/or cost is required. To ensure the most value is obtained from a costly development project, clear understanding of the market drivers is essential as well as forging the right partnerships to ensure other expertise can feed into the development process and firstly building a business case to pitch for the financing. Table 1 provides an overview of the project information.

Table 1. Key project development information

	Aim	Comments
Project drivers	40% lower product cost	Fuel cost volatility resulting in acceptable ROI being highly dependent on fuel price. Target < 18 month ROI. Generator set $/kWe significantly lower than typical energy recovery $/kWe
	50% improvement in product reliability	Target to minimise total cost of ownership
Project scope	Clean sheet design for both the turbo generator (TG) and power electronics (PE)	These are the core components of an ETC system and the clean sheet design allows the two components to be optimised together.
Markets	Land and marine	This paper focuses on the stationary power generation land based application
Key requirements	Compatible with major OEM gensets over the power range of 400 kWe to 2 MWe: Cummins, Caterpillar, GE Jenbacher, MAN, MTU, MWM as examples	The requirement implies a generic system which can be applied to a range of generator sets. Prior to this project Bowman's turbo generator applicability was up to 1.2 MWe – this project was to extend this range to cover the core market identified.
Funding	DECC UK – Turbo generator Innovate UK – Power Electronics Internal funding	DECC - Total project grant ~£0.7m Innovate UK - Total project grant ~£1.1m
Partners	DECC – Cummins Powergen (UK) Innovate UK – Rolls Royce, Lloyds Register, University College London	Key partners to assist with specialist knowledge, skills and test facilities.
Project time frames	DECC – 2014 – 2017 Innovate UK – 2014 - 2018	

3.1. Product development framework

A proven method to develop a successful product is to utilise the gate process, an example is specified in ISO 15288. This method is useful to ensure the right level of rigour is conducted prior to moving through to the next phase of development so allowing the smooth and efficient flow of information between a cross-functional team.

The process developed by Bowman is summarised by Figure 3, which highlights the phases and key steps within these phases to take the product from an Opportunity to Production Release. Although not described, additional phases take the product through to its end of life.

There are key decisions which occur at an early stage of the development which fix the product applicability and product costs and therefore it is critical to get this right for the success of the product. As such, this paper focuses on some of these decisions, highlighted in green on Figure 3.

To highlight the importance of project rigour and making important decisions early, Figure 4 is illustrative of the committed product cost in relation to the project phase gate, where the committed costs occur early in the design process.

Figure 3: Product development gate process

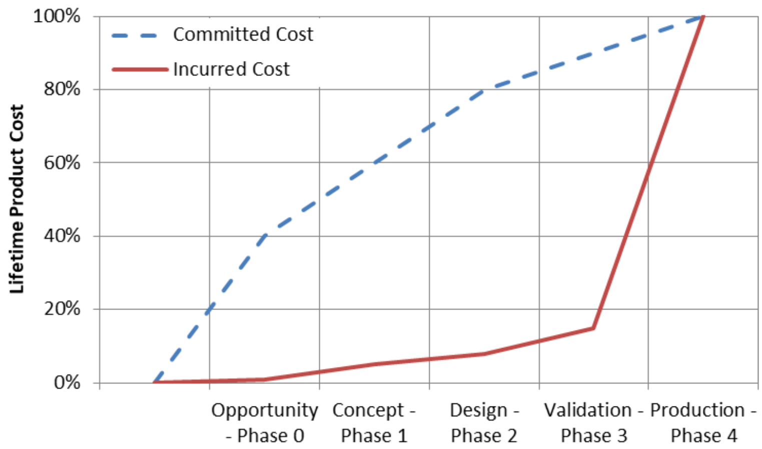

Figure 4: Committed cost during product development

3.1.1. Phase summary

Phase 0: During this phase the partners were assembled and the top level project requirements were agreed.

Phase 1: A key phase for embedded cost: the requirements are captured and significant cost is embedded during this phase.

Phase 2: A key phase for embedded cost: the designed is progressed to design freeze and the majority of the committed cost is embedded early within this phase

Phase 3: The product is verified and validated, from functionality, safety, supply chain, and cost perspective.

Phase 4: The product is approved for production.

3.2. Key Decisions and Design Methodologies

The following section describes the key decisions and methodologies that were made to develop the ETC system. These key decisions fall into two categories: 1) Key market drivers 2) Embedding product cost.

Table 2. Key requirements and decision points

Key market drivers	**Embedding product cost**
Core market (power output requirement)	Turbo generator – Axial flow or radial flow turbine?
System efficiency requirement	Turbo generator – Packaging (horizontal or vertical machine?)

System cost requirement	Turbo generator – Electrical machine architecture?
	Turbo generator – Bearing architecture?
	Power electronics – Silicon choice/IGBT voltage?
	Power electronics – Switching frequency?
	Power electronics – Active versus passive components

3.2.1. Key market driver inputs

During phase 0 and 1 of the project, key requirements were set which define the overall output of the project. A key requirement is the definition of the product power capability. For a single application this can be a straight forward process but for this project, the top level requirement was to have the minimum product family that can address a generator set market ranging from 400 kWe to 2 MWe.

In order to understand how this can be achieved the following simplified steps were taken:

1. Define key generator sets in each power band (typically every 200 kWe increment).
2. Define expected ETC applicable generator set numbers for each power band.
3. Define a turbo generator and power electronic cost model versus power output
4. Define expected ROI and weighting factor (ROI versus sale conversion rate)
5. Simulate a generic ETC system in each power band to understand the ideal power output requirement.
6. Weight the results with the ROI weight factor to broadly identify the key product power points
7. Generate a customer benefit function (fitness function) and map gensets to identify optimum product power point.

From this process an optimisation map could be created which allows a quantification of the most commercially advantageous product power point. This is shown by Figure 5 which effectively shows the Internal Rate of Return for various gensets covering the 400 kWe to 2 MWe range and an overall parameter which includes genset sale quantity estimators to provide a single output (overall fitness function).

This analysis provided a clear indication that the optimum product power point was 110 kWe and this was subsequently set as a soft design requirement (until the cost model was verified).

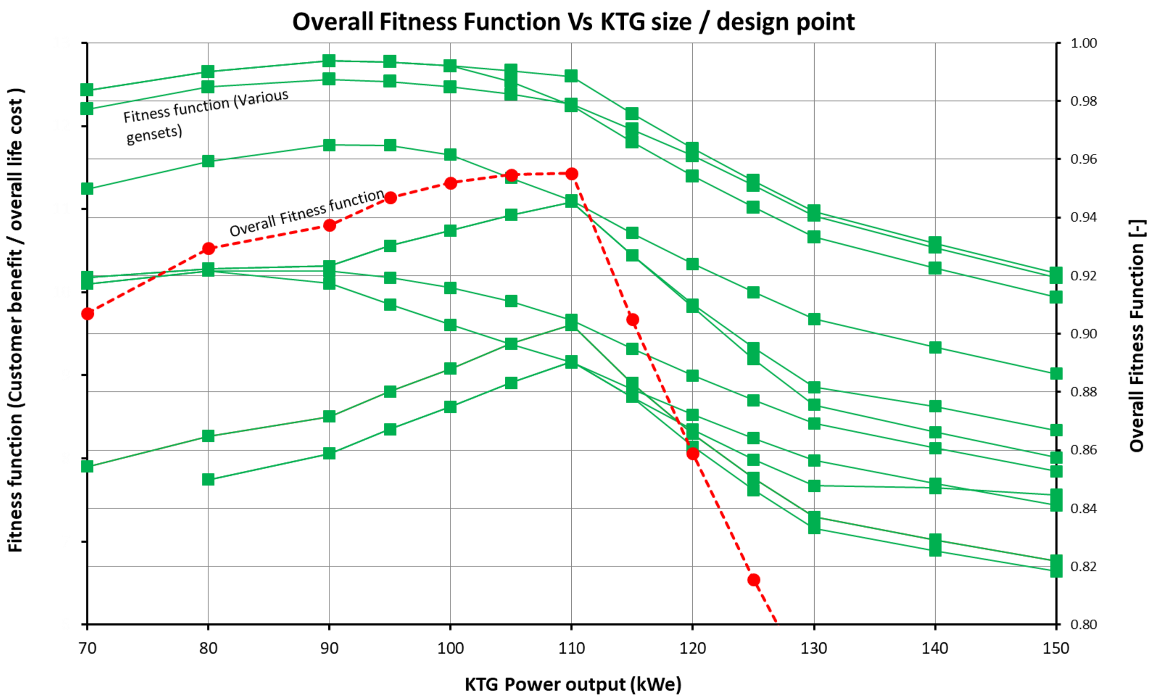

Figure 5: ETC system power decision optimisation

3.2.2. Design Decisions

In order to meet the design requirements of phase 1, a number of design options are available and each one will embed product cost and/or change the ease of applicability of the product to different applications. This discussion has been separated into the turbo generator decisions and the power electronic decisions.

Turbo generator – Turbine type and packaging

A major decision in designing a turbo generator is the choice of turbine type. Exclusively on the generator sets seen in the core power range (400 kWe to 2 MWe) the turbocharger turbines are of radial type. This may seem an obvious decision for the turbine type, but the ETC system works best when the pressure ratio of the turbo generator is relatively low, typically in the region of 1.5 but a turbocharger may have a pressure ratio of greater than 3. This low pressure ratio and the higher volumetric flow conditions seen on the larger generator sets means that an axial turbine type may be the better choice. An initial estimation of size and shape of an equivalent turbine and electrical machine is shown by Figure 6.

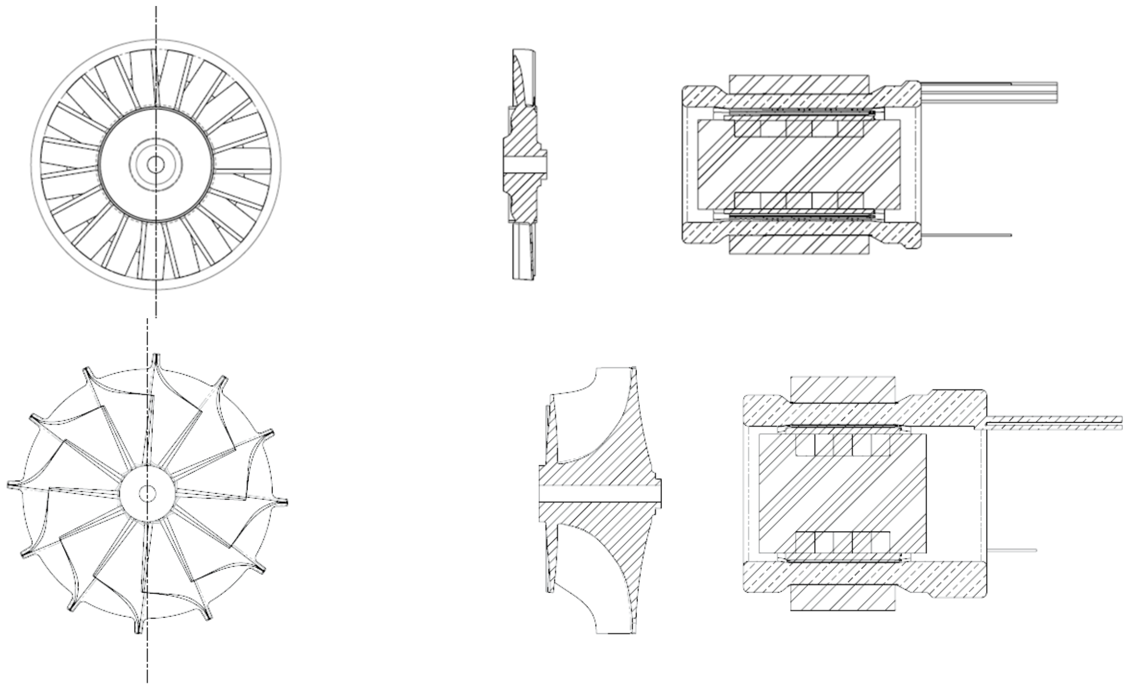

Figure 6: Axial (top) and Radial (bottom) flow turbines

In order to be able to define the best choice the following steps were performed:

1. For both radial and axial flow machines
    a. Define generic aerodynamic turbine maps
    b. Define generic geometry
    c. Define number of turbine stages required to cover the generator set range required (400 kWe to 2 MWe)
2. Define cost (tooling and piece price) model
3. As a follow on of the previous product power optimisation, the improved cost model and turbine maps where used as inputs and the optimisation analysis re-run pivoting around the 110 kWe point for each of the turbine types.
4. For items which are not performance/value related or less tangible, a Pugh matrix and scoring was derived
    a. Examples of these parameters are packaging differences within the generator sets, thrust loading difference, product mass, temperature at electrical machine, number of turbines required, and nozzle guide vane access.
5. A quantified decision can be made with respect to both the performance/value analysis and matrix analysis.

An outcome of this study defined that the axial turbine was the optimum choice requiring 3 different turbine wheel designs to meet the needs of the 400 kWe to 2 MWe genset range.

Another key decision made during the project was to understand whether the turbo generator would be better in a vertical or horizontal configuration, refer Figure 7.
This decision will impact how the turbo generator can be packaged around the customer's generator set as well as changing the internal architecture of the machine from bearing layout, thrust loading, lubricant/coolant drainage.
An example of the packaging simulation can be seen by Figure 7, which was used to assess the optimum orientation of the turbo generator. The outcome of this study was that a horizontal machine was most suited to be packaged on the generator sets.

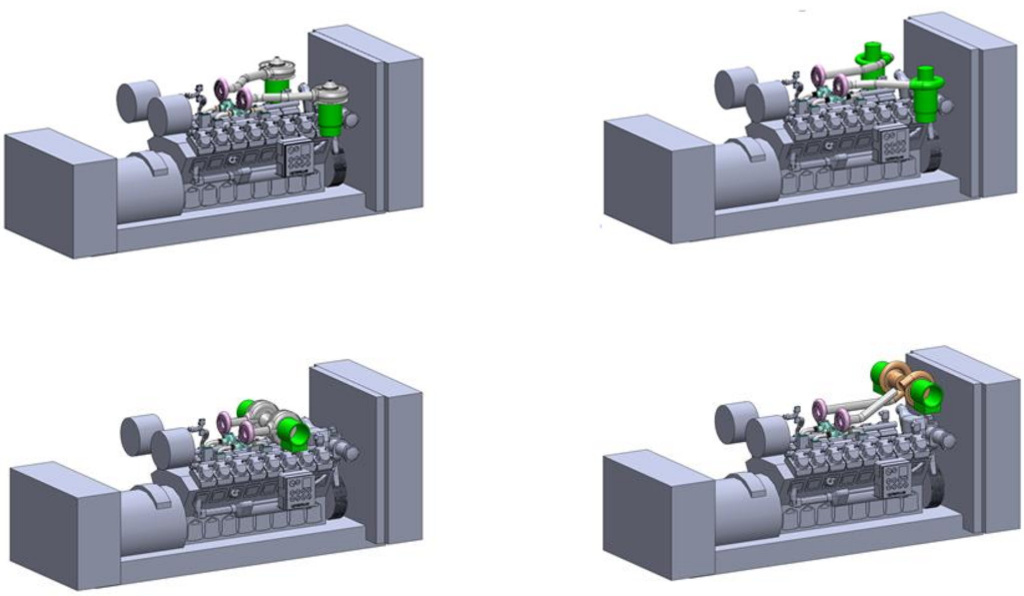

Figure 7: ETC turbo generator – packaging simulation

Turbo generator – Electrical machine architecture

A major design decision when designing a turbo generator is what electrical machine architecture is most appropriate. This is a fundamental decision with a number of workable solutions. The choice of machine is an in depth process requiring a combination of analysis, machine design knowledge, supplier knowledge and understanding of operating profile of the machine.
The following machine types were analysed with the surface magnet machine being the most suitable for this product:

1. Switched Reluctance Machine (SRM).
2. Induction Machine (IM).
3. Interior PM Machine (IPM).
4. Surface magnet Machine (PM).
5. Radial or axial flux rotor.

Power Electronics – Silicon choice/IGBT voltage

With regards to the silicon (Si) choice, the main requirement for the product was cost-competiveness. Full silicon carbide (SiC) modules were discarded due to its high cost for the required current level, as it required paralleling many modules. Hybrid Si-SiC modules were more adequate for the application, but the price of the modules were high for the current levels that are considered. As the space and weight constraints of the industrial customers were not too onerous - where SiC modules would have an edge - standard Si modules were a more suitable choice. Presently, the cost of SiC modules is still too high. Figure 8 shows a summary of the trade-offs between different options analysed - the Mk4+ codename is related to a SiC product.

Once standard silicon modules were selected, a second question is presented on what is the optimal voltage rating of the system. For this, two options were considered: (a) a dual stage, rectifier and two-level inverter topology with 1,700V IGBTs, and (b) a triple stage, rectified, boost converter and two-level inverter topology with 1,200V IGBTs. After creating a complete component specification, detailed cost model and simulation models for each option. The results of the analysis were that the 1,700V was slightly more expensive than the 1,200V option, mainly due to the offset cost of the inductors. The slower 2 kHz switching frequency of the 1,700V option meant that that there were higher filtering requirements in order to meet the strict worldwide grid code requirements for distributed generation. Thus, the selected option was 1,200V IGBTs.

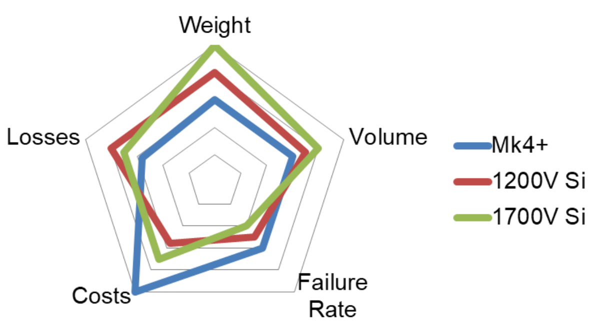

Figure 8: ETC power electronics – IGBT voltage choice

Power Electronics – Switching frequency and passive components

To minimise the impact of the product installation and subsequent retrofit capabilities of the electronics a low overall product volume was desired, but this typically drives the choice of frequency to be as high as possible taking into account the power dissipation limitations of the selected power silicon.

A typical switching frequency for present generation 1,200V IGBT silicon on hard-switching operation is 12 kHz. This was initially selected as a good compromise between size and cost as 12 kHz is viable using standard liquid cooling technologies. But as this device was to be integrated with the water cooling circuit of the engine, this limits the cooling capability of the system, making it more challenging to perform at the extreme operation points. For this reason, during worst-case, steady state conditions, the losses sustained at 12 kHz were too high to be dissipated with a normal single-sided, cold plate technology.

To maintain a competitive price of the overall system, the optimal solution found was to reduce the switching frequency, while maintaining a fairly standard water cooling heatsink technology. Also, the inductors are manufactured with off-the-shelf components, not requiring specific exotic magnetic core materials, complicated winding technologies or liquid cooling – allowing the inductors to be air cooled.

The completion of the design phase 2, required the successful pass of both a Critical Design Review (CDR) and phase review, this allows the project to progress into the validation phase.

Figure 9: Final ETC 1000 turbo generator and Mk5 power electronics

3.3. Design Validation

An important part of any product development cycle is the verification and validation phase. This is where component level through to customer acceptance level verification and validation is carried out. Prior to any unit testing it is necessary to verify the product cost, supply chain, component quality, tooling design, build and service processes.

The next four test stages are significant milestones in the product development process:

- Gas stand testing (performance and safety function)
- On engine-testing (Cummins QSK60)
- Operational environment testing (endurance testing)
- 3rd Party/standards testing

Gas Stand Testing

This is where the ETC 1000 turbo generator and Mk5 power electronics are individually tested to full power as a complete sub-system.

For the turbo generator this is performed using a high temperature gas stand, where a compressor and combustor is used to simulate the exhaust flow of an engine. This provides a flexible environment to test the full envelope of expected exhaust flow conditions of a generator set. As examples of tests conducted during this phase, the turbine’s aerodynamic performance was mapped across its operating range and the machine was tested against its maximum temperature rating (inlet gas temperature of 600 degC).

For the power electronics the testing occurred both individually and connected to the ETC 1000 turbo generator to test over a range of operating windows and ambient temperatures (55 degC max).

On engine testing

This is the first full system test on engine under laboratory controlled conditions. Cummins Power Generation (Ramsgate, UK) provided a test engine and test cell to demonstrate operation on engine.

The agreed test plan followed a procedure which investigated both engine operation and turbo generator operation under varying load conditions, start-ups, shutdowns as well as the vibration and transient aspects of ISO 8528 generator set standards.

The successful completion of the test plan allowed the units to move onto operational environmental testing.

Operational Environment Testing

This is an important validation, as the full system is validated under real operating conditions, typically a number of field units are run over an extended period of time. Three customers operating in different environments (diesel and gas fuelled customers) have agreed to take the ETC 1000 and Mk5 power electronics into the field. The first field customer has been used as a case study in the following section.

3.4. Release to Production

This is the important final stage before the product is released into series production. During this stage the product drawings and Bill of Materials are released; this means that any further changes to the product will need to follow the rigorous Engineering Change Process. Supplier validation, quality checks and processes are complete as well as the release of the production tooling and build processes.

Importantly for both internal teams and customers, training, documentation and manuals are released.

After successful completion of the stage gate, the products can be reliably manufactured and tested through production processes without intervention from the Engineering and Project teams.

4. ETC Case Study

Bowman Power, in collaboration with Energy Developments Ltd, is currently trialling a demonstrator ETC 1000 on a Caterpillar 3516 gas engine at their 97 MW power generation facility in New South Wales, Australia.

Energy Developments currently own and operate one of the world’s largest Waste Coal Mine Gas (WCMG) ventures. WCMG is a hazardous by-product of coal mining, where trapped methane is released from within the coal seams into the coal mine. In order to limit greenhouse gas emissions into the atmosphere, where the gas has more than 25 times the global warming potential of CO2, Energy Developments extract the gas via mine ventilation and coal seam drainage, and employ it as a power generation fuel. The gas is burnt in a gas powered reciprocating generator set and electricity is supplied back to the grid.

Figure 10 ETC 1000 Installation at EDL Tower Coal Mine.

The aim of the ETC installation was to increase the power output of the generator set system for the same fuel usage, and the demonstration has been underway since early 2017, recently surpassing a milestone of 5,000 operating hours and more than 360,000 kWh generated.

The key steps in the application project process are: 1) Perform fuel efficiency simulations, 2) Site survey 3) Agree requirements, 4) Define ETC integration, 5) Agree integration design and test plan, 5) Manufacture hardware, 6) Standard genset performance measurement, 7) Install ETC system, 8) ETC genset performance measurement, 9) Other test requirements and sign-off (close-out).

Prior to the installation of the ETC 1000 system, it was necessary for the standard genset's fuel efficiency to be measured (baseline test) in order to later compare the results to the fuel efficiency with the ETC system fitted. The genset's thermal efficiency is calculated by measuring the net electrical output of the system divided by the incoming fuel power calculated from the measurement of the normalised gas flow rate and calorific value of the fuel. Following the baseline testing, the ETC 1000 system is integrated into the exhaust stream of the host engine's exhaust system, Figure 10. Following the installation, the system is commissioned before the specific fuel consumption is re-measured with the ETC in-place. The system efficiency can be further optimised on-site by changing the nozzle guide vanes within the turbocharger or turbo generator to better match the flow conditions; this may be beneficial for old engines that deviate from the genset OEM's datasheets as additional system efficiency can be gained. At the end of the installation and optimisation phase, the performance results between the baseline engine and the demonstrator engine are compared using the following equations.

$$Percentage\ Power\ Increase\ (same\ fuel\ usage) = \left(\frac{Thermal\ Efficiency_{ETC\ genset}}{Thermal\ Efficiency_{Base\ genset}} - 1\right) \times 100$$

$$Percentage\ Fuel\ Reduction\ (same\ power\ output) = \left(1 - \frac{Thermal\ Efficiency_{Base\ genset}}{Thermal\ Efficiency_{ETC\ genset}}\right) \times 100$$

Where:

$$Thermal\ Efficiency_{Genset} = \frac{Electrical\ Power\ Out_{net}}{Fuel\ Power\ In_{gross}}$$

At Energy Developments, the CAT 3516 experienced a 7.35 percent increase in electrical efficiency for the same power output, equating to an increase of 2.70 percentage points in genset thermal efficiency, refer Figure 11. An example of the genset and ETC electrical power output can be seen from Figure 12.

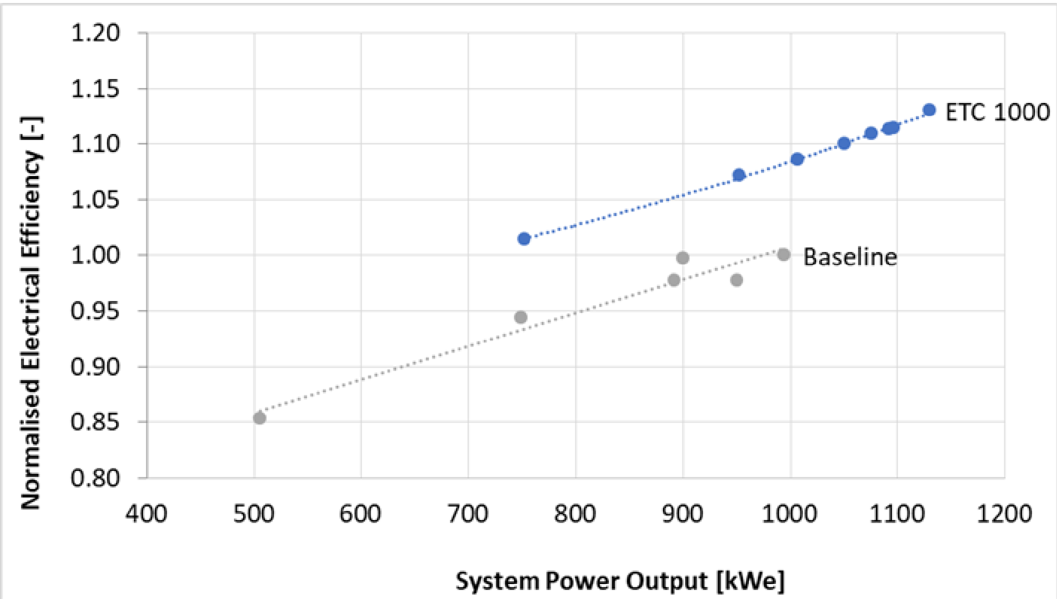

Figure 11 Baseline and ETC Genset Test Results

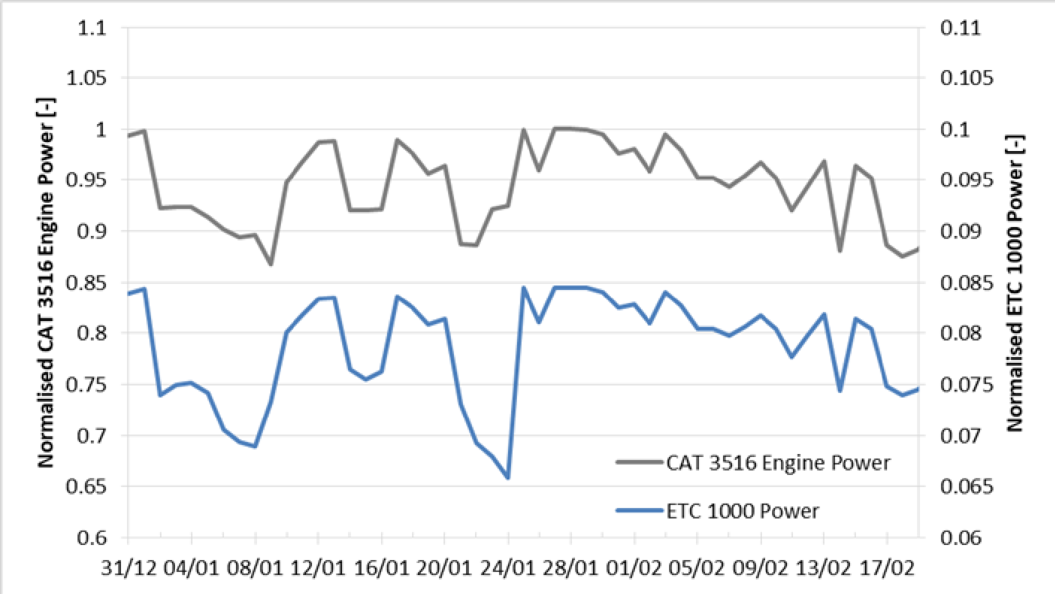

Figure 12 Genset and ETC power output

5. Conclusions

Over the last 14 years Electric Turbo-Compounding has matured as a technology and is being deployed in a range of power generation applications, most notably in land based power generation applications on diesel and gas fuelled reciprocating engines. Engine OEM's, Independent Power Producers and the Power Rental sector are all adopting ETC technology to increase the efficiency of their fleets and gain competitive advantage [2], [3], [4].

The volatility in oil price affects the viability of energy recovery products and a clear driver has been to generate a Return on Investment of less than 18 months irrespective of the fuel price; this has led to a market driven requirement to reduce the product cost of the previous generation ETC system by 40%.

The development of a 'clean sheet' product is often prohibitive due to cost but support from DECC and Innovate UK has allowed the costs to be palatable and has aided the establishment of key engine OEM, certification and academic partners to be part of the development project (Cummins, Rolls Royce, Lloyds register and University College London).

This paper describes the successfully completed new product development which has met its aims of reducing the system cost by over 40% and is on track to have reliability 50% greater than the previous generation due in part to 18 Million running hours of data collected.

The framework and rigour required to successfully develop a product and key decisions have been described, these include the derivation of the product power capability (110 kWe), turbine type (axial flow), orientation (horizontal axis machine), electrical machine architecture (permanent magnet), power electronic IGBT voltage (1,200 V) and a power electronics switching frequency (<12 kHz). These decisions are critical in order to develop a product that can meet the industry requirements and the desired cost targets.

The high level of product validation required has been outlined which is paramount to achieving a reliable product before release. As part of this, in-field Operational Environment testing has been described by means of a case study. Energy Developments Ltd., the lead customer has exceeded 5, 000 hours of run time in the first half of 2018.

The ETC 1000 and Mk5 product has now been released into series production.

6. Acknowledgements

The authors would like to the Department of Energy and Climate Change (now Department for Business, Energy & Industrial Strategy) and Innovate UK for their support of these projects.

7. References

[1] Douglas K, Lopez F, Herrero M, Thalhauser J, Bowing R.: “Electric turbo-compounding application to gas engines for power generation in the 1 – 10 MWe range”, Proceedings of the 22nd Aufladetechnische Konferenz 2017, Dresden, Germany, September 2017.

[2] https://www.bowmanpower.com/news/aggreko-enters-strategic-partnership-bowman-power-group/

[3] https://www.bowmanpower.com/news/wartsila-engines-generate-free-power-using-etc-technology/

[4] https://www.bowmanpower.com/news/bowman-power-and-cummins-announce-strategic-relationship/