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AVAILABILITY AND RELIABILITY IMPROVEMENTS OF A FAMILY OF LIGHT INDUSTRIAL GAS TURBINES

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Abstract

During the last years Siemens has invested heavily into its 25 – 50 MW light industrial gas turbine. This will allow customers to maximise reliability and availability of their equipment while also improving the operability at extreme ambient conditions. So far this has resulted in core engine disassembly interval extension from 20.000 to 30.000 equivalent operating hours with minor hardware changes. This resulted in increased availability by approximately 0,6% and increased reliability as well. Primary improvements were reduced uncertainty in component life, remote monitoring system to detect anomalies at the earliest possible stage and more flexible and accurate requirements on air filtration systems. Improved calculation methods and better understanding of material degradation, crack propagation and failure behaviour of critical components allow better prediction of component life times, thereby allowing parts to be safely operated closely to their failure limits at same or lower risk as before. A consequence of this is that at least initially, fewer parts than before are approved for repair. The Remote Service products monitor Vibrations, Combustion and Performance characteristics. Data from standard instrumentation is used to analyze measurement data from the engine to detect anomalies in the same way as a specialist would do. Remote service is also available for balancing support and detection of incorrectly positioned valves and leakages as well as detection and quantification of air inlet filter and compressor fouling. Additional effort has been made to further improve operability in extreme ambient conditions e.g. arctic and desert environments. Particular attention has been paid to ensuring safe and reliable start procedures at very low ambient temperatures. Further, air filtration recommendations have been updated taking into account service experiences and recent technical development. The combination of improved life prediction tools, advanced remote monitoring and higher operability in extreme climates will reduce risk and further push the time between service interventions.

Definitions and nomenclature

Cold Climate

Area where winter temperatures regularly or occasionally become so low that standard equipment might not work properly any longer. In some contexts e.g. safety requirements on maintenance tools this is interpreted as any area where it is reasonable to expect that temperatures may occasionally reach below -20˚C. From a gas turbine perspective, a gas turbine adapted for cold climate should be possible to operate safely at temperatures down to -50 ˚C and lower.

Disassembly interval

Interval at which the gas turbine core engine is opened for some kind of maintenance activity including inspection and / or parts replacements

HSE

Health, Safety and the Environment

MGT Medium-sized Gas Turbine – Siemens abbreviation for 17 – 50 MW light industrial gas turbines designed and manufactured in Finspång, Sweden

RDS

Remote Diagnostic Service – service provided 'To improve reliability of vital or capital-intensive installations and reduce the maintenance costs by avoiding unplanned maintenance, by monitoring the condition of the system remotely.' (Wikipedia)

1 Introduction

Until the 1980'es the main driver for development of Medium-Sized Gas turbines in Finspong, Sweden, was first cost together with high robustness to allow excessive maintenance intervals, maximum reliability, and extreme fuel flexibility. The main sales markets were power generation applications in Western Europe, Middle-East and South-East Asia with occasional sales for mechanical drive application. With the introduction of high-efficiency, low-emission designs in the 1990'es an increased amount of maintenance is required making maintenance performance much more important. This in combination with the sales network made available with Siemens purchase of the industrial turbomachinery business from Alstom in 2004 made the MGT market truly global. Since then considerable efforts have been made to improve the maintainability and extreme-climate performance for the 25 – 50 MW gas turbines. The overall goal was to i) increase the value of Siemens service products in a competitive environment, ii) to extend understanding of extreme climate conditions and its implications on gas turbine operability to cold conditions and iii) adapting the understanding of hot environments to modern high-performance technology, and making use of the latest innovations. Using a customer-centred approach a range of projects were defined that, while sometimes increasing first cost, can noticeably improve end-user return on investment. In order to implement the improvements in the most efficient yet cost effective way it was decided to develop product concepts for one GT frame at the time and, once it has been validated for that frame, to transfer it to other frames as required dependent on expected customer value. In addition, all findings and requirements are considered in the development of new frames. Most of the given examples are taken from SGT-600 but similar improvements were implemented in all Medium-sized Gas Turbines, MGTs.

This paper gives an overview of a range of products and product improvements that were delivered by these projects. Siemens conclusion is that the improvements have resulted in considerable maintainability improvements which have been confirmed by the market. Additional improvements are an increased HSE focus (Health, Safety and the Environment) within Siemens service organisation and spin-off products such as Air filtration and washing optimisation.

2 Extended disassembly intervals

While some of the MGT range frames were developed with the oil & gas business in mind, most of the sales and therefore service experience was gained from power generation applications where, generally speaking and historically, predictive outage intervals and well predicted outage cost was considered more important than maximising uptime. With Siemens focus on the oil & gas business together with deregulation of electricity markets, availability at desired reliability level and a constant search for cost reduction meant that there was a need to determine parts life limits with higher accuracy than before, and to search for cost effective measures to improve life times for already delivered as well as not-yet-sold engines. A number of measures were identified that altogether make it possible to increase availability by 0,6% with no increase in risk. An important conclusion was that to safely extend maintenance intervals, it is not sufficient to focus only on hot parts.

2.1 SGT-600 hot parts life assessment

A multi-year project was carried out to analyse component life times for SGT-600 core engine parts to provide data on actual parts life times using modern FE and CFD tools, and to assess the sensitivity of component life times to changes in operation conditions, including an extensive turbine component temperature determination test in the test bed. *Figure 1* shows a Turbine blade 1 instrumented with thermocrystals and a calculated full load temperature profile. The result indicated that for many parts, inspection intervals can be extended without increased risk provided that air filtration and monitoring equipment fulfils certain requirements and that some maintenance activities are performed on-condition only. Another consequence is that at least initially, fewer parts than before are approved for repair.

From a maintenance point of view the most important outcomes were: a better understanding of how life times may change due to operation conditions, and improved understanding of how damage in various areas of the parts does influence its integrity. In the future the increased knowledge can also result in maintenance approaches specifically adapted to each customers needs.

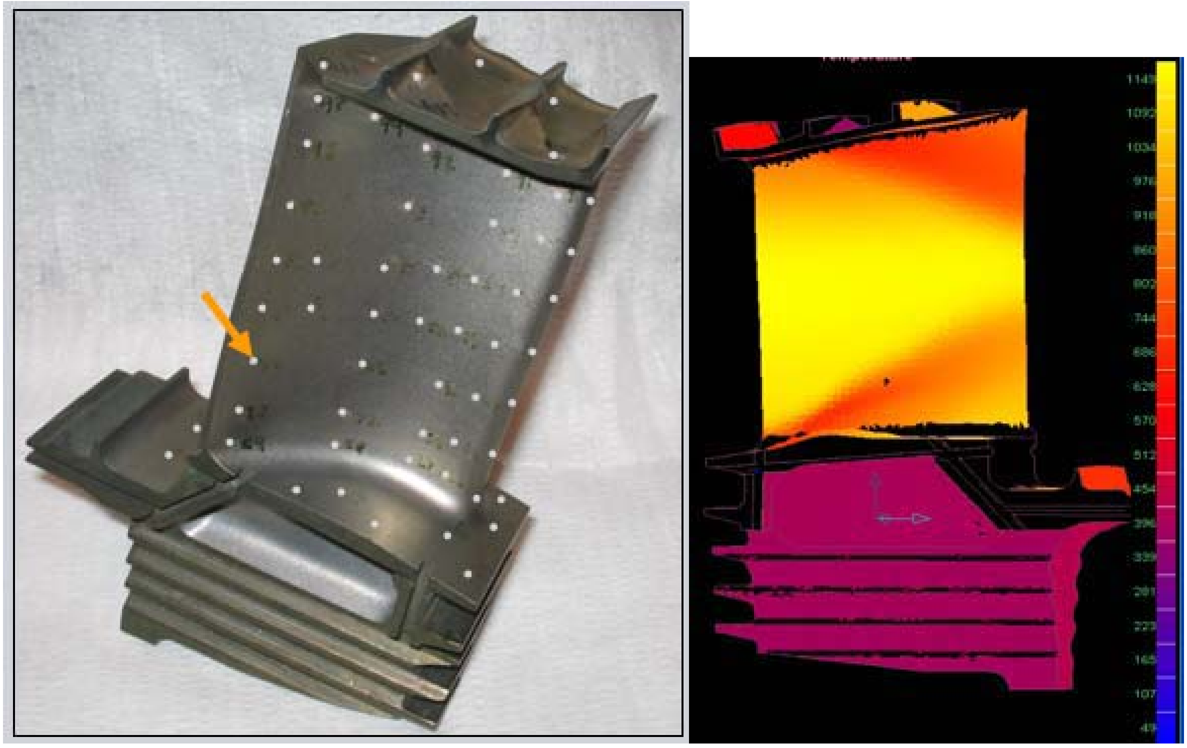

Figure 1 SGT-600 blade instrumented with thermocrystals (left) and a non-optimised temperature profile (right)

2.2 Compressor maintenance interval extension

An extension of hot part maintenance interval also results in a change of outage interval for the compressor section. The compressor is typically not subject to creep and oxidation like the combustor and turbine sections but rather to wet corrosion, erosion and deterioration, high cycle fatigue at certain conditions or combinations of conditions, and low cycle fatigue. Low cycle fatigue is related to starts, stops and major load changes and is dealt with based upon such measures. High cycle fatigue should be designed out for normal operation conditions but may occur in combination with certain conditions like excessive fouling. Wet corrosion, erosion and deterioration need to be dealt with in an adequate way by either prevention or monitoring. In addition, the compressor is highly dependent on a couple of auxiliary functions out of which the most complicated to deal with is the rotor bearings that are positioned in the centre of the compressor assembly. The investigations resulted in both hardware improvements, changed recommendations on inlet air filtration and improved monitoring software to detect faults that could not be designed out at the earliest possible state. Since the monitoring software needs data from standard measurement probes only it can be used on existing plants as well without any hardware changes.

2.2.1 Compressor filtration and wash optimization

Compressor inlet air filters are typically replaced based upon fixed intervals or a specified maximum allowable pressure drop across the filters. This ensures that damaged filters will not be in service for unacceptable periods of time and it also ensures that used-up filters will not cause excessive losses in plant performance.

2.2.2 Compressor monitoring

The compressor is equipped with a protection system that continuously monitors levels of vibrations, bearing lube oil temperatures, air pressures and temperatures and other features. In critical situations the protection system will prevent damage by first raising a control system alarm and, if no action is taken or actions are inadequate to resolve the situation, perform an automated shutdown. This will prevent additional damage of the same type to occur but will provide the operator with no opportunities but to perform corrective maintenance during the resulting forced outage. As part of Siemens remote monitoring effort a so-called agent has been developed that monitors the performance of the gas turbine as a whole. In cases of deviations the system can determine which system that is not performing as expected and also to some extent detect situations where multiple systems are individually performing outside normal conditions but the total performance is within nominal range. This can be used to e.g. determine that the compressor is getting fouled and predict when the fouling will reach a level that either makes it economically feasible to stop for washing or that may reduce the surge limit of the compressor to critical levels. Instead of suffering from a sudden forced outage necessary maintenance can be scheduled at the least inconvenient time in the interval from where the upcoming deviation was first detected until the predicted time when the deviation may first result in a fault.

In addition to the performance agent a vibrations agent has been developed that, together with regular oil sampling, can be used to predict maintenance needs for the compressor bearings thereby allowing safe extension of standard bearing inspection intervals. In case a potential issue is detected it should be handled in the same way as the compressor fouling example mentioned above.

3 SGT-600 reliability improvements

Several instrumentation and measurement improvements were identified that can increase reliability considerably. Similar improvements have been implemented in latest generations of other MGTs as well.

3.1 Combustor acoustic pulsations measurement

Acoustic pulsations in the combustion area, also known as combustor humming, is a phenomenon known from low-emissions combustion systems. Experience shows that even in proven systems, combustor humming may occur under non-normal yet unavoidable operation conditions, e.g. during certain combinations of part load, ambient air condition, fuel quality, and transient events. Knowing whether combustor humming has occurred or not can be the determining piece of data deciding whether an unplanned stop for combustion inspection is necessary, or help assessing the risk associated with postponing a planned outage somewhat due to resource constraints or peak in down time costs. Combustion monitoring is now standard for new deliveries of 25 – 50 MW gas turbines and can be installed with minimum hardware changes on existing units.
The combustor monitoring systems for SGT-700 and SGT-800 have been optimised to further improve response time and to reduce the false alarm rate. The monitoring system now analyses only such frequency ranges where experience tells that pulsations may occur and actually threaten the integrity of the combustion system. In addition functionality to automatically detect and, if possible, compensate for faulty sensors has been added thereby allowing the monitoring system to continue operation, providing as much protection as possible until next suitable maintenance occasion.

3.2 Gas turbine bearing temperature measurement

Due to their position right in the centre of the gas turbine, bearing faults can have considerable influence on unit down time. Therefore even minor improvements in reliability can have considerable impact on plant availability by allowing alarm and trip criteria to be tightened thereby reducing the probability of false alarms from the system. In addition more reliable monitoring solutions can make it possible to extend planned maintenance intervals with constant or reduced risk of sudden forced outages. Should an undesired temperature trend be detected an estimate can be done on the remaining time until the temperature becomes critical, and an outage can be planned at the least inconvenient time within that time span. This also makes it easier to synchronise such a condition based maintenance event with other upcoming maintenance needs.
As a further improvement power turbine design rules for new frames have been updated. Replacement of power turbine bearing probes should now be possible without the need to remove the rotor.

3.3 Power turbine axial displacement probe

Analysis of operation statistics revealed that the SGT-600 power turbine axial displacement monitoring had considerable impact on down time. The reason turned out to be that the probe occasionally fails, often due to cable damage, and that replacement requires disassembly of the complete power turbine. A new probe was developed that has virtually identical ability to monitor axial displacements but is accessible from outside the power turbine exhaust casing.

4 Cold climate operation

Over the years a considerable number of MGTs have been sold for harsh climate application – however most of the sales were older gas turbine types that have since been discontinued or are mainly sold for certain applications today. The oil & gas business offers plenty of opportunities for gas turbines with proven capability to handle cold climate conditions. Requests for quotations from Russian oil & gas companies resulted in renewed interest in adaptation of core engine and auxiliary systems for cold climate applications.

It is important to realise that a key characteristic of most cold places is the huge temperature variation over the year. Table 1 lists 2010 temperature ranges for a few places in cold-climate areas.

Table 1. Examples of cold places in the world

	Max temperature 2010 [˚C]	Min temperature 2010 [˚C]	Temp range 2010 [˚C]	Approximate population
Yakutsk, Russia	40	-51	91	200000
Bettles, USA	36	-48	84	40
Inuvik, Canada	29	-43	72	3000
Banff, Canada	28	-35	63	7000
Hemavan, Sweden	24	-41	65	200
Stockholm, Sweden	32	-26	58	1,3 million

Typical problems associated with cold climate operation are the solidification and general change in properties of many liquids including water, the embrittlement of many materials including many common design steels and rubber, degeneration of emergency power batteries, problems to operate electronic equipment and of course the health and safety of site personnel. Also relevant is the difficulty for control systems to maintain stable operation at huge variations in ambient conditions. Associated problems are that seasonal temperature changes can make roads impossible to use during certain periods of the year as shown in *Figure 2*, and very few daylight hours in the winter, e.g. in Inuvik in northern Canada the sun does not rise above the horizon from early December to early January. This has consequences for erection of plants as well as all maintenance activities.

Figure 2 A vehicle on a spring-time road on the tundra

4.1 Package and auxiliary systems - efficient transportation, erection and commissioning

In order to simplify installation of SGT-600 and SGT-700 in remote environments and considerably reduce commissioning time Siemens has developed a new gas turbine package with reduced weight and footprint that is suitable for single-lift installation. The single-lift package is delivered to site in a single container-like package including lube oil, air filtration and ventilation systems and auxiliary room. Upon arrival on-site the package is put in place and connected to the plant and is then ready for commissioning. Originally developed for standard operation environments, an option is now available that is fully adapted for cold-climate conditions.

A drawback with the single-lift configuration is that due to weight reductions and repositioning of systems it is no longer possible to disassemble the gas generator core without removing it from the package. A nearby workshop with sufficient space and suitable lifting equipment is needed. Even taking this into account, due to the configuration changes, with reasonable transportation times from installation to workshop the total down time is reduced in comparison to previous packages. In situations where a gas generator swap is more suitable this can be carried out in around 24 hours including cooling-down time. This is of course dependent on plant configuration and the availability of special maintenance tools, lifting equipment and personnel to carry out the work.

4.2 Core engine modifications

All MGT packages have been thoroughly investigated to determine their suitability for cold climate operation. The investigation revealed that most of the parts are in fact suitable for operation at any operation condition that can realistically be expected.

Part of the reason is that in today's standard package the most sensitive systems are installed in an auxiliary room that is heated to prevent freezing. In addition, in order to allow testing in the Swedish test rigs all non-heated parts of the package are already suitable for temperatures down to around –30 ˚C. For areas where temperatures below -30 ˚C can be expected it is required to install the package inside a heated building. This is not only to protect the unit itself but also to protect personnel and to ensure that it is possible to carry out routine maintenance.

During operation the engine will be cooled by air coming in at temperatures that may occasionally approach -60˚C. Since the air is being heated in the compressor by the compression work it is only the air inlet and the first part of the compressor that will be subjected to ambient temperatures below –30 ˚C except during pre-initiation ventilation and the initial starting sequence before the compressor has begun compressing the air. Three solution tracks were investigated: Firstly a general solution that can be applied to all current frames with changes in core engine only using proven technology thereby eliminating the need for lengthy validation; secondly frame specific solutions for most relevant frames that may include minor core engine changes and control system upgrades but no major redesigns; and finally updated design guidelines for future frames and frames currently in concept and early design phases.

4.2.1 Solution applicable to all current frames

After analysis of improvement needs it was found that to prevent too cold air from entering the compressor, the air can be heated by electrical inlet air heaters in front of the compressor. Advantages are that no changes whatsoever are required in the core engine, and that the solution can be applied to any units including existing units should they be relocated to harsher climate or need to fulfil stricter requirements. Disadvantages are of course the increased complexity of the plant with another system that can potentially affect reliability and the additional auxiliary power needed to start the plant.

4.2.2 SGT-600 current frame improvement

In SGT-600 there are three parts that might potentially restrict the ability to operate in cold climates, namely the struts supporting the rear compressor stator, a few of the initial compressor guide vane stages and the compressor inlet piece. While some parts could directly be replaced by cold-climate proven solutions already in use in other MGTs, no such solution could easily be found for the rear compressor support struts. Further analysis did however reveal that the structural integrity of the struts is at risk only during a certain sequence during start-up and only in combination with elevated vibrations. Therefore a solution was developed where the compressor rotor vibration criteria are tightened during start-up and relaxed once the critical sequence has been passed with margin. This solution obtained is much cheaper to use than the more general pre-heating solution because it requires no additional power and adds no hardware that could affect availability. Further details can be found in [2]. In case the system prevents start-up from being completed due to elevated vibrations, the root cause of the vibrations has to be determined. This can often be done remotely by global experts if the site is connected to Siemens remote monitoring system.

4.2.3 Future frames

SGT-750 and all future frames are fully adapted for cold-climate operation either as standard for all sales or subject to the selection of a cold-climate option.

5 Remote monitoring

To check and monitor the health of a machine is important to reduce risk for unplanned stops due to machine problems. Monitoring is normally done by operators at site using the control system alarm and trips, daily checks, and by inspection during stand-still. The harsh environment and remote location of sites in arctic climates call for remote services to monitor machines when the machine cannot be reached by personnel, and support in detecting anomalies during operation to take proactive actions. Recently early warning systems have reached a new level of maturity and are now widely applied in industry. In combination with an increasing number of sites connected to internet this has made remote diagnostic services, RDS, possible.

5.1 Remote diagnostic service (RDS)

Systems like the RDS go under many names such as early warning, decision support, and expert system. RDS aim to support the operator to compute and filter out important information hidden in data and thereby give better basis for decisions, this is described in [3], and examples of such systems developed in [4], [6].
For some years Siemens has developed a generic system (*Figure 3*) suited for MGTs. The system includes automatic data collection, secure data transfer, AI technology for anomaly detection, built-in expert knowledge, learning from solutions, and presentation of findings in a web portal. The system monitors performance, vibration, combustion and some auxiliary components like valves and air inlet filter. A similar system for monitoring of Siemens large gas turbines and generators is the Power Diagnostic Centre [5] which has been on-line since 2002. Experiences from the Power Diagnostic Centre have been used, and technology reused in the development of the system for MGTs.
The following will treat the system for MGTs which is called Early Warning and is the tool that is the basis for Remote Diagnostic Services (RDS). The aim of the service is to detect anomalies as early as possible and send a response to the maintenance personnel to make them aware and if necessary take proactive actions. To automatically produce a response through RDS, the unit must be connected by a Siemens secure data transfer connection to bring in data for analysis at the Siemens analysis centre. Detection of changes in machine behaviour is performed using sophisticated algorithms originally developed for design and test bed calibration purposes. The response from the early warning system is published on a web-portal which can easily be reached world-wide. In the portal the responses can be read and downloaded for further analysis if wanted.

5.1.1. Sequence of steps to detect anomalies and produce events

The sequence of steps from detection of anomalies to sending response to web-portal can be recognized from *Figure 3*. Step by step the procedure is as follows:

(1) Measurement data is transferred over secure data link from site to Siemens data collection platform called STA-RMS, (2) Data is stored in STA-RMS, (3) the Early Warning tool called PowerMonitor automatically fetches data from STA-RMS and performs anomaly detection using the algorithms, rules, and models in the software, (4) If an anomaly is detected, an event is sent back to the STA-RMS database, (5) Manual treatment of an event by operator is needed for events that might be false indications, (6) All events are documented in the ticket system, (8) The analyzed events are put on the Siemens web portal and the customer is informed that new events are available. The Events contain a description of the anomaly i.e. fouling of compressor is more than 2% or high vibrations in bearing 1, and information about the circumstances when the anomaly was detected i.e.: steady-state, full load, gas operation. (7) If needed the operator can escalate an event to engineering experts for further analysis. The expert further examines the event to decide if there is genuine anomaly or not. How the solution was made is documented in the ticket system and the solution database.

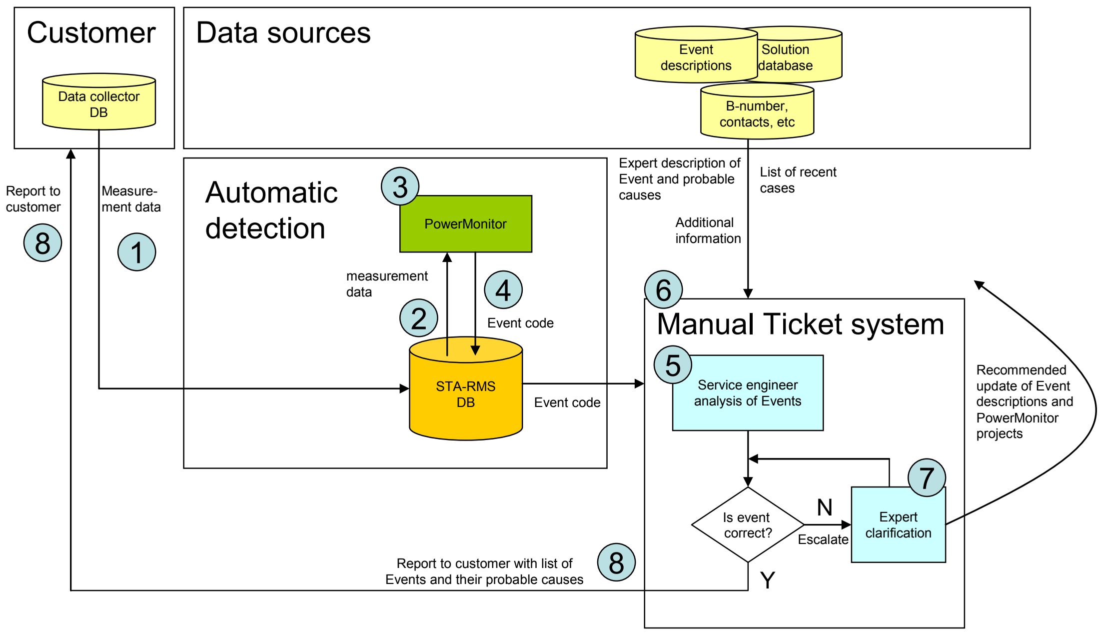

Figure 3 Graphic shows the process from detection of anomalies to publishing events. The numbers link the graphic and the description in text above.

<u>5.1.2 Knowledge in the Remote Diagnostic System</u>

The Early Warning system contains three main knowledge containers. In *Figure 3* they are denoted PowerMonitor (3) that contains the algorithms to detect anomalies and produce events, and in the upper right corner of *Figure 3* are the Event descriptions and Solution database. In PowerMonitor the methods normally used by experts for first analysis of data in their respective field are modelled. For combustion the turbine exhaust temperature profile is modelled and analysed while for vibration the run-up, on-loading and steady-state vibrations are analysed using polar plots and run-up integrals comparing sequential run-ups. The performance model is used for calculation of compressor and turbine performance and degradation. Based on these detected anomalies and the corresponding events are fetched from the Event database. The events are the experts' statement given the detected anomaly. The second source of knowledge is the solution database that is built up from experience from actions on reported Events, more on that in section 5.1.4.

5.1.3 Use of events

Reports from previous events are used as part of the information to take decision for maintenance actions. Such actions may be:

- to decide whether to balance the rotor at a coming inspection or the next
- when to clean the compressor
- when to change inlet air filters
- what to inspect during stand-still

The response can also be used for statistical analysis to get a better understanding of current machine health and change over time.

5.1.4 Learning from fleet

An important feature is the learning of the connection between Events and the solution or action taken. Every generated event is creating a ticket and must be analyzed by remote diagnostic operator before it can be closed. Closing the ticket means a solution has been found for that event and it can now be stored in the solution database. It is very important to ensure that the information stored in the ticket is correct. Learning from previous generated Events is performed by searching the solution database for similar events and machine types and if possible draw conclusions about what action to take.

5.2 Increased maintenance intervals and insurance

In the North American market insurance companies has realized the reduced risk resulting from the use of remote monitoring systems [7] like the one in *Figure 3*. This has led to requests for such systems and discounts for customers that use them.

6 Conclusions and summary

Historically the main driver for MGT development was cost and robustness to allow excessive maintenance intervals and extreme fuel flexibility. The main sales markets were power generation applications in Western Europe, Middle-East and South-East Asia and a few mechanical drive applications. With the introduction of high-efficiency, low-emissions designs an increased amount of maintenance is required making maintenance performance much more important. Further with access to Siemens sales network the MGT market became truly global. In order to meet customer expectations a number of improvement initiatives were initiated. The outcome was a series of initiatives to better determine life characteristics of hot parts of older products and to fix a number of annoying potential issues that, while increasing first cost somewhat, provides customer value by reducing down-time should a problem arise. A number of actions made it possible to extend core engine disassembly intervals by 50% with same or reduced risk, thereby increasing availability by 0,6%. A new service has been developed called remote diagnostic service making it possible to detect anomalies earlier using expert algorithms to treat uploaded data and present events on a web portal to be read at any time. Thus making it possible to analyse operation data every day even for machines located in arctic climates. The learning capability of the system provides all customers with fleet experience and therefore is more efficient in finding solutions.

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