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REMOTE ASSISTANCE INTERVENTION AND DIAGNOSIS (RAID) FOR ROTATING MACHINES

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ABSTRACT

Over the past 10 years, TOTAL's rotating equipment operational fleet has more than doubled in number and in power (In 2014: 306 shaftlines* for 3.68 GW). The impact of a unit shutdown has grown both in terms of production and safety hazard for workers. Among other initiatives, to respond to this new operational context, TOTAL decided to develop its own remote monitoring center at the TOTAL's Scientific and Technical Headquarters in Pau, France. The goal of this center is to establish predictive analytics and diagnosis for all units in operation throughout the globe using a dedicated software package: SmartSignal.
(*these shaftlines include turbine driven equipment and electric driven equipment (>3MW))

SmartSignal software is based on the analysis of the deviation between a monitored site value and a predicted software value. This predicted value is defined through a model of the unit based on the correlation of historical data during normal operation of the unit. An excessive level of deviation between the site and predicted value, initiates a warning signaling a possible catastrophic outcome.

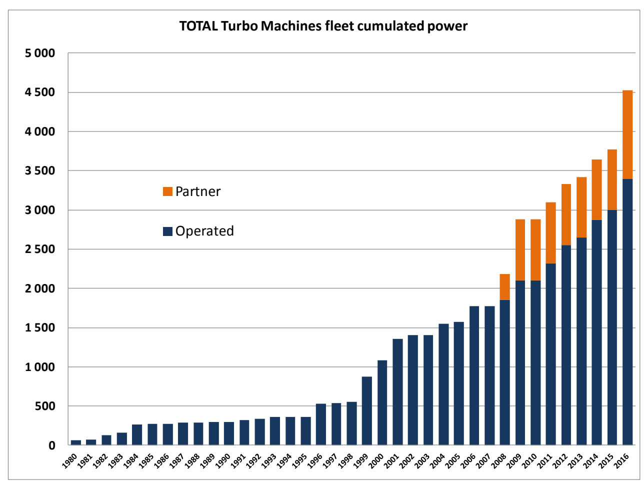
Therefore, the center aims to: reduce unplanned production losses, reduce maintenance costs due to breakdowns, increase unit availability and, of course, improve operational safety. To date, over one hundred and fifty pieces of rotating equipment are followed by the RAID. TOTAL intends to deploy this remote assistance to the complete fleet within the next five years.

INTRODUCTION

The oil market has shown a significant increase in the oil & gas rate from 2000 to 2006 and, apart from a market crisis in 2008, the rate of oil has since remained at a level where oil & gas operators were pushed to find oil and operate rigs in more remote environments and at higher production rates. As a result, the units have grown in number, size, and complexity; therefore, their reliability has become even more critical.

FLEET EVOLUTION AND ANALYSIS

TOTAL has undergone the same kind of growth, from the deep offshore, to the arctic, or to desert environments.



The remoteness of sites, as well as the harsh environment, pushed TOTAL to understand how to evolve its operating way. This change started with the tracking and the analysis of each breakdown so as to understand its origin: design, environment or operation. According to this analysis, TOTAL determined that anything not linked to design had to be improved by better understanding the patterns leading up to failures. A perfect example of one of these patterns is the combination of a salty environment with sulfur in the fuel gas, and the corresponding temperature in the hot section of the gas turbine, that can lead to type 1 or type 2 hot corrosion.

TOTAL then split these different patterns between what could or could not be detected through monitoring. On a gas turbine, the analysis concluded that 30% of the breakdowns could have been avoided through unit monitoring, whereas on other rotating equipment such as centrifugal compressors or pumps, that factor increased to 80%.

GAS TURBINES		
Could be anticipated through monitoring?	**YES**	**NO**
Axial compressor	9	21
Hot section	10	16
Power turbine	1	2
Bearings	2	10
TOTAL	**22**	**49**
Percentage	**31%**	**49%**
CENTRIFUGAL COMPRESSORS		
Could be anticipated through monitoring?	**YES**	**NO**
Seals	9	2
Aero section	5	
Gas scrubber	7	
Antisurge valve	4	1
Couplings	1	4
TOTAL	**26**	**7**
Percentage	**79%**	**21%**

Based on this analysis, TOTAL decided that a remote monitoring strategy had to be developed and deployed throughout the fleet.

REMOTE MONITORING STRATEGY

A remote monitoring strategy was envisioned to match TOTAL's goal of increasing availability for its fleet, but a realistic deployment method first had to be identified.

The eventual goal is the same for all operators: to increase availability in order to avoid production losses while reducing maintenance costs.

Remote monitoring and diagnosis is commonly proposed by turbine Original Equipment Manufacturers (OEMs) in a full health care contract. This service is promoted as being able to insure the operator a higher availability of its units. However, one of the downsides is that this type of remote monitoring will only cover the OEM's supplied equipment. Therefore, for an Oil & Gas operator with a wide fleet and a high diversity of equipment, this solution is not sufficient.

Moreover, the remote monitoring provided by OEMs is based on studying the deviation of a parameter compared to design criteria. Although this deviation must be considered, effective monitoring cannot be limited to it. The remoteness and harsh environment of TOTAL's sites often leads it to operate units not as per nominal design. This does not mean that they cannot be operated but it does require taking the specific context into account.

Eventually, TOTAL had to define what tool it would use to perform this task: detecting in advance any potential degradation that could lead to failure.

CHOICE OF THE REMOTE MONITORING TOOL

TOTAL's analysis on operational breakdowns led to specific requirements for selecting the remote monitoring tool. For each type of breakdown that could have been detected through monitoring, a correlated alarm parameter was defined. For example, a correlation exists between the efficiency of the axial compressor and the filter differential pressure. The simple trending or alarming of the inlet filter differential pressure is insufficient and does not illustrate the condition of the axial compressor.

Therefore, the method consists of calculating the isentropic efficiency of the compressor using the pressure and temperature of the inlet and discharge of the compressor, and correlating it with the speed of the gas generator (for twin shafts units) and the differential pressure of the filters.

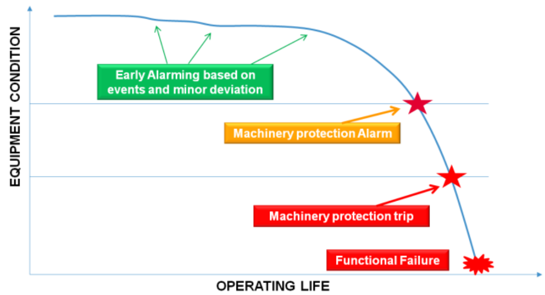
$$\eta_{isentropic} = \frac{T_{isentropic} - T_{inlet}}{T_{discharge} - T_{inlet}}^{*}$$

$$\frac{T_{isentropic}}{T_{inlet}} = \left(\frac{P_{discharge}}{P_{inlet}}\right)^{\frac{1-\gamma}{\gamma}^{*}}$$

*Temperature expressed in K and Pressure in Bar abs, γ being 1.41 for air.

An obvious correlation is an increase of filter differential pressure associated with a decrease of axial compressor efficiency at a given speed; a less obvious correlation is a decrease of filter differential pressure associated with a decrease of the axial compressor efficiency at a given speed. In the first case, it leads to axial compressor fouling combined with filter plugging, and in the second case, it leads to filter degradation inducing axial compressor fouling. While this correlation is not specified in the maintenance manuals, it happens to be significant on sites.

The tool chosen had, as a minimum requirement, to take into account such correlations. It also had to allow for thermodynamic performance calculation, and in addition, be able to monitor all the elements of TOTAL's fleet worldwide with a manageable amount of alerts. It should be emphasized that the concept of this monitoring is not to replace the existing control system, but to anticipate the unit's behavior.



Based on these requirements, TOTAL reviewed a variety of tools available on the market and narrowed them down to a pilot study with two possibilities, SmartSignal being one of them.

REMOTE ASSISTANCE, INTERVENTION AND DIAGNOSIS (RAID) CENTER

SmartSignal's tool was TOTAL's final choice to meet all of the requirements. To validate this choice, a one year pilot was launched on one hundred different pieces of rotating equipment throughout the TOTAL fleet.

SmartSignal's software is based on the analysis of the deviation between the measured site value and the predicted software value. For any gas turbine, a set of models is established. For example, a twin shaft industrial gas turbine will include: gas generator mechanical, power turbine mechanical, performance, fuel control system, combustion and cooling models.

Each of these models includes an identified list of operating parameters. The historical data for these parameters will allow the construction of a matrix correlating them with the operational state of the machine. Only healthy, normal operational behavior of the unit will be kept in the matrices. With each new data sample, the correlated parameters will be grouped into a vector. This vector will then be compared to the matrix, and the estimated model value will be determined according to a similarity based modeling (SBM) algorithm. SmartSignal's software takes into account these correlated parameters, and generates alarms when the machine deviates from its normal behavior.

The alerting is initiated by the deviation of the measured value compared to the predicted value. In case of abnormal deviation, an alert is raised and the user is advised. The user can then investigate through the software whether this alert will require additional site investigation, whether the deviation is still acceptable and can wait until next scheduled unit maintenance, or whether this is a new operational mode that needs to be added to the system.

CASE STUDY: ADAPTATION OF THE MODEL

To start, these empirical models are defined based on 6 months of running history. This history will allow, as explained above, to establish a reference behavior for each model on each piece of equipment.

To be more specific, for a gas turbine, the performance model will include as a minimum the following parameters: the power output of the unit, the ambient temperature, the combustion air filter differential pressure, the compressor inlet pressure and temperature, and the compressor discharge pressure and temperature. These seven parameters will then be correlated with one another and will represent the base of the performance model.

$$\begin{pmatrix} turbine\ power \\ ambiant\ temperature \\ filter\ diff\ pressure \\ compressor\ inlet\ temp \\ compressor\ disch\ temp \\ compressor\ inlet\ press \\ compressor\ outlet\ press \end{pmatrix} \begin{pmatrix} MW \\ °C \\ mmH_2O \\ °C \\ °C \\ bara \\ bara \end{pmatrix}$$

Therefore, a given operating condition will be represented by a vector of measured values from which SmartSignal will calculate the estimated values of the corresponding operating condition.

Measured value **State Matrix** **Estimated value**

$$\begin{pmatrix} 3.409 \\ 11.7 \\ 21.86 \\ 9.1 \\ 336.3 \\ 1.05 \\ 10.25 \end{pmatrix} \times \begin{pmatrix} 3.502 & 3.415 & 3.321 & \\ 11.2 & 11.8 & 11.41 & \\ 22.01 & 20.04 & 21.75 & \\ 9.5 & 10 & 8.8 & etc\ ... \\ 340.2 & 350.02 & 338.7 & \\ 1.02 & 0.998 & 1.01 & \\ 10.3 & 10.21 & 10.5 & \end{pmatrix} = \begin{pmatrix} 3.387 \\ 11.8 \\ 21.79 \\ 9.3 \\ 337.6 \\ 1.07 \\ 10.34 \end{pmatrix}$$

The green squared case in Figure 1.

The level of correlation between the measured value and the estimated value entirely depends on the state matrix and the data used to establish it. In the selected example, the level of correlation is 99% between the two vectors.

When facing a condition not included in the state matrix, the estimated value will clearly deviate and the correlation level will decrease.

Measured value **State Matrix** **Estimated value**

$$\begin{pmatrix} 3.145 \\ 11.9 \\ 22.53 \\ 10.1 \\ 335.84 \\ 1.09 \\ 10.08 \end{pmatrix} \times \begin{pmatrix} 3.502 & 3.415 & 3.321 & \\ 11.2 & 11.8 & 11.41 & \\ 22.01 & 20.04 & 21.75 & \\ 9.5 & 10 & 8.8 & etc\ ... \\ 340.2 & 350.02 & 338.7 & \\ 1.02 & 0.998 & 1.01 & \\ 10.3 & 10.21 & 10.5 & \end{pmatrix} = \begin{pmatrix} 3.314 \\ 13.48 \\ 22.58 \\ 10.71 \\ 337.7 \\ 1.08 \\ 10.31 \end{pmatrix}$$

The red squared case in Figure 1.

This new operating condition faced on the same unit results in a lower level of correlation which has decreased to 92%.

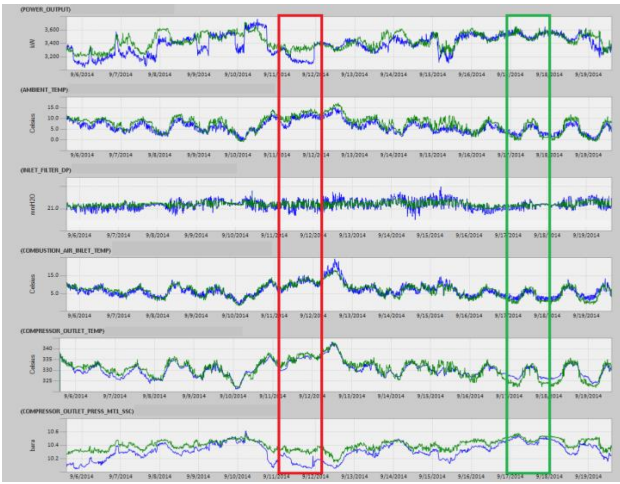


Figure 1 - Gas turbine performance case study

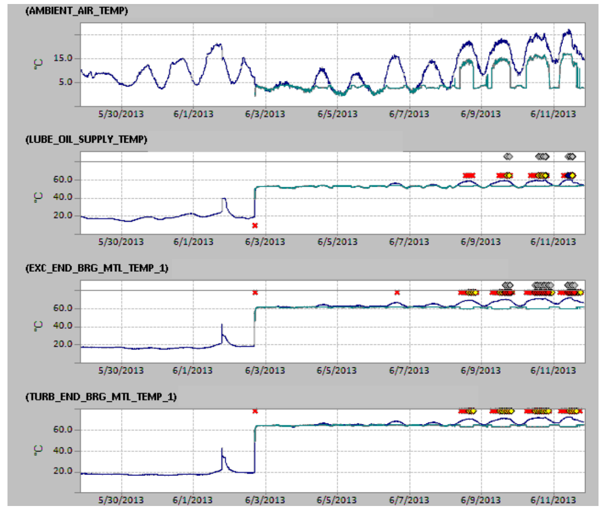


Figure 2 - Gas turbine ambient temperature case study

Nevertheless, this deviation is not the proof of a malfunction of the unit; it may just be an operational condition not well defined in the reference matrix. Adding these additional operating condition points to the reference model will improve the accuracy of the SmartSignal model, preventing false positives from alerting over time.

For each model, the principle will be the same in terms of vectors and state matrix, only the parameters included and reference data will vary from one model to the next. Specifically, the gas generator mechanical model will include as a minimum: the power output, the ambient temperature, the gas generator speed, bearing temperatures and vibrations, oil pressure, and oil temperature.

$$\begin{pmatrix} \text{turbine power} \\ \text{ambiant temperature} \\ \text{gas generator speed} \\ \text{inlet bearing temperature} \\ \text{outlet bearing temperature} \\ \text{inlet bearing press} \\ \text{outlet bearing press} \end{pmatrix} \begin{pmatrix} MW \\ °C \\ rpm \\ °C \\ °C \\ bara \\ bara \end{pmatrix}$$

Obviously, the ambient air temperature has a direct influence on the thermodynamic behavior of the gas turbine, but it can also impact the mechanical criteria of the unit (see Figure 2). The change in the ambient air temperature impacts the aero-cooling of the oil which results in a change of the oil characteristics, and thus in the bearing behavior. However, these new environmental conditions may still be acceptable and adding them to the reference matrix will, once again, increase the accuracy of the SmartSignal model.

In summary, the model and its reference data provide a baseline from which deviations in equipment behavior can be detected and interpreted. The addition, over time, of new operating conditions will fine tune the model and improve the correlation between the measured and estimated value.

CASE STUDY: ALERTING

SmartSignal alerting includes three major types of parameter deviations:

The first is in line with what every control system does - alerting when a measured value surpasses a defined threshold. However, the defined SmartSignal limit is within the alarm setting of the control system and surpassing the threshold will only be converted into an alert if it persists for more than a defined period.

The second, and more unique, method of alerting is based on the deviation between the actual value and the model value. By creating an additional set of thresholds (often called the "dynamic band") centered on the estimated value, deviations in actual equipment behavior can be detected earlier than with the first method alone.

The last, is in line with what a rotating equipment engineer would analyze for a given parameter deviation. Based on his knowledge of the unit and the site specific conditions, he will naturally correlate in his mind this deviation to other parameter shifts. SmartSignal has coded part of this knowledge into the software by correlating certain parameters and quantifying their individual influence.

As a specific example, if the exhaust temperature increases on a turbine wheelspace seal measurement, the key point is to understand if it is due to a change in operating condition or an emerging problem with the equipment. If it results from a plugging of the cooling air passages, can it be seen on the other temperature measurement of the same wheelspace? Does this deviation require an immediate action?

Most turbines equipped with wheelspace instrumentation have four temperature measurements by stages, two forward of the disk and two after. The wheelspace temperature measurement is there to assure that the turbine disk is adequately cooled and that neither its creep resistance nor its design lifecycle will be impacted. Therefore, an excessive wheelspace temperature doesn't require a direct shutdown of the unit, but will require a planned intervention.

In this case, the SmartSignal model alerted on a cooling incident. The parameters associated to this alert were: the two forward wheelspace temperature measurements, the temperature difference between these two forward temperatures, the ambient temperature, and the gas generator speed.

The SmartSignal cooling model typically includes as a minimum: the power output, the gas generator speed, the axial compressor inlet and discharge temperature, the axial compressor inlet and discharge temperature, the wheelspace temperatures of each stages.

$$\begin{pmatrix} turbine\ power \\ ambiant\ temperature \\ gas\ generator\ speed \\ compressor\ inlet\ temp \\ compressor\ discharge\ temp \\ compressor\ inlet\ press \\ compressor\ discharge\ press \\ wheelspace\ forward\ temp \\ wheelspace\ after\ temp \end{pmatrix} \begin{pmatrix} MW \\ °C \\ rpm \\ °C \\ °C \\ bara \\ bara \\ °C \\ °C \end{pmatrix}$$

Through this SmartSignal tool, TOTAL was able to identify that the problem wasn't linked to a change in operating condition. Through the performance model, we could also confirm that this wasn't due to a degradation of either the axial compressor or a leak on auxiliary air piping, implying less cooling. The combustion model allowed us to complete our analysis by determining that the fuel ratio was equivalent to similar operating conditions in the past.

A review with the site team and the OEM allowed TOTAL to conclude that this increase in wheelspace temperature was most likely the result of a mechanical clearance problem on the turbine stage and that an intervention will be necessary before the temperature reaches the alarm value.

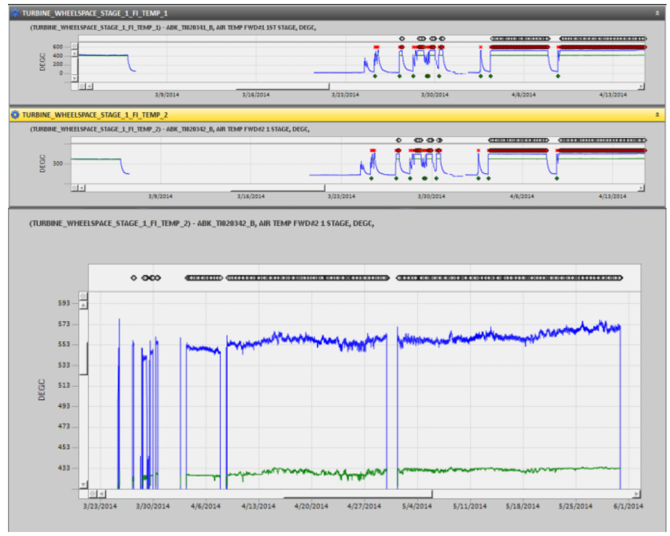


Figure 3 - Gas turbine wheelspace temperature case study

The possibility to anticipate and plan for such an intervention for an Oil & Gas operator is crucial. This is especially true for functions such as those performed by this shaftline, which directly impact the production. Any day of shutdown results in a direct loss of production, and any day of unplanned shutdown usually takes at least twice the downtime of a planned shutdown.

CONCLUSION

At the end of the pilot year, the SmartSignal software appeared to clearly meet the demands of TOTAL's remote monitoring strategy.

After having implemented SmartSignal monitoring last year, TOTAL was able to detect, in advance, many of the same problems that it used to face in the past which could have been detected by this type of remote monitoring. Moreover, this monitoring allowed TOTAL to increase its operational know-how, to challenge itself on how maintenance could evolve to a more condition-based approach, and to challenge the OEMs on machine and package design criteria.

TOTAL has therefore decided to deploy this strategy to the complete fleet worldwide within the next five years.