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USING DATA FOR SMARTER OPERATION OF A GAS TRANSMISSION NETWORK – KEEPING THE GAS FLOWING

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ABSTRACT

National Grid owns and operates 7,500 miles of high pressure gas transmission pipeline in the United Kingdom. Helping to move and compress the gas are 71 compressors, 62 of these are gas turbine driven, located at 24 different compressor stations and terminals. When the network was built the flow of gas was predominantly north to south, now with the introduction of LNG terminals the network therefore needs to be more flexible to meet the new mix of supply and demand. A lot of data is available on the operation of the machines and there are data driven innovation projects designed to help improve the efficiency of operations. National Grid recognise that there is a lot to learn from the data they have and this can be used to optimise the maintenance and repair of their assets.

Digital data is at the forefront of these innovation projects and there is a lot of data available which up until recently has been simply “filed away”.

National Grid have partnered with DNVGL to collect and analyse this data to assist in their goal for more efficient operation and maintenance of their aging machines. Data acquisition hardware is installed at each compressor station collecting machine and process information, this data and systems are used for condition monitoring, emissions reporting and compliance. The data which was collected included running data (vibration, temperatures, pressures, flows), operational data (starts, stops trips), maintenance data (routine, repairs and failures), and failures log. Once collected the data was checked and cleansed and additional character added (is the point in alarm, increasing, decreasing or deviating) and then analytics performed to look for characteristics around known maintenance and failures from the operational logs. The collected data can then be used to allow National Grid to manage the operation and maintenance of its whole fleet.

INTRODUCTION TO NATIONAL GRID

National Grid transports high pressure natural gas across the UK through a network of over 7500km of pipeline. They have over 600 above ground installations and operate a current total of 61 gas turbine and 9 electric motor driven compressors located on 23 compressor stations and one terminal. The transmission network was originally designed to move gas from entry points in north east Scotland, Humberside and the Norfolk coast to the major demand centres such as London and Birmingham.

CHALLENGES FACED

Changing demand

The rapidly evolving nature of the natural gas supply and demand leads to National Grid needing to be as smart as possible with their operations.

The characteristics of the supply and demand are changing all the time, and are very different to the original pattern of operation envisaged for the National Transmission System. The long term decline in UK Continental Shelf supplies, the commissioning of interconnectors to Europe (including Norway and Ireland), the gradual emergence of alternative gas supplies and the advent of bulk LNG importation terminals in the far west of the UK and in the south east have all acted to alter the pattern of supply. The growing penetration of renewable power generation coupled with the decommissioning of much coal fired generating plant coupled with the ability to export gas to mainland Europe has resulted in significant changes in demand for gas across the network characterised by a need for greater flexibility in operation.

The flexibility required to accommodate the new market conditions was not anticipated when the network was originally designed over the course of the past 40 years or so, and National Grid need to adapt to meet the new requirements, while delivering a cost-effective service for their customers.

Some of the assets in the extensive National Grid network are approaching the end of their design life whilst others are impacted by new environmental legislation. National Grid needs to be able to optimise their maintenance, overhaul and replacement programs, and new build design to maximise the value they can provide to their customers.

Better understanding of the condition of the assets helps to reduce the operational risks for the organisation. If a machine is in a poor condition, it is at higher risk of an unexpected shutdown. This increases the risk of flow disturbances in the network, which in extreme cases can lead to an unsettling of the market and sharp short term price increases.

With pressure on resources and budgets, effort must be focussed carefully to allow efficient operation of the wider network. To achieve this, consideration must be given at a higher level than the individual components involved in the bigger picture. National Grid, in collaboration with DNVGL, are becoming more “data-smart” in the management of their fleet resources.

The current critical rotating machinery fleet of 70 gas compressors are driven by a mixture of electric motors and gas turbines. These prime movers cover a range of machines covering different power outputs, models and OEMs all delivered over the past 40 or so years.

Central management

A significant challenge when managing a fleet as diverse as this is the requirement to make appropriate comparisons and decisions based on information from all the different sources. Information needs to be collected and reported in a consistent manner in order to avoid misidentification of areas requiring attention. Without a consistent approach, differences in the collection or processing of the information can lead to misleading analysis.

As digitalisation progresses, the ability to collect, control and manage data efficiently will become more vital to the operation of any business. In the case of a business with the scale of National Grid, where dozens of different systems are responsible for collecting and storing related data, this can be a significant challenge. Data formats will vary from system to system, and when a cross-system study is desired, involvement of different suppliers will be required. The more systems and stakeholders that are involved, the higher the costs of any study.

Central support and remote condition monitoring

Given the requirements for cost effective operation and delivery of value to customers, positioning the expertise required to cover every eventuality to operate a single machine locally on every site is simply not feasible. A central team of engineers comprised of National Grid and DNVGL engineers has been formed. These are specialists in areas critical to keep a machine operational in the long term, but not necessarily related to day-to-day running. An example of this is expertise in vibration analysis. The challenge is making the site based information available to remotely located personnel in an efficient manner so that matters can be dealt with as effectively as it would be given local support at every location. This includes providing necessary decision support information to determine whether the presence of an expert at the location is required. To allow the remote support team to achieve their objectives, historic and real time information must be accessible immediately at all times.

Central operation and data accessibility

Due to the nature of the changing supply and demand patterns across the gas transmission network, significant changes in the pattern of operation of the compressor fleet are commonplace. The majority of the gas network is controlled from a central control room. Although remote operation from a central location allows greater responsiveness, flexibility and optimisation across the network, due to the limited amount of information relayed back to the central control room, clear visibility of some of the finer details available of machine operation available on site is inevitably lost.

Becoming data smart

The first step on the path to becoming data smart is data collection. Variable data format, quality and resolution are important factors to consider. Because of the variation in make, model and age of machines and their associated control systems across the National Grid fleet, there is a high degree of variability in the quantity and format of the data available at each location. Attempting to standardise on a common control system and data / comms format across the network is regarded as impractical and would take a long time to implement, so any work to modify existing monitoring systems must of necessity be duplicated across a range of platforms, which is inherently costly.

Most analytical processes require uniform data, with non-uniform data typically resulting in a disproportionate increase in complexity of the analytical processes. The result therefore is that data quality typically falls to the lowest common denominator as one poor source can reduce the value of the wider data. For example; consider an organisation wishing to apply a machine learning program to interrogate operational data from 10 different sources. Initial work is required to convert the data collected from the 10 sources into a common format in order to allow processing, so development of 10 conversion processes are required. Next, variations in the data must be considered. For example, consider if in this example data for five sources is logged at 1 minute intervals, and the other five sources have data that is logged hourly. Any analysis carried out can only derive valid conclusions based on either the hourly data from ten sources, or 1 minute data from the five.

Reliability data

An accurate representation of the reliability of the fleet is critical in managing available operational resources. Key to this is first gaining an understanding of the reliability of each individual machine train. Centralising and automating the data collection ensures uniform treatment across different locations and machinery types to give accurate representation of performance and reliability without the potential for differences due to manual input of data. 24/7 monitoring also ensures that no events are missed, such as outside of working hours or during busy periods. Historical experience has shown that events are less accurately recorded during busy periods and outside of normal working hours when a manual record is kept. In circumstances of urgent failures, more concern is rightly given by local personnel to investigating and implementing the resolution to the issue, rather than accurately recording the problem. The accuracy and method of quantifying failures and interruptions to supply can also vary according to the individual responsible at the time of the event, which varies across different locations, shifts and, over a longer term, changes in personnel.

Legislative reporting

There is a legal requirement to report certain data to the authorities with the exact details of the parameters to be reported varying according to the regulatory regime. The operational permits of all gas turbine driven compressor machinery trains include a requirement for real time environmental monitoring and subsequent statutory reporting. Required environmental data includes fuel usage, production information, with emissions data including emissions of CO, CO_2, CH_4 and NO_x. for the gas turbines and CO_2, CH_4 and production data for the electric motors. The penalties for misreporting emissions data are severe. Recording of this data for all operational machines needs to meet accuracy and reliability standards with only limited interruptions allowed. Any interruptions to the recording of the data need to be identified and resolved immediately.

SOLUTIONS IMPLEMENTED

Central operation

The requirement for central monitoring support leads to the requirement for visibility of the remote locations via secure data links. National Grid use the DNVGL developed **alert** condition monitoring software. All of the solutions discussed in this paper are implemented via the use of the **alert** system. These remotely accessible condition monitoring systems enable the real-time status of the entire fleet to be seen from any remote location. The remote systems are installed at each location and individually interface with the local control network, logging all the data in a common format. Data from every piece of instrumentation on site which are read into the control system are collected by the condition monitoring system at between 1 and 10 second resolution. Customised communications solutions are designed on a location specific basis, including OPC, Modbus and bespoke software solutions. A real-time calculations database takes the measured data and processes it to give additional information of additional value. For example, readings of fuel flow, gas composition and output power are processed to give a value of overall machine efficiency. Statistical calculations are also performed, giving information such as hourly average temperatures and performance, or total flow through a compressor. The condition monitoring system is the same for each site and is independent of the different manufacturers unit controllers and station control systems, thus providing a common solution and data platform. This includes process, environmental and condition monitoring data, and allows the impact of any action taken by the central control room to be observed immediately (subject to the frequency of data collection).

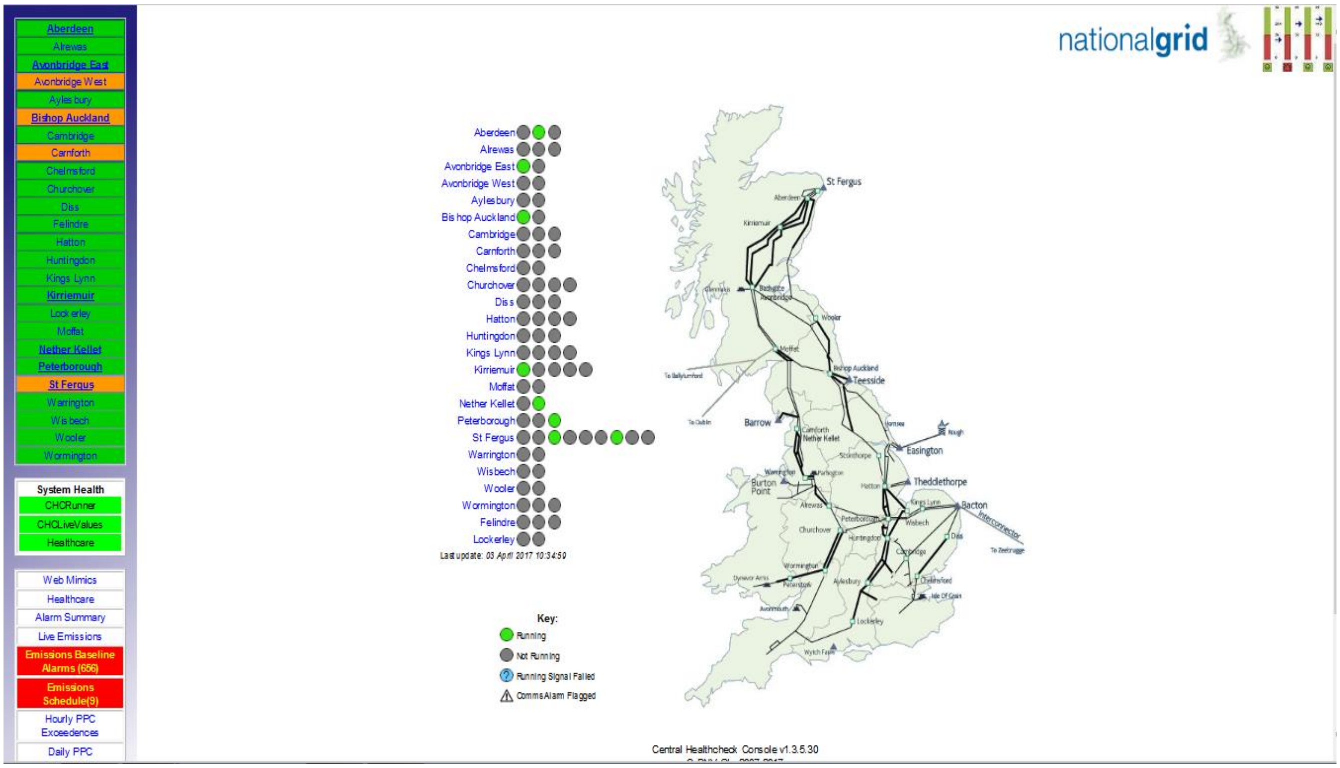


Figure 1 – Fleet overview

Figure 1 shows an overview of the real-time status for the whole transmission network, the map shows the location of the compressor stations and the high pressure pipelines. The dashboard indicates the running status of each machine and a status of the monitoring system at each site.

By making real-time operational data remotely available, the central control room have detailed visibility of the live status of every unit in the fleet. Dashboard displays have been designed to give overviews of critical operational data, and remote users can access information such as the status of alarms, vibration levels, process data and position of the current operating point on the operating envelope. This enables more effective operation of the fleet and gives increased awareness of any conditions that might cause issues in particular areas. The development of custom reporting tools allows any interested and duly authorised parties in the organisation to access the information relevant to them. A Microsoft Excel interface allows data ranging from reliability and process information through to mechanical, environmental and emissions data for any machinery train to be downloaded. This allows data to be easily shared across different departments and, where appropriate with third parties. Where similar information is of interest to different areas of the business, the work involved in collecting and processing the relevant data is not duplicated.

Changing demand

Changes to the compression requirements across the gas network may result in the need to assess the capabilities of machinery trains to meet compression requirements which are significantly from their original design. Sophisticated online compressor maps can be used to help simulate the performance of a compressor machinery train at any set of operating conditions. Figure 2 shows a compressor map where operating scenarios can be evaluated. Engineers have the capability to specify any suction and / or discharge conditions, flow rates required and even gas compositions. This means that future operation can be simulated and tested for adaptability.

Figure 2 – Compressor map simulation

Reliability data

The condition monitoring system on each site automatically logs data each time a start or stop command is sent to a unit or the machinery train trips. This information is all sent back to a central system, allowing automatic calculation of start probability (SP) and the mean time between failure (MTBF). This is done at unit, site, reporting area and fleet level, and can also be categorised by criteria such as engine model.

Additionally, unit availability is tracked. This information is combined with any maintenance schedules and the reliability data which is being logged to allow a calculation of mean time to repair (MTTR). The MTTR allows an element of context to be assigned to the SP and MTBF figures. As with a typical risk assessment, the reliability figures include not only the frequency of an event (the SP and MTBF), but also the severity of the events occurring (quantified through MTTR).

Automating the logging of the reliability data removes the possibility of human error, in terms of missed events and mis-categorisation. Accurate recording of the reliability data is critical in the ability to prioritise the focus of support and minimise the risk of human factors leading to the focus of attention in areas which have no impact on unit availability or reliability. By centralising the data, reliability information is available to users throughout the business. Interested parties might include reliability engineers, site mangers, support teams, central support teams, contract managers (for third party support) as well as providing a means of reporting on performance to senior management. Subject to the appropriate authorisations, each area of the business has easy access to the same information.

Maintenance optimisation

Part of smarter operation of the fleet involves optimising maintenance activities. Central management of the fleet allows for effective planning of major maintenance activities. Current and historical operational hours for every unit is available centrally. This enables the forecasting of future operation and prediction of reliability, and this information is fed into long term planning of major maintenance activities, such as overhauls. This information can be used to ensure activities that interrupt production do not coincide in the same time frame resulting in unacceptable risks to network reliability and availability. The forward view of operating and maintenance requirements can also be used as the basis for negotiating third party support and spares requirements. The calculated remnant life of each machine takes into account the OEM and National Grid specific criteria, including factors such as running hours, run hours at peak duty, number of starts, stops and trips allowing priority to be given to those areas where investment will be most effective. Figure 3 below shows an example of the tracking of current life use of machines, and the effects of future demand projections. The blue bars show the current life of a machine, with subsequent coloured bars representing the estimated life used in the next few years moving forwards. The estimates are based on a combination of an assessment of historical demand, historical performance and reliability analysis, and forecasted future demand.

individual Exhaust Cone Temperature (ECT) readings are corrected to ISO conditions to allow valid comparison between machines across the fleet and to eliminate the impact of external variables such as ambient temperature and pressure.

A digital twin of every machine train has been created to allow the expected behaviour of each individual machine to be predicted for the prevailing operational conditions, and alerts are configured to give warning not only when a parameter is too high or low in absolute levels (e.g. a temperature approaching or reaching an alarm set point), but also to highlight instances where a parameter is higher or lower than expected (e.g. a temperature is higher than it should be at the current load and is increasing independently from other parameters).

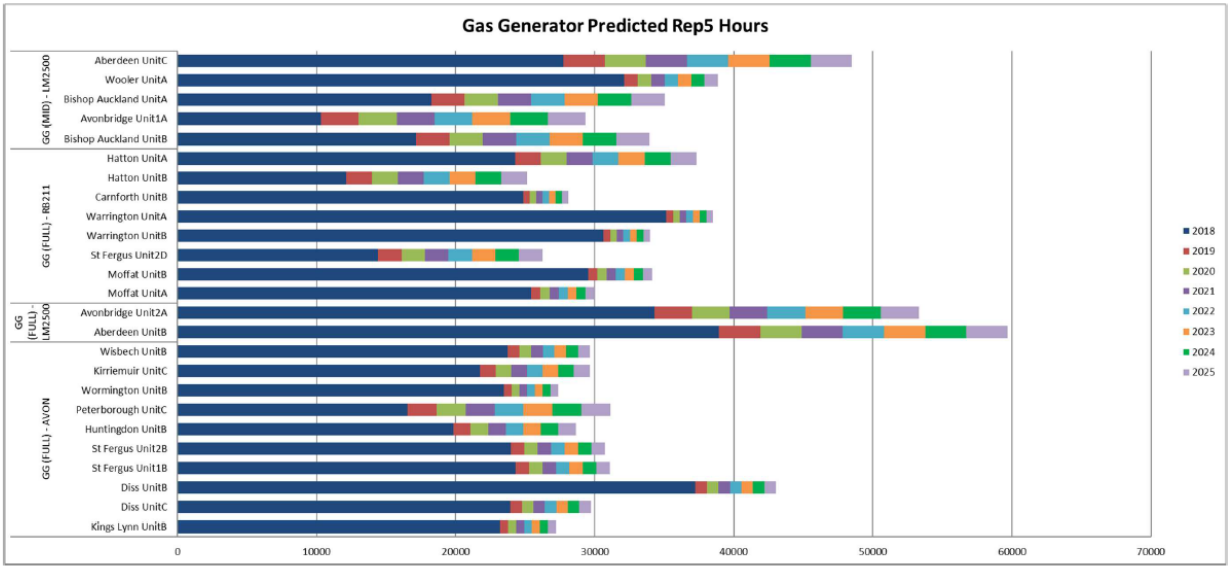


Figure 3 – example life predictor

The alerts derived from the predictions of the digital twin are configured on both measured and calculated parameters, so information is provided not only that certain temperatures are higher or lower than expected, but also that the derived parameter such as the efficiency of the machine is too low. These alerts are used to give an early warning of degradation in condition of the machinery train, sometimes well in advance of a protection system reaching an alarm threshold.

Figure 4 below shows the degradation of a bearing on a power turbine. The upper line shows actual bearing temperature, the lower line shows the deviation from the data twin. The deviation from the digital twin exceeds the allowable threshold and a warning was given almost two months prior to the bearing reaching the protection system alarm setpoint. Vibration levels did not vary in this case until the final few days when the excessive temperature was affecting the performance of the lube oil. This early warning allowed detailed investigation of the causes of the temperature increase to be undertaken in a timely manner and to be able to plan for replacement of the bearing well in advance of failure.

<u>Central support and remote condition monitoring</u>

Making condition monitoring information remotely available means that support teams can provide condition monitoring and machinery diagnostics support in a fast and effective manner. Remote access to detailed vibration information, such as spectrum plots and orbits, has allowed successful detailed diagnostics to be carried out without the need for mobilisation of external teams to site. Trim balances have even been completed without the need for a vibration expert to visit site by remotely operating the unit and having local staff make the required mechanical changes (installation of balance weights) as specified by the diagnostics engineer.

An important consideration of condition monitoring is that an entire machine train should be monitored; vibration gives only a part of the picture. Real-time (at worst 10 second resolution) calculations are permanently being carried out on every machine in the National Grid fleet, monitoring every parameter related to the condition and performance of the machinery train. Information such as the efficiency of a gas turbine or process compressor, and the efficiency of the air compressor and gas generator turbine sections, are being monitored automatically by the condition monitoring system. Parameters such as compressor delivery pressure and temperature and the

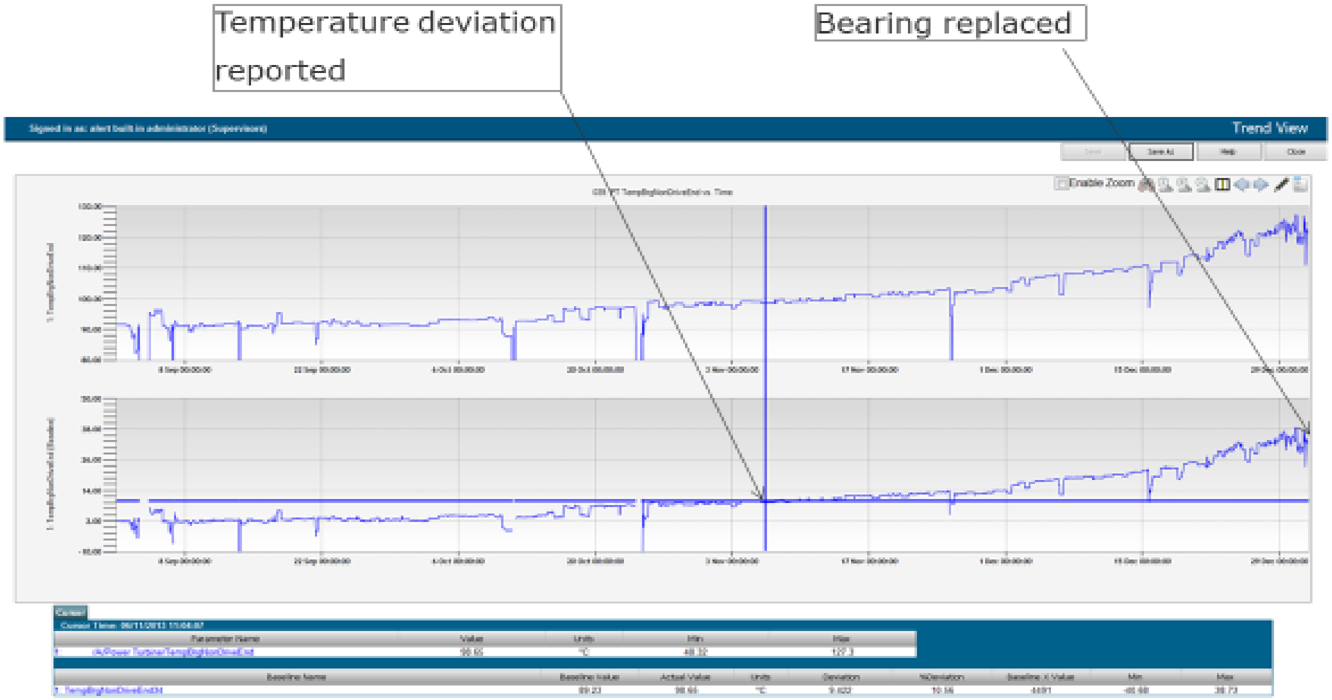
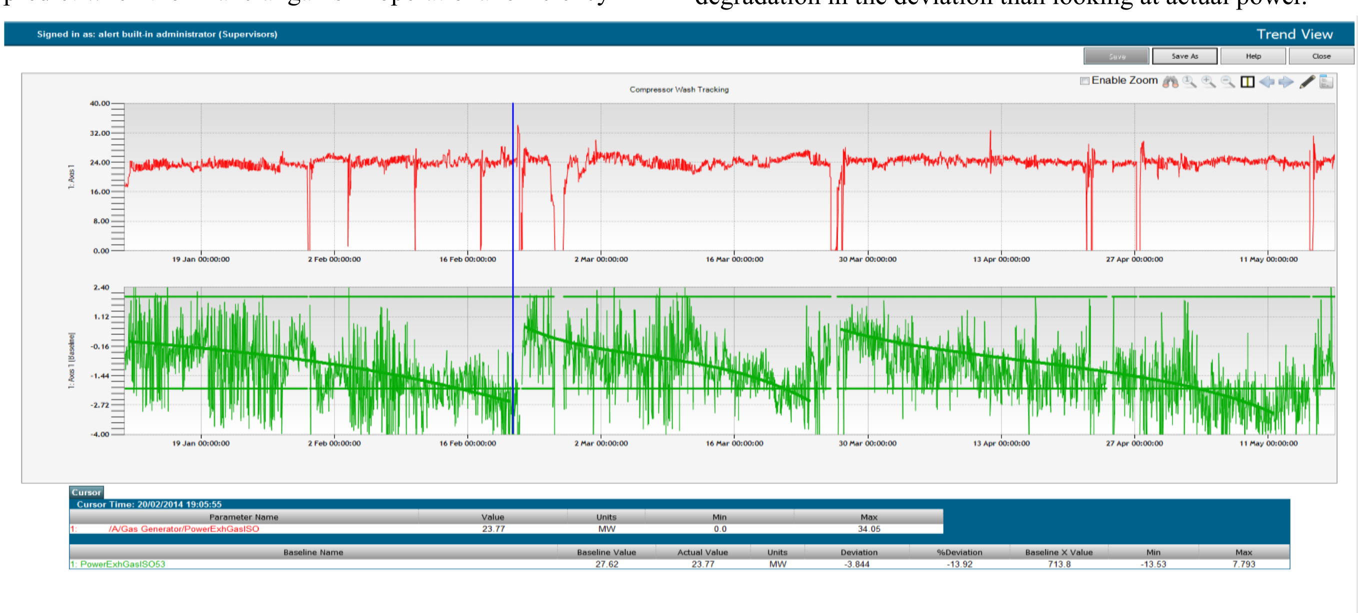


Figure 4 – Bearing temperature digital twin deviation

One of National Grid's goals is to move where possible from a time-based to a condition-based maintenance program. Relaying operational data to a central support location allows non-critical maintenance tasks to be planned and optimised. An example of this is engine compressor wash scheduling. By tracking the performance of every unit, the operational hours and the maintenance tasks performed, real time calculations can predict when the financial gains in operational efficiency will be sufficient to justify carrying out the work.

Figure 5 below shows the performance of a gas turbine over a six month period. The top trend shows the actual output power of the machine, and the lower trend shows the deviation from the expected performance of the machine. The lower trend clearly shows three distinct periods of deterioration in performance relative to the expected power output across this period, each time with the performance returning to normal following a shutdown, where corrective action (a compressor wash) has been performed. It is easier to see the performance degradation in the deviation than looking at actual power.



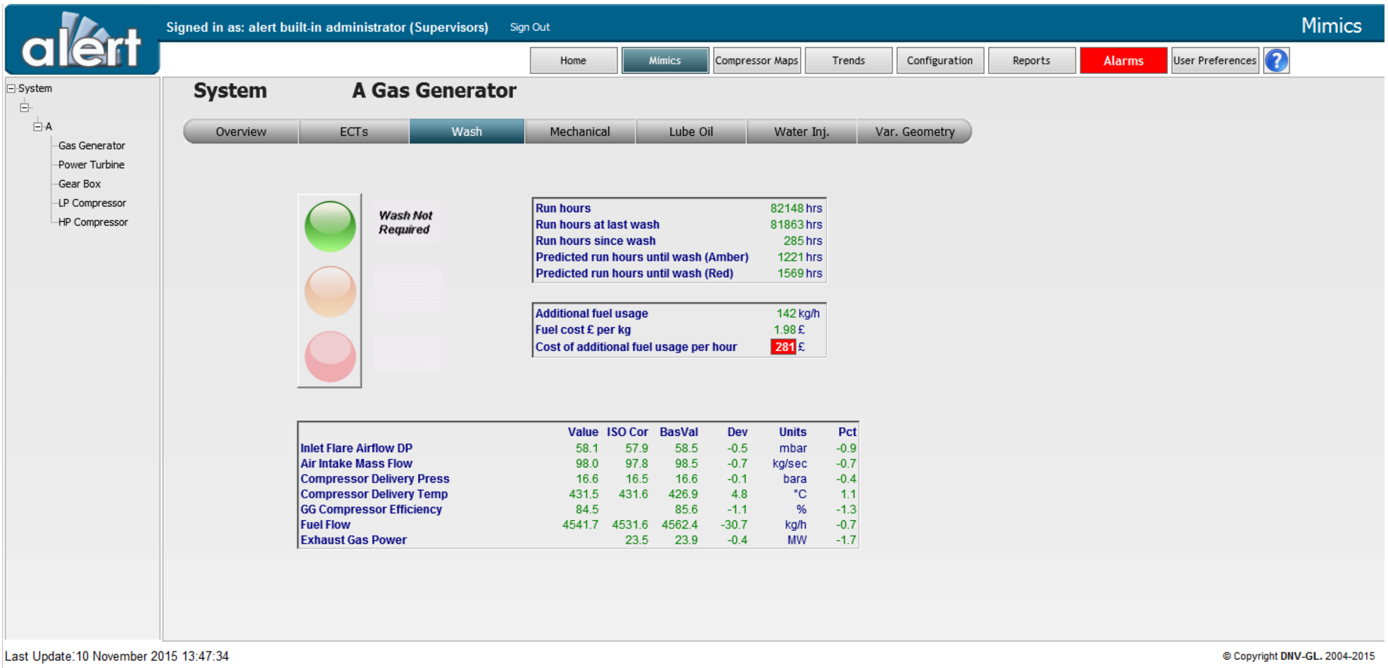


Figure 6 – Compressor wash traffic light display

Figure 6 shows a dashboard version of the same information. Criteria have been established to define the cost/benefit of shutting down a machine to perform maintenance, and is visualised in a traffic light display. If the current condition of the machine is not causing a sufficient loss in performance to justify a shutdown period, the traffic light highlights in green. Amber shows the operators that the deterioration is approaching a level at which losses are of concern, and red means a shutdown is justified. For each status, a prediction is made of the operational time until degradation leads to a change in wash recommendation status.

Centralisation of this data allows for simple reporting of the status of the whole fleet. An example extract is given below.

Aylesbury	Unit A	Wash not required	25/10/2017
	Unit B	Wash not required	25/05/2010
Bishop Auckland	Unit A	Wash not required	20/04/2018
	Unit B	Wash required	02/09/2016
Cambridge	Unit A	Wash required	01/12/2017
	Unit B	Wash not required	07/10/2017
	Unit C	Wash soon	Pre 2016
Carnforth	Unit A	N/A	
	Unit B	Wash not required	28/02/2017
	Unit C	Wash not required	11/07/2016
Chelmsford	Unit A	Wash not required	02/05/2018
	Unit B	Wash not required	21/12/2017
Churchover	Unit A	N/A	
	Unit B	N/A	
	Unit D	Wash required	15/08/2016
	Unit E	N/A	

Figure 7 – example fleet summary

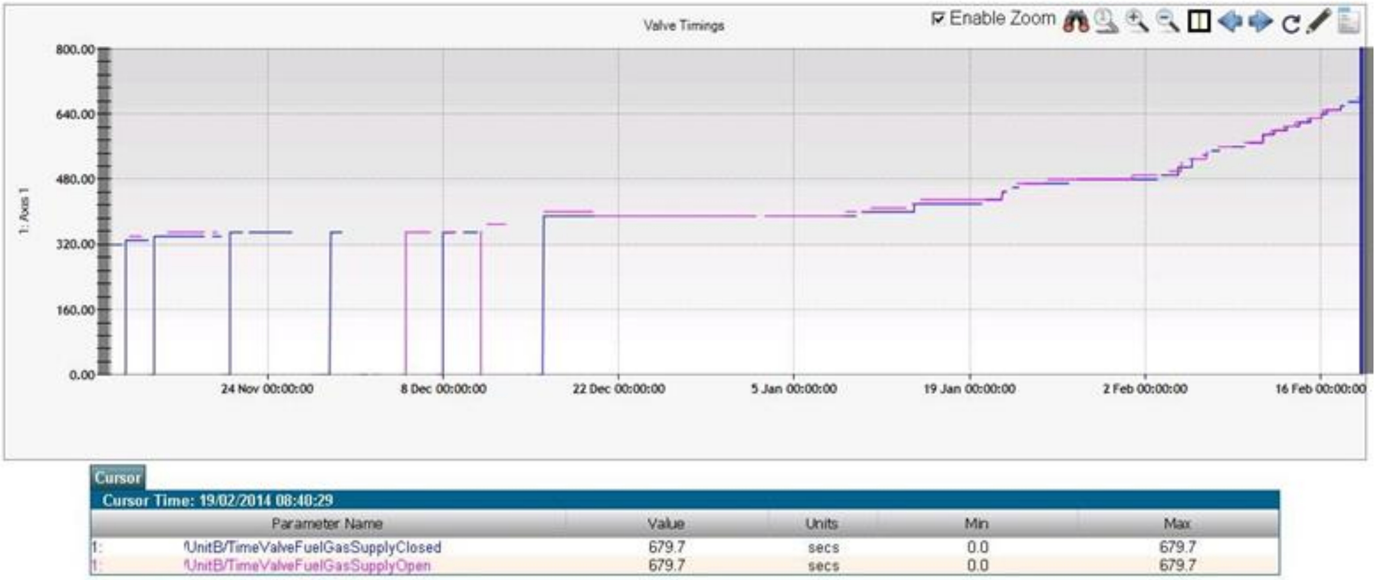


Figure 8 – Time taken for a valve to close increasing

Another element of fleet condition monitoring is auxiliary equipment which can affect the performance and operation of the rotating machinery. The open/closed status of every valve installed on a compressor station across the fleet is monitored. Timers are configured to track the time each valve takes to transition from an open to a closed status, and are monitored for any evidence of valves taking longer than expected to transition, indicating a potential seizure. Figure 8 shows a trend of valve timing, the deterioration is clearly seen.

<u>Legislative reporting</u>

National Grid have implemented real time environmental reporting of NOx and CO emissions by means of a predictive emissions monitoring system (PEMS). Process data combined with the live gas composition readings and fuel measurements on site allows emissions to be determined with all the appropriate environmental information being monitored in real-time for every site. This information is automatically logged and displayed on a central dashboard. Any deviations from the permitted limits automatically alerts the relevant personnel. Deviations which give rise to an alert can include exceeding an emissions limit value, or a loss of data caused, for example, by an instrumentation or communications failure.

Auditing and reporting is made easier by the fact that throughout the year, all the relevant information from every reporting source is being automatically collected in one location, and the tools required to format the data appropriately are pre-configured.

<u>Future of engineering – data sources - solution</u>

Several ongoing projects have already demonstrated the value of commonly logged operational data for National Grid. These vary from the simple to the complex. An example of a simple requirement of data extraction might be an accurate determination of operational hours of every machine in the fleet. But given the appropriate data stored centrally, a seemingly more complex requirement, for example determination of the amount of time any given compressor has spent within a specified margin of its surge control line, can be determined with the same degree of accuracy and ease.

An active research project is currently investigating the ability to predict the start probability of an off-line machine and the probability of an on-line machine tripping in the next hour by using data analytics to identify leading indicators of issues which could lead to a machine failing to start or tripping when on-line. The ability to make accurate predictions of these parameters will greatly enhance process operations at critical sites.

The project is using operational data from a sub-set of 11 gas turbine driven compressor trains all employing the same prime mover. The source data includes start, stop and trip data for each gas turbine together with data from every instrumented and calculated parameter at 10 second resolution over a 14 year period. This equates to over 500 billion data points in total. Without a long-term data store, common across the different sites and control systems, this would not be a feasible investigation as the investment required to collect, cleanse and convert the data from varying sources would increase the complexity of the data collection making it an unmanageable requirement.

In a second research project following an unexpected catastrophic failure of the HP turbine blades on a gas turbine, research is being carried out into methods of predicting, and therefore preventing, further similar failures. Traditional condition monitoring and machinery protection systems were not sufficient in this instance due to the nature of the failure, which was fatigue related. In this case, there were no changes to parameters such as vibration in the run up to the failure which occurred without warning.

Figure 9 – Catastrophic failure of HP turbine blades

By analysing the extensive historical data logs, DNVGL were able to investigate the failure. It was found that specific long term factors which contribute to thermal fatigue could be identified. It has been determined that these indicators are not symptoms, but causes of the failure. This has allowed the development of a new monitoring solution which is being applied to the affected units. When dealing with the management of an aging fleet of assets, the capability to adapt to new challenges and learn from experiences such as this is crucial. This is an example of where the efficient storage of long term data provides value unforeseen earlier in the life cycle of the machines. Analysis of historical data such as this and realising the value that it provides would not have been possible without data-smart thinking well in advance of the requirement arising.

The future

As cloud technology continues to advance, data will become more open and more accessible for more people. Instant access to data will become an expectation for a digital generation accustomed to having information at their fingertips. Centralised systems will make much more data available to wider audiences than a typical existing architecture.

Use of cloud based systems will lead to more cost effective solutions. Savings will be possible in areas including hardware, reduced site visits from personnel (time and expense), and system modifications. For example, an architecture with physical assets on 25 sites requires any patches and upgrades to be rolled out and deployed 25 times, whereas a centralised system requires only one roll-out.

As the digital revolution progresses, cyber security will become a greater concern. Historically I.T. and O.T. have been two distinct areas, but are becoming more closely aligned and overlapping in some areas to fit with modern practices. Companies will need to become more aware of the effects of new technology regarding their security, and system design will be a more critical area than ever.

Clearly any data acquisition and storage system must consider cyber security. With any centralised data storage and handling system it is essential to provide a secure mechanism to upload the data to the central archive location, to secure the central archive or data store and to provide a secure means to access the data.

As machine learning and other "big data" platforms become more commonplace, the value of the quantity and quality of data available will increase more quickly than the ability of an organisation to collect it. Cloud based data will allow the controlled sharing of information, giving asset owners not only control of their own data, but the ability to supplement it with information confidentially provided by willing participants across an industry that would previously have been considered sensitive. Increased accessibility of data will allow more data driven research.

Data format and quality will then become a priority concern. Different procedures and implementations of data collection will create similar problems to the issues circumvented on a smaller scale by National Grid's implementation of a common across the board data repository. In this event, a standard data format, or processing procedure, is likely to be necessary. Commonly accessible formats, such as .csv files, are inefficient methods of storage. The benefits of format accessibility will need to be weighed against the size and efficiency of the medium.