Flexible Distributed Power Generation using the Industrial Trent Gas Turbine

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Abstract

As the penetration of power generation onto the electricity networks from intermittent renewable sources such as solar and wind increases, power generators and network operators are being forced to reconsider the design of power plant. Instead of large, centralised power plant operating at base load, today's market requires flexibility of operation and fast responses to support these intermittent generation sources. In addition, as we move into a more carbon-constrained World, there is increasing pressure to switch from coal and liquid fuels to natural gas as the primary fuel for power generation, bringing increasing opportunities for gas turbines.

Traditionally gas turbine power plants have focussed on combined cycle (CCGT) configurations to maximise full-load efficiencies using large 'Heavy Duty' gas turbines, typically in a 1+1 or 2+1 configuration. However, these configurations are relatively slow to react to changes in grid power demand, have reduced efficiencies at part-load and increased operational costs due to the load cycling and frequent starts. The large size of the turbines also leads to long plant construction times and maintenance downtimes.

This paper examines the use of flexible power plant, both open cycle and combined cycle, based around the Industrial Trent gas turbine for base load, intermittent and peaking applications. As an aero-derivative gas turbine, the Industrial Trent is ideal for power plant where frequent starts and stops are required, and offers higher availability than a traditional combined cycle plant due to the core swap capability. The paper looks at various different combined cycle plant concepts to maximise operational flexibility to meet the demands of Grid Operators, including an Organic Rankine Cycle option for a water-free solution, and examines the economic and environmental benefits for some operational modes compared to a conventional combined cycle plant or flexible power solutions based on alternate technologies.

1.0 Introduction

An unbalanced power generation portfolio with the introduction of subsidised intermittent renewable power generation with despatch priority is destabilising electricity markets and Grid systems by removing capacity from transmission grids for firm generators. This is forcing fossil fuel power plants previously designed for base load into cycling mid-merit and peak load applications. These intermittent operating periods are destroying the market pricing structures needed for long term investment decisions and increasing the market exposure of generators through forward contract trading imbalance. These factors are pushing large CCGT power plants out of the market, requiring grid operators to consider capacity payment mechanisms that support inflexible assets and ensure security of supply, or develop strategies to encourage operators of CCGT plants to operate assets as spinning reserve, negating the low carbon benefits of natural gas. On top of this, environmental legislation and political uncertainties are removing existing coal capacity and casting doubts over the future of nuclear power.

The historical generation portfolio of power plants has no correlation upon future generation requirements due to the increasing levels of intermittent renewable power generation. With electricity traded forward in half hour blocks, this favours intermittent renewable power generation, such as wind, as it enables more accurate forecasting of available generation than previous market designs where electricity was traded hours in advance. However, intermittent renewable power generation requires back-up power generation
to balance the system and ensure supply security and system stability. Closing the trading gate to 30 minutes in advance caused the existing power plants to provide this balance, leading to them becoming increasingly stressed both economically and mechanically due to the cycling and faster starting times required. Moves in some parts of the World to reduce the gate closure time still further to 10 to 20 minutes will exacerbate the problem still further.

![The Duck: The California ISO's Flexibility Curve](image)

**Figure 1: The impact of Renewable Power Generation on Grids**

With natural gas proposed as the bridging fuel to a 100% renewable or zero carbon future power generation, the onus to provide intermittent renewables back-up capacity will fall on gas turbines and gas engines. Of the available technologies, aero-derivative gas turbines, like the Industrial Trent, are ideally suited in meeting the challenges faced by the Grid Operators both today and in the future.

Modern industrial and heavy duty gas turbines were designed to provide high efficiency base load combined cycle operation with high exhaust and steam cycle temperatures. With thicker, heavier sections, load cycling and fast starts increases component thermal stress, leading to reduced component life and more frequent maintenance interventions. An increase in the operation and maintenance (O&M) costs and hence the cost of electricity generated is incurred. Gas engines, while able to start and stop frequently and cycle without maintenance penalties, require relatively frequent maintenance interventions and have high combustion emissions compared to aero-derivative gas turbines. Gas engines also incur a relatively high parasitic loss to keep them warm and in hot standby mode in order to enable them to start quickly – a cold engine can take 10 to 12 hours to reach an initiate to start condition. In addition, due to the maximum power output available of around 20MW per unit, larger power plant require large numbers of units, which while offering a great deal of flexibility, creates issues with synchronising to the grid and can actually lead to an increase in the time required to bring a power plant to full load compared to a similarly sized plants using a smaller number of gas turbines.
Aero-derivative gas turbines such as the Industrial Trent are by nature designed to achieve a lot of fast cycles, with no Equivalent Operating Hours (EOH) or stress factors applied for cycling operations, while still maintaining high open cycle efficiencies, which can be improved if required by utilising combined cycle configurations. The Industrial Trent is capable of fast starts, high load ramp rates, full load rejection and fast shutdowns, with no lockout period, while the core engine swap procedure ensures high availability, making the Industrial Trent a highly suitable product that meets and exceeds the challenges facing power generators and grid operators today.

2.0 The Industrial Trent Gas Turbine

The Industrial Trent gas turbine is the highest efficiency simple cycle gas turbine available today, with over 100 units sold for power generation and mechanical drive applications worldwide and a proven history from aircraft engine lineage.

The Industrial Trent gas turbine core is a three-spool design derived from the Rolls-Royce RB211 and Trent aircraft engines, with a performance lineage founded in Boeing 747, 757, 767, 777 (Trent 800) and Tupolev TU204 applications. The Industrial Trent shares the same core as the Trent 800 aero engine product line initially developed during the 1990s for wide bodied aircraft, and now with more than 500 engines in service and over 20 million service hours achieved.

The Industrial Trent is currently situated in the 42 to 66 MW market segment for industrial power generation (IPG) and a similar shaft power output in a mechanical drive (O&G MD) application. The initial product development industrialized three core areas: the lift fan was replaced with an aerodynamically
matched 2 stage axial Low Pressure Compressor configuration that delivered the same pressure rise as the standard aero core; the Low Pressure Turbine was adapted, converting thrust output to rotational energy, by increasing the length of the last 2 blade rows of the 5 stage power turbine, and the combustion system was adapted to provide dry low emissions (DLE) and wet low emissions (WLE) alternatives for the control of exhaust emissions.

Figure 3: Industrial Trent Gas Turbine core

The modular package design is optimized for Operation and Maintenance and minimal installation time. With the core exchange principle allowing offsite maintenance of the core turbine, overhaul outages are reduced to less than 2 days downtime.

Figure 4: Industrial Trent Generator Set Package
The Industrial Trent can be supplied in various configurations to meet the needs of a specific project. For emissions control, both Dry Low Emissions (DLE) and Wet Low Emissions (WLE) are available on gas fuel, while only WLE is available for emission control on liquid fuel. WLE has the advantage of providing a power enhancement compared to a ‘dry’ turbine. For additional power enhancement, Inlet Spray Intercooling (ISI) can be supplied. ISI introduces water into the gas turbine air inlet to reduce the ambient inlet temperature and decrease the energy required for compression, resulting in an increase of both power and efficiency for ambient air temperatures above 7°C.

A summary of the available configurations and gas turbine performance is shown in Table 1 below.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Power Output (MW)</th>
<th>Efficiency (%)</th>
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</thead>
<tbody>
<tr>
<td>DLE</td>
<td>53.1</td>
<td>42.4</td>
</tr>
<tr>
<td>DLE + ISI</td>
<td>63.5</td>
<td>43.2</td>
</tr>
<tr>
<td>WLE</td>
<td>66</td>
<td>4.4</td>
</tr>
<tr>
<td>WLE + ISI</td>
<td>66</td>
<td>41.5</td>
</tr>
</tbody>
</table>

Table 1: ISO performance data for 50Hz Industrial Trent configurations

3.0 Open Cycle Configurations

The Industrial Trent aero-derivative heritage and the modular package design make it a highly suitable unit for open cycle applications. The two main open cycle applications are peaking and cogeneration, but it is also possible with some modifications to utilise the Industrial Trent for synchronous condensing applications.

3.1 Peaking and Cycling for Grid Support

In peaking applications or applications where frequent start/stop load cycling is expected, conventional economic models are not applicable. The key evaluation criteria are not $/kW or heat rate, but the Internal Rate of Return (IRR) on through life costs. Hence while an open cycle aero-derivative gas turbine is less efficient than an optimised combined cycle plant utilising heavy duty gas turbines, the lower CAPEX and reduced O&M compared to a combined cycle plant costs outweigh the higher fuel consumption because of the limited number of operating hours.

![Figure 5: Typical Power Generation Economics Chart](image)
In these applications, fast response and high availability are two key attributes required by the generators. With the ability to start from cold and have 100% load available for despatch in less than 10 minutes, the Industrial Trent offers probably the fastest power response time on the market. In addition, the Industrial Trent is highly suitable for cyclic applications with no Equivalent Operating Hours (EOH) penalty associated with cycling or multiple daily starts for high stress operating cycle duty as shown below in Figure 6, and there are no lock-out periods after shutdown. The Industrial Trent has a 25000 hour overhaul regime and is capable of 7500 cold starts between overhauls. Additionally, the Industrial Trent has very low black start and standby power requirements: the gas turbine will start up and commence power generation on gas pressures of 22 barg with a power requirement of less than 350kW.

Figure 6: High stress operating cycle chart for an Industrial Trent peaking gas turbine unit

The chart below shows a typical start curve with a load ramp of 21MW/minute, but under certain circumstances the ramp rate can be increased – up to 75MW/minute has been demonstrated on one site enabling full load to be achieved in around 8 minutes from cold. This compares very favourably with reciprocating engines where OEM marketing material suggests 5 to 10 minutes to full load can be achieved on hot or warm starts, although it has to be noted that this applies to gas engines with power outputs of 20% to 40% of the output of the Industrial Trent.
Several papers have been written on the so-called ‘Pulse Operation’, where the power plant is required to start up, operate for just a few hours and then shut down again. Most economic comparisons for this type of operation have been done by comparing gas engines, either in open cycle or combined cycle, with a conventional 1+1 or 2+1 CCGT utilizing heavy duty gas turbines. The long start up time and high maintenance penalties for multiple starts (or the start costs) of the heavy duty gas turbines used in this comparison indicate the economics of pulse load operation favour the gas engine. However, with fast start up and shutdown times, high ramp rates and no start-up costs, the economic argument for utilising gas engines rather than an aero-derivative gas turbine such as the Industrial Trent becomes much less compelling.

Table 2: Assumptions for Pulse Load Calculations for 100MW case

When calculating the cost and efficiency of a ‘pulses’ of different length (see reference 2), fuel and operating costs for the start-up and shut down periods, which lie outside the settlement period (or pulse) were included in the calculation. Thus the faster the unit starts up and shuts down, the lower the fuel cost
and the greater the pulse efficiency. While the open cycle gas engine solution is slightly more efficient and potentially starts slightly faster than the Industrial Trent, the additional fuel used during the operational pulses is compensated for by the lower maintenance cost of the gas turbine option. With a less obvious economic argument between the technologies, other factors such as emissions profile, availability, reliability and start reliability need to be considered.

The Industrial Trent economic argument in such applications can be improved by including combined cycle configurations. These are discussed more fully in Section 4, but it is possible to achieve full plant load in a conventional steam combined cycle within 40 minutes from start-up, compared to the 50 minutes quoted for gas engines in combined cycle, and in 10 minutes using Organic Rankine Cycle technology kept in a hot standby condition. For a comparison of 'steam' combined cycle configurations, the Industrial Trent has a faster start-up, lower maintenance costs and a higher efficiency solution that improves the overall economics.

![Figure 8: Approximate cost comparisons for different length pulses for gas engine and Industrial Trent configurations](image)

From Figure 8, it can be concluded that for short ‘pulse’ operating periods an open cycle gas turbine configuration, and for longer ‘pulses’ a combined cycle gas turbine configuration, is the most attractive economic solution.

3.2 Cogeneration

Cogeneration – the simultaneous production of power and heat from a single source – is often the most energy efficient way to produce the electricity and process heat required by industries or buildings. By utilising a Distributed Generation principle and locating power generation closer to the actual consumers, the waste heat from power generation can be usefully recovered to provide this process heat while the power generated displaces imported electricity from the grid. The high energy efficiencies achievable, often in excess of 80%, lead to a reduction in global greenhouse gas emissions compared to generating the power and heat separately.
Cogeneration schemes are generally heat matched, and the electricity that is produced is a by-product. The site can either import electricity to make up any shortfall or export surplus power to generate additional revenue. In peak power times, an economic decision may be to shut down the primary production process and export as much electricity as possible.

Like all gas turbines, the Industrial Trent has the majority of its wasted energy in the exhaust gas stream. The relatively high exhaust gas temperature allows an efficient production of process steam. As the oxygen content in this gas stream is still relatively high, it is possible to install a duct burner between the gas turbine and the boiler to boost the exhaust gas temperature and increase steam production, as shown in Figure 10 below. This configuration increases overall energy efficiency compared to an unfired solution, and also allows the Cogeneration plant to have a degree of flexibility to optimise the match between electricity production and heat production as process or market conditions change.
3.3 Synchronous Condenser

As well as providing peaking power, the Industrial Trent can also provide reactive power compensation duties. Simply by adding a clutch mechanism between the generator and the Low Pressure (LP) turbine, the gas turbine can be isolated from the rotating alternator and the alternator used to provide the reactive power needed by the system operator. By carefully selecting the most appropriate locations in the network, the flexibility of the Industrial Trent package to provide either kiloWatts or VARs at a single location enables a system operator to maximise the use of this asset. This asset will optimise and stabilise grid system operation due to a large quantity of intermittent renewable power generation.

4.0 Combined Cycle Configurations

At times project economics are optimized by improving efficiency, especially for mid-merit power plant which operators require to run for longer operating periods than a peaking power plant. Combined cycle - utilising the waste heat from gas turbines, or gas engines, to produce steam to generate additional electricity using a steam turbine – is the well-proven choice to achieve this.

While the larger industrial gas turbines and the heavy duty gas turbines have been optimised for combined cycle operation with high exhaust flows and temperatures, the Industrial Trent was designed for optimum simple cycle efficiency and so has a relatively low exhaust gas temperature of around 450°C at full load, compared to over 600°C for a heavy duty gas turbine. However, by utilising Once Through Steam Generator (OTSG) designs, the Industrial Trent can provide an efficient, flexible, economic combined cycle power plant with fast start-up capability. The Industrial Trent is also one of the few gas turbines that can show an economic benefit from introducing a duct burner into the combined cycle plant design.

ISI can be employed as well throughout the whole operating period of the CCGT, or just during the initial start-up phase to boost power until the steam turbine starts generating power.

4.1 Multi-Unit CCGT

The low exhaust temperature of the Industrial Trent requires the use of a low pressure, low temperature Heat Recovery Steam Generator (HRSG). This has a number of benefits on the HRSG design, in particular enabling the use of lower cost tube materials, thinner wall sections, reduced thermal stress when cycling the steam plant and eliminating creep. High cycle fatigue failure is a major concern in high temperature steam plant, but in this design the highest steam temperatures are below the creep temperature limits. This prevents the steam side of the CCGT from reducing the plant flexibility offered by the gas turbine.

Combining the Industrial Trent gas turbine with an OTSG offers a fast start, highly flexible CCGT plant due to the ability of the OTSG to run dry and its dynamic heating surface allowing fast flexible operation. The low exhaust gas temperatures of the Industrial Trent are well suited to an OTSG, while an added benefit of using an OTSG is the reduction in make-up water volumes required as no steam blow-down is required. This combination ensures no life impact on any components due to frequent starting and stopping, with the possibility to undertake several hundred starts per year. The compact nature of an OTSG also complements the modular package design of the Industrial Trent to create a compact, low footprint, fast build multi-unit power plant.

From cold, it is possible for a 2 on 1 Trent DLE CCGT to reach 100% plant load within 40 minutes of start initiation, with 80% of station power available from the two gas turbines within 10 minutes of start-up.
A duct burner can be added to each OTSG to boost steam production and power output. As can be seen in Figure 11 above, once the steam turbine has reached full load, duct firing can be switched on and the total power output increased by up to 50% within 10 minutes to further increase the operational flexibility of the power plant. Using a 2 on 1 configuration, this enables a power plant to operate efficiently and with low emissions from around 20% of rated station load to 150% of rated station load, with the ability to change loads rapidly and frequently during operation.

In all instances, the CCGT configurations discussed achieve net plant efficiencies in excess of 50% with a high degree of flexibility in operation, maintenance and economic decisions.

**Figure 11: Industrial Trent DLE '2 on 1' CCGT Start Curve**

**Figure 12: Industrial Trent DLE ISI Embedded Flexible CCGT diagram**
4.2 ‘Single Shaft’ 1+1 CCGT

For single unit sites, or for sites where expansion is foreseen to be phased over a number of years, a single shaft option could be considered. By having a double end drive alternator with the steam turbine coupled to the alternator via a clutch mechanism, it produces a very compact CCGT plant with a high power density. This configuration also enables the gas turbine to operate in simple cycle for low peaking demand, increasing the operational flexibility of the power plant. As for the conventional CCGT configuration, a duct burner can be installed if required to further boost power generation, enhancing the plant flexibility still further.

4.3 ‘Dry’ CCGT

In an increasing number of locations around the World, water is deemed a scarce resource and power generation must compete with industry, agriculture and people for this resource. Therefore there is increasing pressure to move away from water cooling and steam cycles requiring make-up water and seek out alternative ‘dry’ combined cycle technologies, such as Organic Rankine Cycle (ORC) or Supercritical CO\textsubscript{2} (SCO\textsubscript{2}) with Air Cooled Condensers.

While perhaps not offering yet the same level of efficiency at full load as conventional steam combined cycle, significant efficiency improvements can be achieved compared to open cycle operation at lower cost than a high pressure (HP) steam system. The cost of the steam cycle can be reduced by using a low pressure steam system (LP) with reduced steam temperatures to a similar cost level as ORC and SCO\textsubscript{2}, but the efficiency falls to a similar level as well.

Due to the flatter efficiency characteristics of the ORC and SCO\textsubscript{2} turbines, the ‘dry’ solutions tend to have better part load efficiencies than these LP steam designs, an important feature for a flexible power plant which may be required to operate at part loads for long periods of time. While not an efficiency optimised solution, acceptably high efficiencies can be achieved even at high ambient temperatures, with the benefit of requiring zero water. The working fluids used in these ‘dry’ combined cycle solutions also eliminate the potential for condensation within the turbine, and as closed systems require no make-up fluid or fluid treatment, unlike water which requires considerable treatment to meet the quality requirements of the boiler and steam turbine. This enables the ‘dry’ solutions to offer lower operating and maintenance costs compared to steam, another benefit to offset the efficiency reduction.

![Figure 13: Comparison of efficiency for an Industrial Trent in open cycle and with an ORC system at a 40°C ambient temperature](image-url)
An interesting feature of ORC is that the turbines rotate at relatively low speeds. For an ORC turbine matched to the exhaust gas conditions of the Industrial Trent, the speed of rotation is typically 3000rpm, the same speed as the LP turbine and alternator. This opens the possibility to develop a single shaft concept as for the conventional steam combined cycle concept discussed earlier, offering the potential to reduce the CAPEX of this configuration and increase the efficiency compared to a ‘standalone’ solution.

An ORC system can also be kept in ‘hot standby’ condition by installing a small gas burner to maintain the working fluid at an elevated temperature. By also utilising the exhaust gases of the gas turbine during the start-up phase, the ORC system can be brought on line more quickly, and full load achieved within 10 minutes of gas turbine start. Thus by combining the Industrial Trent with an ORC turbo-generator, full plant load can potentially be achieved within 10 minutes of start-up, and similarly fast shutdowns can be achieved. Using this concept, the ORC solution may actually be the most economic option under the ‘pulse load’ scenario described in section 3.1 even though it is not as efficient as the conventional combined cycle configurations.

**Conclusions**

With generators and system operators facing ever changing challenges as renewable power generation increases, it is imperative that their assets are as flexible as possible in order to maximise their economic viability while still ensuring supply security and correct system operation.

A power plant based on an aero-derivative gas turbine such as the Industrial Trent offers not only operational flexibility due to the gas turbine’s specific characteristics, such as its ability to operate without penalty in high stress cyclic operating cycles, but also in the range of power plant configurations that can be adopted, allowing a single power plant to operate economically as a either peaking plant, a mid-merit plant or a base load plant. The gas turbine features and plant concepts also allow power to be despatched quickly when required, with both open cycle and combined cycle configurations able to put power on the bars in between the 10 and 30 minute gate closure times required by markets and system operators.

**Acknowledgements**

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### Nomenclature

<table>
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<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>CAPEX</td>
<td>Capital Expenditure</td>
</tr>
<tr>
<td>CC</td>
<td>Combined Cycle</td>
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<tr>
<td>CCGT</td>
<td>Combined Cycle Gas Turbine</td>
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<tr>
<td>DLE</td>
<td>Dry Low Emissions</td>
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<tr>
<td>HP</td>
<td>High Pressure</td>
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<tr>
<td>HRSG</td>
<td>Heat Recovery Steam Generator</td>
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<tr>
<td>ICE</td>
<td>Internal Combustion Engine (Gas Engine)</td>
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<tr>
<td>ISI</td>
<td>Inlet Spray Intercooling</td>
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<tr>
<td>LP</td>
<td>Low Pressure</td>
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<tr>
<td>O&amp;M</td>
<td>Operation and Maintenance</td>
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<tr>
<td>OC</td>
<td>Open Cycle</td>
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<tr>
<td>OEM</td>
<td>Original Equipment Manufacturer</td>
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<tr>
<td>ORC</td>
<td>Organic Rankine Cycle</td>
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<tr>
<td>OTSG</td>
<td>Once Through Steam Generator</td>
</tr>
<tr>
<td>SCO₂</td>
<td>Supercritical Carbon Dioxide</td>
</tr>
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