Trip Reduction in Turbo Machinery

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Abstract

Industrial plant uptime is very important for reliable, profitable, sustainable and smooth operation. Emergency shutdown events (known also as trips) and failed start events (machineries not starting upon demand) have major impact on plant reliability and all plant operators are focussed on the efforts required to minimise the number of trips & failed starts. The performance of these Critical to Quality (CTQs) are measured with 2 metrics, MTBT (Mean Time Between Trips) and SR (Starting Reliability). These metrics helps to identify the units requiring more effort to improve the reliability of the entire plant.

Baker Hughes Trip Reduction Program (TRP) is structured to reduce these unwanted trips and failed start events, and it is founded on some pillars and operational steps:

1. Real time machine operational parameters remotely available to capture the signature of malfunction, including related boundary condition (operational phase, ambient conditions).
2. Real time alerting system based on diagnostic and prognostic analytics, available remotely.
3. Remote access to trip logs (timeseries of signals, sampled at very high frequency around the event of trip) and alarms from unit control system, which are key to study the sequence of events and identify the causes.
4. Continuous support to field engineers by remotely connecting with subject matter expert.
5. Live tracking of key Critical to Quality (CTQs)
6. Benchmark against fleet of similar units
7. Break down to the cause of failure to component level
8. Investigate top contributors, identify design and operational root causes
9. Implement corrective and preventive actions
10. Assess effectiveness of implemented solution.
11. Develop new analytics for predictive maintenance, based on product knowledge and lessons learnt

With this approach, Baker Hughes team is able to support customer in achieving their Reliability Key performance Indicators for monitored units, huge cost savings for plant operators. This paper explains this approach while providing a successful case study, in particular with reference to twelve Liquified Natural Gas (LNG) and Pipeline operators across the world, with about 140 gas compressing or power-generation gas turbine driven units which adopted these techniques and significantly reduced the number of trips and improved their MTBT.

1. Introduction

Reliability and Availability of machine is the vital factor and performance gauge for customer to have an effective run of the machine. Undesirable anomalies and events leading to machine forced shutdown, known to be as trips and fail starts, impact the reliability of the machine. Minimizing these unwanted trips and fail starts is foremost priority to improve overall reliability and availability of machine.

The remote continuous monitoring of machine operations and the diagnosis of undesired events is key to understanding the signature and the causes of the malfunction. It helps to suggest continuous improvements and avoid production interruptions in the future.

The target of the Trip Reduction Program is to progressively eliminate the causes of the spurious emergency shut-downs (trips) and failed starts. The program defines the top contributors and critical issues for the project, analyze the issues and suggests for corrective and preventive actions, after digging into the root causes. Across the installed fleet, thanks to the information collected and the analyses executed to dig into the causes of the trips and failed starts, the Trip Reduction Program allows a continuous reliability improvement of the products.

It works on metrics which gives a direct reflection of machine performance, with the capability to drill down to component level to understand the cause of the problem. The remote connection with machines and the continuous engagement with field service engineers, with the maintenance and operations team within the customer's organization, help to quickly collect the field evidences for further engineering analyses and to rectify the causes of the issues, once the solutions are identified. The collection of data within a specific operational plant or across the fleet of similar machineries, allows to visualize the top offenders across the fleet. Associated with deep investigations of the problem, it provides the operational root cause and the solution for improving both the design of new units and the fleet already installed.

2. Machine Remote Monitoring

Thousands of machine operational parameters are remotely connected with Baker Hughes iCenters (multiple Monitoring & Diagnostic centers across the globe), with a 24 hours x 7 days monitoring and diagnostic service. The continuous monitoring of machine parameters helps in understanding the operational behavior. Rule-based analytics are built on data and provide real time alerts in case anomalies are generated from the machine as an early detection and warning, following the prognostic approach. Figure 1 shows the typical dashboard from iCenter highlighting the anomaly detected for remotely connected projects

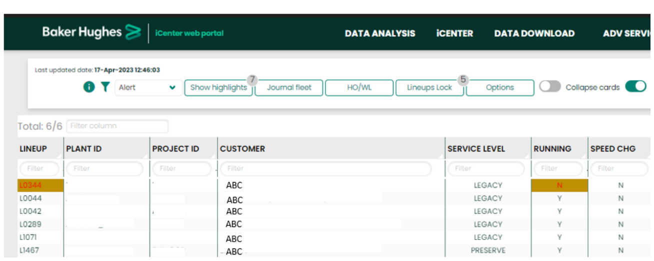

Figure 1: Remote Monitoring dashboard at iCenter

2.1. Real Time Alerting System through Analytics

The rule-based analytics developed, run in backend to capture any anomaly with machine operational parameters when connected with iCenters and under monitoring. Both "simple" deviation rules and physics-based "complex" rules and analytics predict the behavior of machine and alert the users to perform a corrective action.

1. Pre-defined rules magnify the scope of an early detection of machine parameters going beyond the limits and take suitable recommended action.
2. Early detections through analytics are notified to customer so that unwanted trips can be avoided and suitable action can be performed

Not only abnormal behaviors and deviations from the historical operational parameters raise flags to remote diagnostic engineers, so that operators can be informed and alerted for a prompt reaction in the field, but data serve also as the basis to focus proactively on the top contributors to trips and failed start events, so that engineering investigations can be started to remove the causes of such unwanted events. Figure 2 informs about the detected anomaly based on simple and physics-based rules beyond the threshold limits. For example, a discrepancy between the readings of two or more sensors that are supposed to read coherent values of the pressure pulsations in a combustion chamber, although below the alarm value, or anomalous shaft axial displacement in a rotating machinery.

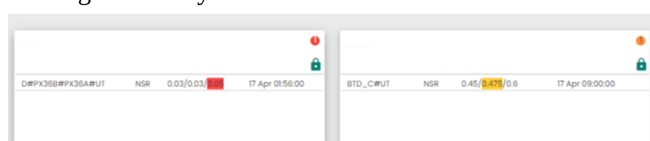

Figure 2: Remote Monitoring Anomaly detection

2.2. Remote Access to Logs

Logs help to perform basic troubleshooting and understand the root cause of the problem. In case of trips or fail starts, logs support in identifying the area for the investigation, to understand the sequence of events and therefore they allow a drill down to the components that have created the issue.

Logs are generated locally by the control panel of the machinery, and captured continuously in the iCenter databases. Specific event logs are generated in case of machine malfunction. These logs are remotely accessible for the experts to investigate, provide recommendations and solutions to bring the machine back online quickly. Figure 3 shows the logs generated when machine trips.

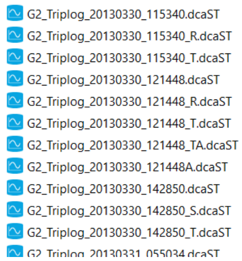

Figure 3: Logs generated during machine shutdown

3. CRITICAL TO QUALITY

Performance of the machine are being measured through metrics Mean time between trips (MTBT) and Starting Reliability (SR). These metrics benchmark the machine performance over the past years and across the fleet. Metrics helps to understand what the top contributors in the particular project are and help to focus the improvement effort.

Trip Reduction Program keep a track of metrics, top contributors and deeply analyze and study the event which resulted in an interruption of the production through generated logs.

3.1. Mean Time between trips and Starting Reliability

MTBT and SR are key performance indicators for the machine. Mean Time between trips (MTBT) defined as a ratio of service hours to number of trips. It is a measure of how many hours machine has been running without unwanted emergency shutdown event.

MTBT definition is derived from the MTBF definition reported in standard ISO 3977-9 (para 3.67), the difference consisting in intending the forced outages as any emergency shut down events only.

$$MTBT\ (h) = \frac{SH}{TRIP}$$

where, **SH** = service hours cumulated in the analyzed period of time. It represents the amount of time during which the unit is actually operated within the analyzed period. It can be calculated as the operation time between the end of the starting sequence and the subsequent shutdown signal.

TRIP = number of emergency shut down events, after the end of the starting sequence, cumulated in the analyzed period of time.

Starting Reliability (SR) defined as ratio of successful starts to starts attempted. It is a measure of the probability a machine will successfully start whenever it is requested to do so.

SR is defined according to ISO 3977-9 (see para 3.104)

$$SR\ (\%) = \frac{SS}{SS + FS} 100 = \frac{SS}{SA} 100$$

SS = number of successful starts, intended as the number of times for which the starting sequence is successfully completed.

FS = number of failed start-up attempts, intended as the number of times for which the starting sequence has been aborted.

SA = total number of starting attempts (number of times the starting sequence has started).

3.2. Anomaly Detection

Early warnings or operational anomalies are being detected, having the potential to cause a machine shutdown and a production interruption. Anomalies are prioritized based on a criticality base (severity of possible effects and real rate of occurrence). Investigation is performed to identify the cause and proactive action is taken to prevent the effects of the anomalies.

3.3. Top Contributors

Continuous monitoring of the issues occurring at project and across the fleet, provides visualization of top contributors, the issues recurring and impacting the reliability and availability of the machine. Trip reduction program targets to capture and act on these top offenders to provide design improvements and solutions for the issues. Figure 4 shows the top contributors which impacts the reliability of machine and needs attention. Different colors represent the status of investigation for a particular issue.

Figure 4: Top contributors

3.4. Identify Design and Operational root cause

Identifying top contributors and further investigation leads to identification of the failure mode.

Then root cause analyses are performed using different methodologies and tools embraced within Baker Hughes, such as Shainin® methodology, 5-Whys, Apollo Root Cause Analysis, Ishikawa (fishbone).These are all well known and institutionalized methods in the Oil & Gas and other industries, to dig into the root causes of the issues and develop effective solutions.

As needed, investigations are performed in lab on the returned parts from the installed fleet, to look into the failure causes and providing most effective solutions.

4. Action Tracking

Recommended solutions are being tracked for the implementation at the different projects. In fact, typically the implementation of corrective actions takes place with time schedules dictated by the plant operational constraints.

To measure the effectiveness of the solutions, it is crucial to know exactly the moment when the actions are performed on the specific units or machine, so that the cause-effect relationship can be established.

4.1. Effectiveness of Implemented solution

It is key for the results of the TRP program and for the satisfaction of the Customer to measure the effectiveness of the solutions implemented in the field.

In order to have an objective measure of the field effectiveness, statistical models are applied to the data acquired with the remote connection, to measure the reliability growth.

4.1.1 Reliability Growth Model

Typical fleet reliability growth analysis involves the use of time-between-failures data, obtained from the systems during the operation.

In case of TRP, the exact moment of the malfunction is recorded and the "time" is calculated as the cumulated number of operational hours, or start-up attempts after which a specific trip, failed start or anomaly event has occurred.

The method selected for estimating the reliability growth of complex repairable systems, such as those supplied by Baker Hughes, is the well-known Crow-AMSAA model, based on the theory of a Non-Homogeneous-Poisson-Process and on a "minimal repair" approach.

The instantaneous failure intensity λi(T) of a system is modeled as a power function:

$$\lambda_i(T) = \lambda\beta T^{\beta-1}$$

where λ is the scale parameter and β is the shape parameter that characterizes the shape of the intensity function. β value indicates how the failure intensity is changing over time:

- $\beta<1$ → Failure intensity is decreasing
- $\beta=1$ → Failure intensity is constant
- $\beta>1$ → Failure intensity is increasing

T is the time (cumulated number of: operational hours or start-up attempts).

The expected number of failures at a given time T is:

$$N(T) = \int_0^T \lambda(t)dt = \lambda T^{\beta}$$

Maximum Likelihood Estimation (MLE) is used to estimate the parameters λ and β of the model.

The Failure Intensity is used as evaluation function. Based on specific Trip Reduction Project time of failure events, the model allows to estimate the failure intensity and to monitor its changes over time, to correlate with the implementation of corrective and preventive actions on the fielded units.

In this context a corrective actions implementation dashboard is also necessary to track, for each unit, the corrective action implementation date.

In fact, by knowing the exact date of its implementation, the statistical effectiveness of the solution can be calculated. Internal target is also set to assess whether the company is satisfied by the field effectiveness of the solutions or other actions should be done to improve further. Depending on the severity of the issue, a target of 80% or more is selected for the reduction of the initial value of the failure (trips/failed starts/anomaly event) intensity, above which the corrective action can be considered statistically effective.
Figure 5 shows a typical example of Reliability Growth Crow-AMSAA model, where dots representing the issues occurred over the time (time expressed as cumulated operating hours) and change in slope reflects the effectiveness of the actions implemented.
When a change point in the model is identified, it can be useful to apply two different statistical regressions over the set of data (via Maximum Likelihood Estimate). An example of calculation of the reliability growth using the "change point" (also known as "change of slope" or "break point") is here reported

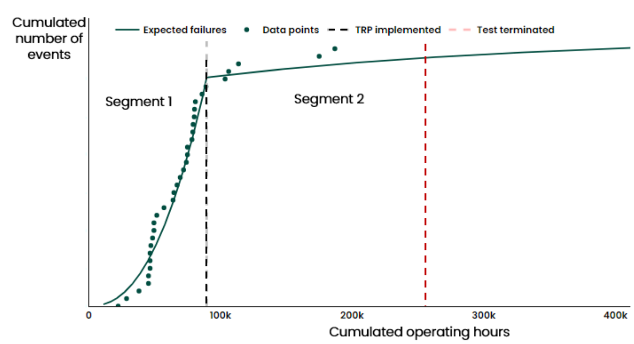

Figure 5: Reliability Growth Crow AMSAA model

In the example, the break-point is identified in correspondence of the implementation of the actions, when

the cumulative amount of operating hours was about 89000 hours (vertical dashed line in black color).
In such type of analysis, two different models are used to represent the behavior before and after the break-point.
The instantaneous failure intensity immediately before the break-point can be calculated, from segment 1 of the model:

$$\lambda_i(T) = \lambda\beta T^{\beta-1}$$

$\lambda(89211\ \text{hrs.})$ = 4.94E-8 * 1.77 * 89211 ^(1.77-1) = 5.71E-4 hrs^{-1}

The instantaneous failure intensity at the end of monitoring (see second vertical red dashed line) can be calculated from the segment 2 of the model:

$\lambda(258320\ \text{hrs.}) =$ 10.85 * 0.0893 * 258320 ^ (0.0893-1) = 1.14E-5 hrs^{-1}

Therefore, the instantaneous failure intensity has finally decreased by:

(1- (1.14E-5 / 5.71E-4)) = **98%**

The effectiveness of the solution is demonstrated and the specific issue can be closed.

5. CASE STUDY

A real case from the experience with industrial application of aeroderivative gas turbines is presented to illustrate the approach of Baker Hughes to the continuous reliability improvement, based on the remote data connection with fielded units.
In fact, many machineries running in industrial plants, particularly for the liquefaction of natural gas (LNG plants), for the electrical power generation and for the gas compression over pipelines, are remotely connected to Baker Hughes iCenters and they continuously transmit their operational data.

Gas Turbine Axial Compressor (T3) Discharge Temperature

Gas Turbines axial compressor discharge temperature is a parameter used for the turbine operational control and for asset protection purposes. Figure 7 is typical installation of T3 temperature sensor with its cable and aeronautical connectors

Figure 6: Axial compressor sensor installed

Across the fleet, several repetitive, instrumentation malfunction events of the axial compressor discharge temperature signals were identified. RM&D continuous monitoring and diagnostic service detected the anomalous behavior of such temperature sensor, which has been showing sporadically incorrect (not physical) readings during the machine operation, indicating a malfunction in the acquisition loop. Figure 7 represents the trends captured for temperature sensor during machine running through Baker Hughes iCenter, clearly indicating erratic behavior.

Figure 7: Example of temperature trend from remote data connection

Different signatures of the malfunction were identified, such as drop down to negative values, erratic behavior or data frozen to unreliable values, captured through remote monitoring in iCenters. Similar failure modes were observed across the fleet in various projects over the years, represented in figure 8

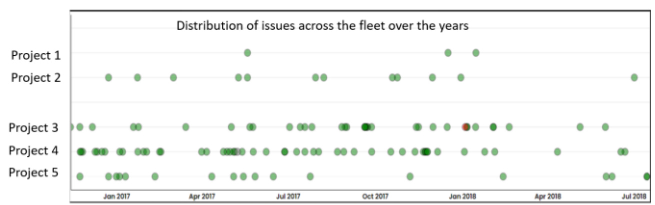

Figure 8: Axial compressor T3 sensor reading malfunction events across projects from remote connections

A dedicated investigation through Shainin® methodology was carried out to rule out step-by-step failure causes and converge to the area of the sensor assembly where the main cause of the malfunction resided, drilling down to the smallest component level, such as the pins of the aeronautical connector the sensor is equipped with.
Further step towards a detailed investigation, some malfunctioning sensors were removed for analysis. A simulation setup was prepared in the lab to reproduce the similar phenomena using testing tools.
The identified cause of failure was a fretting corrosion forming between the pin-socket interface inside the aeronautical connector. During the machine operation, due to vibrations, pin and socket inside the connector don't hold properly and fretting corrosion forms between the surfaces of the two parts. Oxides are produced and the electrical resistance of the entire loop changes, up to the point to alter the temperature reading or even to interrupt the continuity in the measurement loop.

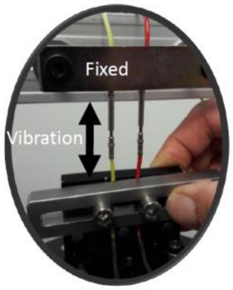

Figure 9: laboratory setup to reproduce the pin-socket fretting mechanism at room temperature

Every abrupt change in the relative position of pin and socket (sudden change in vibrations, or the opening and closing of the connector) acts as a sort of self-cleaning action, restoring the functionality of the acquisition loop (see figure10 and 11)

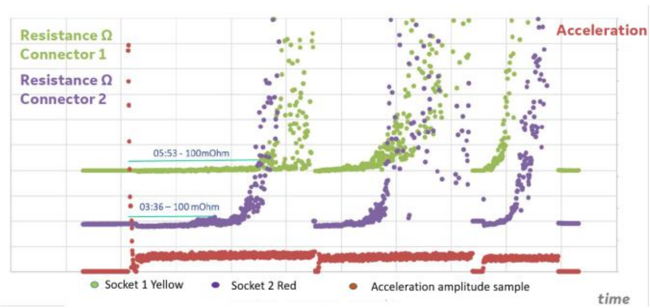

Figure 10: resistance of connector pin-socket assembly as a function of vibrations and reset at change of vibrations level

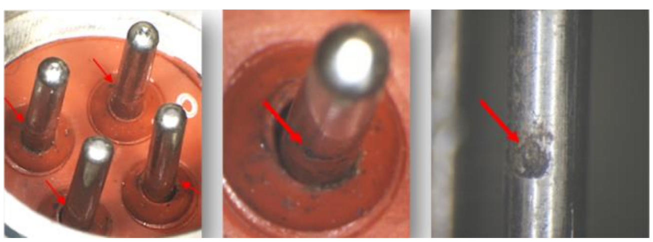

Figure 11: evidence of connector pins damage by localized fretting

The physics of the malfunction and its mechanism was therefore understood and reproduced in the laboratory under controlled conditions.

Amongst other possible design change choices, the application of a specific anticorrosion lubricant for connectors has demonstrated to mitigate the occurrence of temperature sensor erratic or lost signals. It is designed to be applied periodically on pins and receptacles (sockets) of aeronautical connectors. The investigation led to identify a mitigation plan for the installed fleet, consisting of a maintenance practice to be applied during the outages for planned maintenance.

After the validation in the laboratory, the Customers were informed about the recommended periodic lubrication activity for the sensors under study and connectors of other critical signals of the machines.

The field effectiveness of the application of the lubricant on the connectors was validated through Reliability Growth Analysis model, which showed that the failure intensity could be reduced by more than 90%. Significant improvement is observed in the reduction in frequency of issues which is getting visualized by the change in the slope of the number of events over the cumulated operation time of the units.

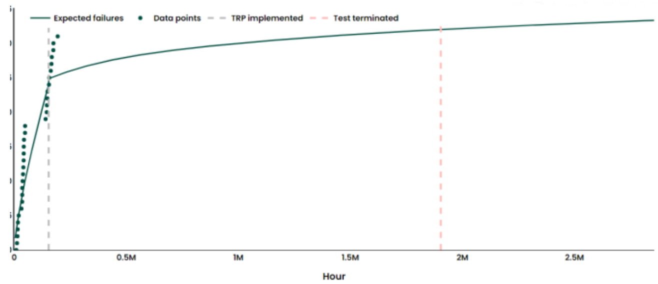

Figure12: Effectiveness review- failure intensity change in slope

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6. CONCLUSION

The RM&D (Remote Monitoring & Diagnostics) system enables Baker Hughes experts to remotely access operational data of plants operating worldwide, and to exercise algorithms, which detect possible abnormal operating conditions of rotating machineries through operational signatures. The experts, with ready access to design information, operation and maintenance information, and laboratories to replicate the issues, plus the in-depth knowledge about the turbo machineries, can leverage the data and the extracted information to sustain the root cause analyses.

The Baker Hughes Trip Reduction Program leverages the diagnostic and prognostic capabilities offered by the RM&D service to effectively improve the reliability of the products, thus supporting customers in achieving their Reliability Key performance Indicators for monitored units, huge cost savings for plant operators.

NOMENCLATURE

BH *Baker Hughes*
TRP *Trip Reduction Program*
MTBT *Mean Time Between Trip*
SR *Starting Reliability*
CTQ *Critical to Quality*
RM&D *Remote Monitoring and Diagnostic*
LNG *Liquefied Natural Gas*
RGA *Reliability Growth Analysis*

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Gilda Pedoto is a Lead engineer and experienced in Trip Reduction Program (TRP) service at Baker Hughes, Florence Italy. She received her master's degree in automation engineering and the PH.D. in Information Engineering from University of Sannio, Benevento, Italy. During the PH. D, she spent fifteen months in Johns Hopkins University in Baltimore, MD, USA working on predictive modeling based on biomedical data. Gilda has 9 years of industrial experience, working in aeroderivative and heavy duty gas turbine reliability improvement for Baker Hughes customers with the TRP service active. In her current role, she's the front line for several LNG plants, collecting issues from field and working with experts to solve them.

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