CONDITION AND PERFORMANCE MONITORING OF TURBO MACHINERY BY THERMODYNAMIC MODELLING

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ABSTRACT

The paper discusses aspects of Performance Monitoring (PM) of turbo machinery. The paper is focusing on Gas Turbines (GT) but PM is relevant also for steam turbines, pumps and natural gas compressors, and for non rotating components like air filters and heat exchangers. One important aspect is the need for a correction methodology otherwise the real performance cannot be evaluated. This will be illustrated by data from real installations. A PM system is useful for a number of purposes as indicated in the following list.

Monitoring and forecasting short term (0 - 6 months) degradation. Many operators can see a potential to improve profit by optimizing short term cyclic maintenance.
Monitoring and forecasting long term (> 6 months) degradation. This knowledge can be one input among others for planning the long term maintenance.
Process data validation. A PM system, where appropriate warning levels for the relevant performance variables have been set at both a lower limit and an upper limit, will provide process data validation. A break down or drift in a thermodynamic sensor such as temperature, pressure, power or flow will be discovered. If a sensor is drifting it is often more easy to discover this via a relevant performance variable than the sensor itself.
Combined CM and PM trouble shooting. An integrated system such as OPENpredictor™ contains both mechanical Condition Monitoring and Performance Monitoring. An integrated system encourages the user to examine possible correlations between mechanical and thermal performances because all information is contained in the same database, and all data is retrieved and analyzed with the same user interface.

To support the above statements, several trend plots from the OPENpredictor™ condition and performance monitoring system will be presented. It should also be emphasized that a PM system is supposed to collect data over several years. One objective of the thermodynamic models is to be as accurate as possible. However, even more important is the systems ability to detect changes in the machine relative performance over time. Therefore, when the PM models have been fine-tuned and handed over to a customer they should not be further changed.

1. INTRODUCTION

The paper discusses aspects of Performance Monitoring (PM) of turbo machinery. The paper is focusing on Gas Turbines (GT) but PM is relevant also for steam turbines, pumps and natural gas compressors, and for non rotating components like air filters and heat exchangers. Real machine performances are presented in order to illustrate the principals.

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Monitoring and forecasting long term (> 6 months) degradation. This knowledge can be one input among others for planning the long term maintenance.

Process data validation. A PM system, where appropriate warning levels for the relevant performance variables have been set at both a lower limit and an upper limit, will provide process data validation. A break down or drift in a thermodynamic sensor such as temperature, pressure, power or flow will be discovered. If a sensor is drifting it is often more easy to discover this via a relevant performance variable than the sensor itself.

Combined CM and PM trouble shooting. An integrated system such as OPENpredictor™ contains both mechanical Condition Monitoring and Performance Monitoring. An integrated system encourages the user to examine possible correlations between mechanical and thermal performances because all information is contained in the same database, and all data is retrieved and analyzed with the same user interface.

2. METHODOLOGY

2.1. Equations

The thermodynamic equations in a PM model are derived assuming steady state condition which means that the model fulfils heat and mass balances.

2.2. Performance server

Because the thermodynamic models are based on steady machinery operational state the PM system should include methodology that excludes transient and gradient machine states.

A performance variable is typically evaluated two times per hour (configurable). In a normal situation one performance server calculates all performance variables for a machine. This means that the performance variables for this machine will be evaluated simultaneously and stored with the same time stamp in the database. In case the system monitors several machines there is one server for each machine.

2.3. Correction methodology

Figures 1 to 3 illustrates the problem of assessing the performance of a machine, in this case a large industrial gas turbine. Figure 1 shows the actual output and actual thermal efficiency over three and an half year. The plots are synchronized. In winter time the cold air temperature may give a false impression of high performance. During summer time the machine may operate with load changes every day and thus with a lower thermal efficiency at part load. Figure 2 shows the relation between thermal efficiency and power level for a given air temperature. Figure 3 shows the relation between thermal efficiency and air temperature at 100% power.

In order to have an interpretable result, the model must have a correction methodology. For a gas turbine all performance variables are corrected to a reference ambient, meaning a constant air temperature, pressure and humidity.

When the gas turbine is running on part load the system should correct the performance to 100% load. This would imply part load modelling which would also imply the use of a compressor and turbine map. Such data is propriety information of the GT manufacturer. Still, an OPENpredictor™ PM system can be configured independent of the manufacturer and without the need for detailed technical data. This is achieved via classification which means the machine operation is divided into machine operational states. One typical machine state can be "Load 95 – 100%". During a fine tuning period the baselines (the expected performance variables) are defined per machine state, and these are based on real operational data. The defined baselines are valid for the actual GT at the actual installation. This will automatically capture the influence on performance from supporting hardware installations such as air intake design, air filter design and outlet ducting. Trends, configuration of warnings and forecasts will be made for each individual machine state.

Figure 4 presents both actual (blue) and actual corrected (pink) output for the machine state that corresponds to 100% load. The air temperature is shown in a synchronized plot. We can conclude from this plot that this operator is successful in keeping a stable actual corrected output over time. The same conclusion can be said for actual corrected thermal efficiency over time, figure 5.

3. HOW TO USE THE INFORMATION

3.1. Optimizing short term maintenance

Many operators can see a potential to improve profit by optimizing short term maintenance. A typical example is GT crank wash. The optimal cycle (time interval) for a crank wash is when the accumulated production loss due to compressor degradation equals the loss caused by the maintenance stop to recover. A PM system will monitor the degradation rate and form, and quite often it is found to be linear and repetitive. By knowing the economical value of the production, the down time and all costs associated with a crank wash the optimal cycle can be established. Figure 6 shows the actual corrected GT compressor efficiency for a two-shaft mid size GT. The operator executes a GT crank wash on an eight week cycle. As it appears from the graph, the degradation rate and efficiency recover is quite repetitive, although not 100 % repetitive.

The same reasoning is valid for optimizing pre-filter exchange. The purpose is to optimize profit by minimizing production losses from output degradation and maintenance stop. The objective is also to prolong the lifetime of the fine filter and to assure that the fine filter can be changed during a planned overhaul. It is less accurate to assess the filter fouling by just looking on delta-p over the filter. For this purpose a corrected delta-p is calculated and sometimes a corresponding filter loss coefficient is determined, as illustrated in figure 7.

Figure 8 shows the effect of a pre-filter exchange on a large size industrial gas turbine. The pre-filter was exchanged starting with the first rows and completed a few days later for the remaining rows. The pink curve is the fine filter delta-p, the blue is pre-filter delta-p and the green is total delta-p. The actual corrected output (pink curve) increased with approximate 0.8% which for this large GT corresponds to 2 MW. Again looking on the actual output (blue curve) cannot give a precise indication on the improvement.

3.2. Process data validation

A PM system can be used to detect sensor problems. It is easy to determine if a sensor is not working at all. However, if a sensor is drifting then it might be harder to detect just by looking on the sensor readings. By looking at which performance variables are affected it is quite often easy to conclude which sensor is drifting. Figure 9 provides an example. The fuel flow meter for a large size GT was broken and replaced. After replacement there was a period of calibration problems. When the new flow meter is measuring different than the old one this can be seen in the actual corrected fuel flow, actual corrected thermal efficiency, expander efficiency and the turbine inlet temperature (not shown in figure 9). The plots relates to the machine state that corresponds to full power.

3.3. Combining CM and PM

An integrated condition and performance monitoring system encourages the user to examine possible correlations between mechanical and thermal performances because all information is contained in the same database and all data are retrieved and analyzed with the same user interface. This significantly improves the understanding of the total machine performance. Below is given a few examples on how certain parameters or events affect both the mechanical and thermal behaviour.

For a single shaft gas turbine the air flow at part load is controlled via compressor Inlet Guide Vanes (IGV). Without this feature the part load performance would have been even worse. At full load the IGV is 100% open. At approximate 50% load the IGV is 0% open and cannot further reduce the air flow. Below 50% load the load is controlled only via reduced turbine inlet temperature which will result in a very bad performance. The IGV is an important process parameter for the machine state determination and is used to determine the steady state machine states both for CM and PM. Figure 10 shows the correlation between IGV position, load, GT compressor efficiency, and overall vibration level (mm/s RMS) measured via an accelerometer on bearing 1 (NDE)

Some high impact but unlikely events, for example blade damage in a turbine or compressor row, will obviously be seen in both CM and PM variables.

Normal events such as GT crank wash will typically result in an improved GT compressor efficiency of 1 - 2 %-units as shown above. It is also possible that the removal or redistribution of fouling particles can affect the dynamic behaviour of the rotor. Figure 11 suggests that changes of the OTA 1*RPM phase may be correlated to crank events. (At some longer stops other measures might be the root cause for the OTA phase change.) The OTA was measured using an accelerometer on bearing 1 (NDE) on a gas generator.

3.4. Figures

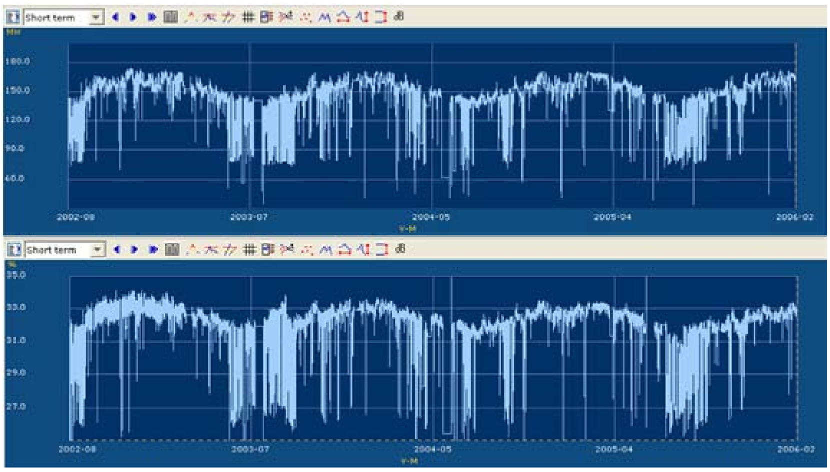

Figure 1. Actual electric output (upper) and actual thermal efficiency (lower)

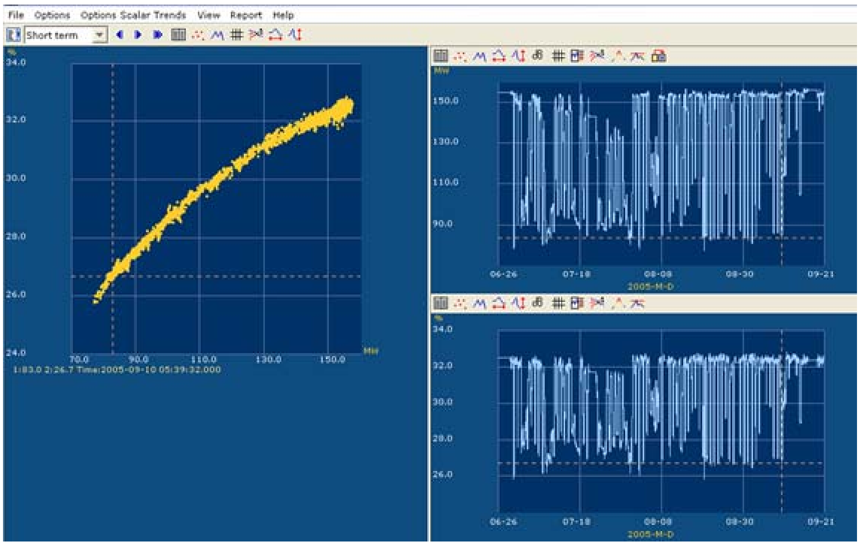

Figure 2. Thermal efficiency versus electric output at constant air temperature

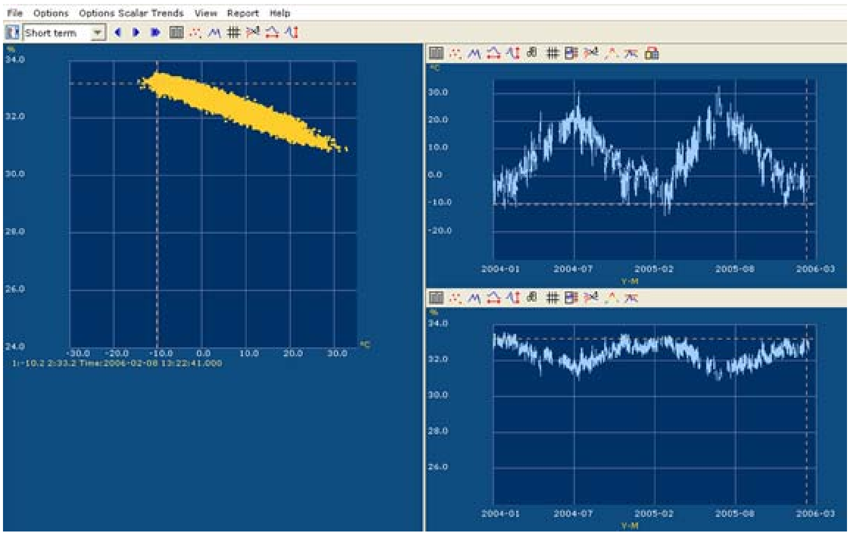

Figure 3. Thermal efficiency versus air temperature at full power

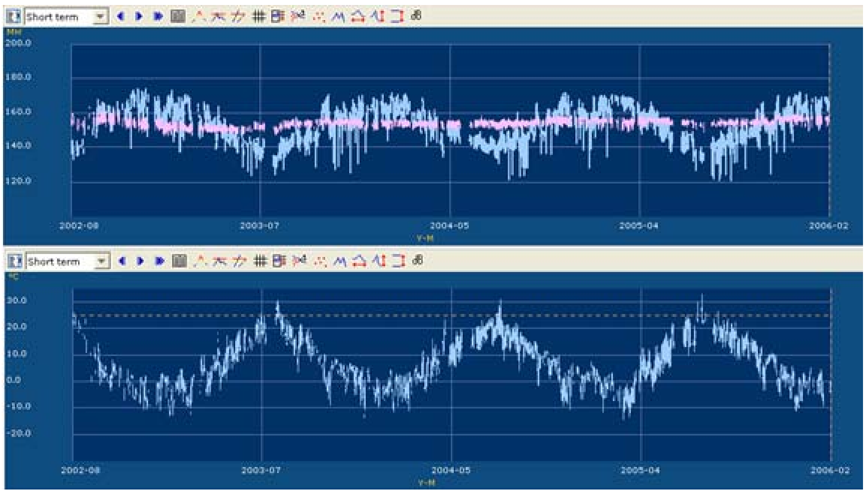

Figure 4.Actual and actual corrected output (upper) and air temperature (lower)

Figure 5. Actual and actual corrected thermal efficiency (upper) and air temperature (lower)

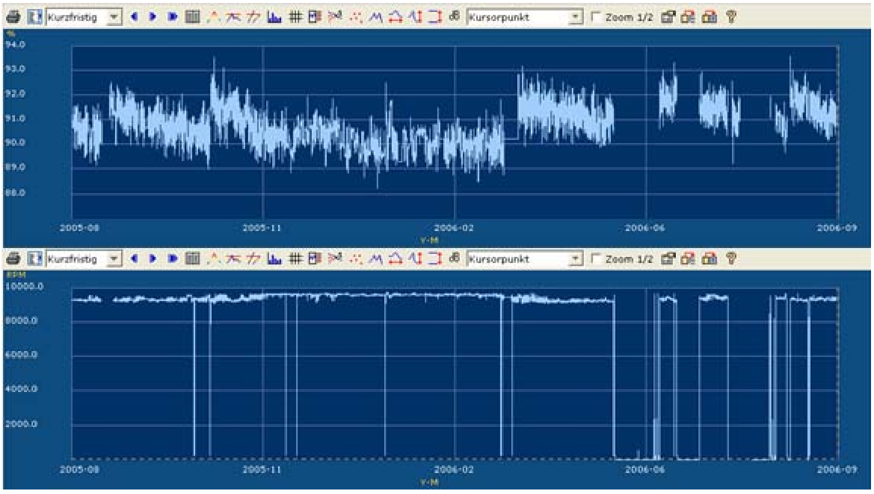

Figure 6. GT compressor efficiency (upper) and gas generator speed (lower)

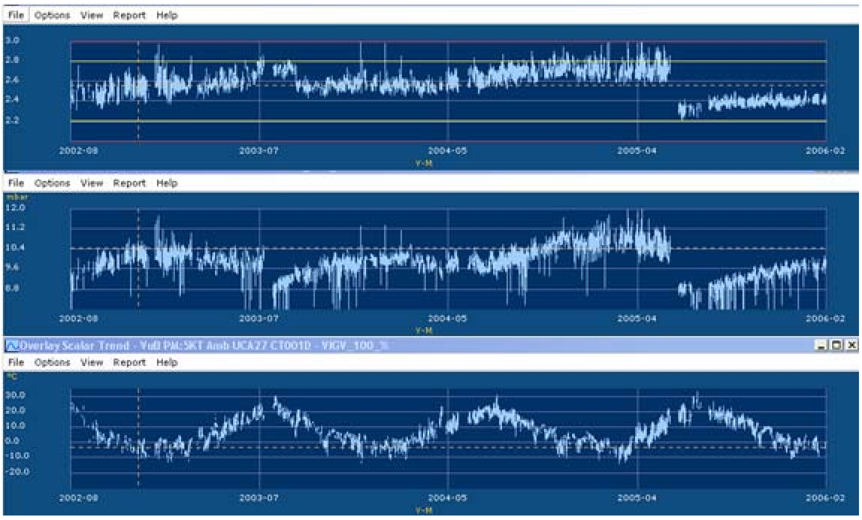

Figure 7. Filter loss coefficient (upper) and filter delta-p (mid) and air temperature (lower)

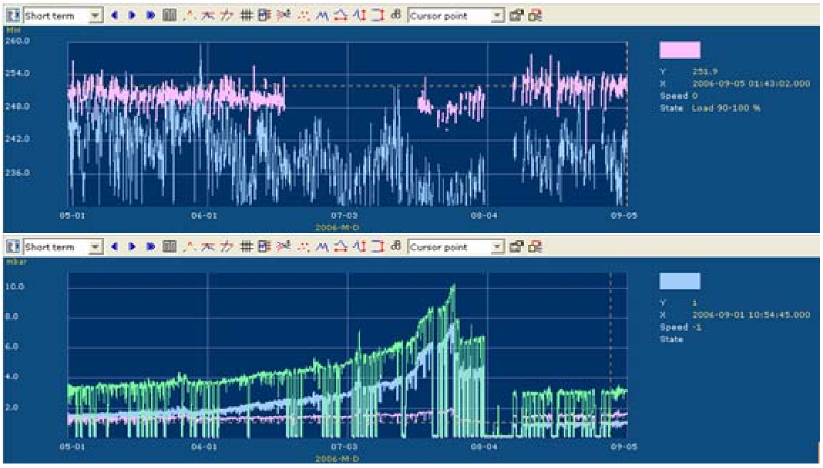

Figure 8. Actual and actual corrected output (upper) and filter sections delta-p (lower)

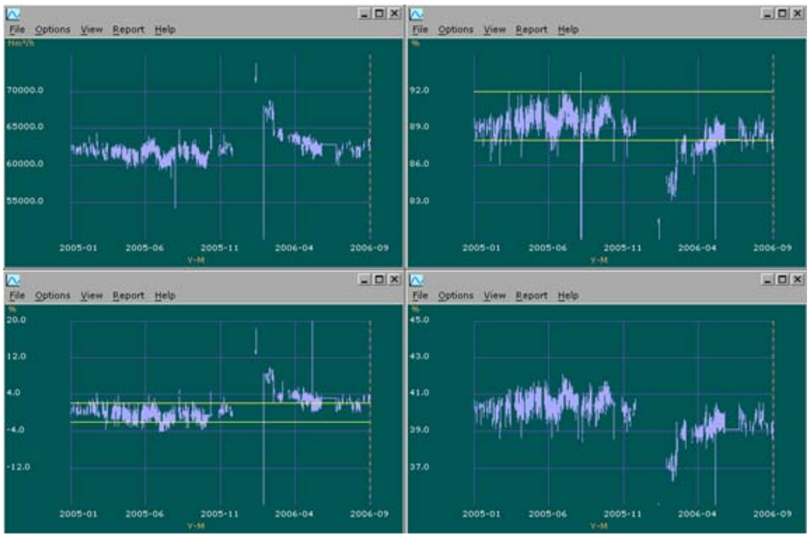

Figure 9. Actual corrected fuel flow (upper left) and expander efficiency (upper right) and thermal efficiency degradation (lower left) and actual corrected thermal efficiency (lower right)

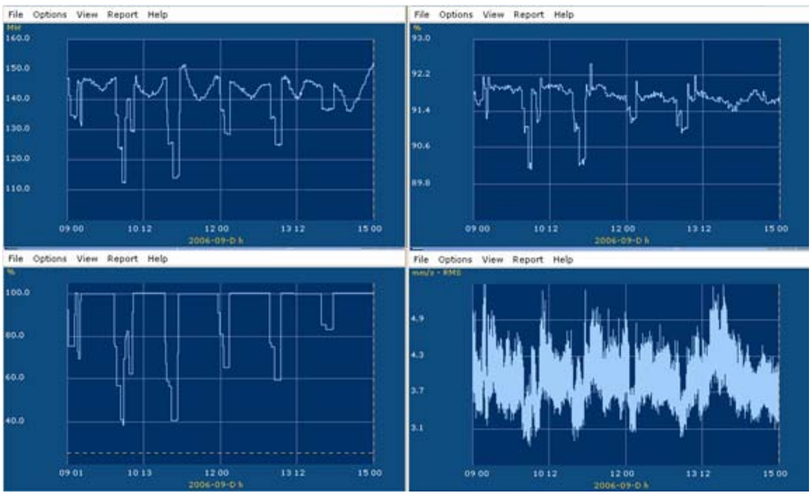

Figure 10. Electrical output (upper left) and GT compressor efficiency (upper right) and IGV position (lower left) and overall vibration level (lower right)

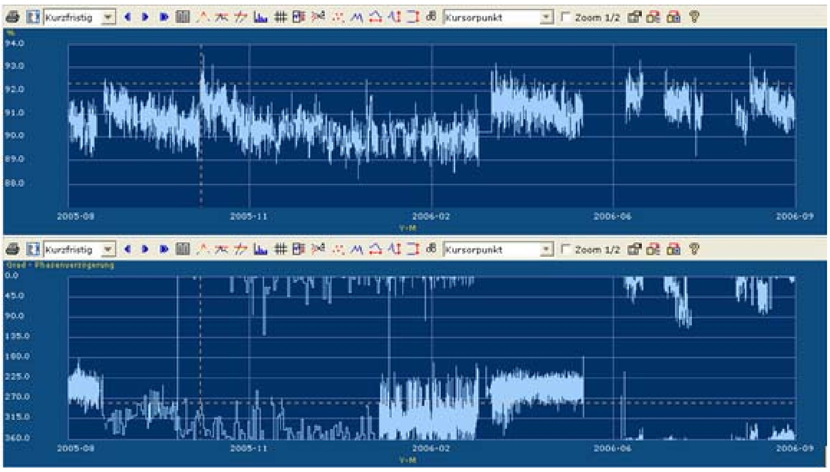

*Figure 11. GT compressor efficiency (upper) and OTA 1*RPM phase (lower)*

4. CONCLUSIONS

There are several objectives for using a PM system. The most important is probably the potential to improve profit by optimizing short term cyclic maintenance. The paper emphasizes the importance of a correction methodology. It was illustrated for gas turbines but a correction methodology is needed also for other turbo machinery when the real performance is to be evaluated.

It should also be emphasized that a PM system is supposed to collect data over several years. One objective of the thermodynamic model is to be as accurate as possible. However, even more important is the systems ability to detect changes in the machine relative performance over time. Therefore, when the PM models have been fine-tuned and handed over to a customer, they should not be further changed, whereas the warning levels for performance variables of course can be subject for further review.