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INSTRUMENT & CONTROL – MACHINERY ROBUSTNESS IMPROVEMENTS AGAINST SPURIOUS TRIPS

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ABSTRACT

Experiencing a spurious trip of a turbomachinery train due to an unreliable or faulty instrument or control system can be a very costly and frustrating experience. Nevertheless, a commonly overlooked area within turbomachinery packages is the robustness of the instrumentation and controls design against spurious trips. End-users generally have minimal inputs to the OEMs ‘standard’ alarm and trip functions when procuring a turbomachinery packaged equipment.

Collaboration between OEM and end-users with regards to instrumentation and control design can lead to the engineering and delivery of fit-for-purpose turbomachinery packages that maintains reliability (safety) and increases availability (operational). This tutorial explores the possibilities and mechanisms to rationalize the trip functions and improve the instrument and controls design robustness against spurious trips for any given turbomachinery package in a collaborative environment.

INTRODUCTION

Instrumented trip functions within a turbomachinery package are expected to trip the unit to prevent escalation of an unsafe condition. The impact of an unsafe condition could range anywhere between mild to severe, affecting the equipment, operator or the surrounding environment. For several critical trip functions, the unsafe condition could potentially result in catastrophic damage to the equipment resulting in loss of lives, major fires and significant repair and replacement costs as well as opportunity loss as a result of equipment outage. However, for other non-safety critical trip functions, it could be a pre-cursor or a warning to prevent a further continued operation in an undesirable state which calls for immediate rectification by the operator.

The economic cost impact of a spurious trip of a turbomachinery train varies depending on its criticality to the operations, the sparing philosophy at site, the speed at which the trip can be rectified and machine re-started and a host of other considerations. Considering that turbomachinery packages are usually critical and integral to the facilities operations, the figures in table 1 are a good indicator of the spurious trip cost impact of these equipment across industries.

Process Application	Spurious Trip Cost
Oil & Gas Platforms	Up to $2 million/day
Polystrene	20 days to recover at $20k/day=$400k
Refinery Coker Heater	$35k/day
Refinery Catalytic Cracker	$500k
Complete Refinery	$1 million/day
Ammonia & Urea Plants	$1 million/day
Power Generation	$100k/MW hour to $millions/site
Ethylene	$1 million to include getting product to spec

Table 1: Spurious Trip Costs in Different Industries. [R1]

Although it could be argued from a spurious trip perspective that it is always better to be 'safe than sorry', frequent spurious trips also do have a negative impact to the equipment. Frequent start-up and shutdown cycles following spurious trips increases the wear and tear of the mechanical components. It is also during these periods of shutting-down and starting-up that the likelihood of safety incidents increases as frequent personnel presence and involvement at site becomes a necessity.

PETRONAS's Operating Units has had its share of spurious trips resulting from instrumentation failure over the years resulting in major production losses. Over the years, PETRONAS's operating assets have diligently worked to resolve these spurious trip issues as they occur from time to time by understanding failure mechanisms and proposing specific resolutions. These investigation cycles are necessary and will still continue to be relevant. However, this traditional approach to address trip incidents could be viewed as reactive. Furthermore, it has limited effectiveness if a robustness design review is not considered for the trip incident i.e. despite the best maintenance efforts, the trip can happen again.

Over the last 2 years, a novel approach "Instrumented-Machinery Robustness Improvement" has been adopted to focus instead on the design robustness of the trip instrumentation in turbomachinery packages to minimize spurious trips resulting from instrumentation failures. The fundamental philosophy of this exercise is that 'a single instrument failure should not result in a turbomachinery train trip'. The exercise is exhaustive and evaluates every single trip function within the package that are potential threats to spurious trips of the turbomachinery train. Once identified, the exercise evaluates the risk, the current design and potential solutions for each trip function individually.

SAFEGUARDING PHILOSOPHIES AND CONFORMANCE TO STANDARDS

Determining the required shutdown functions for turbomachinery trains have always been the purview of the OEM. Despite being the dominant standard in the manufacturing and design of turbomachinery equipment, the popular API standards as listed in Table 2 are very much mechanical engineering driven and have very little mandatory requirements with regards to the design of instrumentation and controls within the standards.

Common Applicable API (American Petroleum Institute) Standards
API 611, 5th Edition, 2008 - General Purpose Steam Turbine
API 612, 7th Edition, 2014 - Special purpose Steam Turbine
API 616, 5th Edition 2011 - Gas Turbine
API 617, 8th Edition 2014 - Axial, Centrifugal Compressors and Expanders
API 618, 5th Edition 2007 Errata 1 and 2 (2009 and 2010) - Reciprocating Compressors
API 670, 5th Edition, 2014 - Machinery Protection System
API 614, 5th Edition, 2008 - Lubrication, Shaft-sealing and Oil-control Systems and Auxiliaries
API 692, 1st Edition 2018 - Dry Gas Sealing Systems for Axial, Centrifugal, Rotary Screw Compressors and Expanders

Table 2: Common API standards in design and manufacturing of turbomachinery packages.

As an example, Table 3 below shows the base recommended alarm and shutdown requirements found in API616, 5th Edition 2011 - Gas Turbines for the Petroleum, Chemical, and Gas Industry Services. Notice that mandatory shutdown functions are a fraction of those that require to be alarmed and of those, half are listed as optional.

Condition	Alarm Annunciated
radial shaft vibration	X
axial thrust position	X
overspeed	X
casing vibration	X
high thrust or radial bearing temperature	X
low fuel supply pressure	X
turbine exhaust overtemperature	X
failure of exhaust overtemperature shutdown device	X
high differential pressure in each air inlet filter	X
combustor-stage flameout	X
control system failure	X
failure of starting clutch to engage or disengage	X
low lube-oil pressure	X
high or low lube-oil reservoir level	X
lube-oil filter differential pressure	X
lube-oil spare pump operation	X

Table 3: Recommended Alarm and Shutdown in API616 Table 6 [R2]

Most OEMs packages however, have alarm and shutdown features that easily meets and usually far exceeds the mandatory API requirements. OEMs decisions on the number of instrumented alarm and shutdown functions and how they are implemented is subject to several factors among others including:

- OEMs safeguarding philosophy
- OEMs proprietary equipment and auxiliaries design
- OEMs internal R&D
- OEMs preferred sub-system, control system and instrument vendors/partners
- Previous lessons learnt from OEMs fleet incidents
- Technical advancements and Obsolescence in instrumentation and controls

Determining Instrumented Shutdown Functions

The decision making on required instrumented alarm and shutdown functions within a turbomachinery package is determined by the OEM based on their proprietary equipment and auxiliary components design. Where other components are packaged into the turbomachinery train, e.g. Dry Gas Seal systems, Gearbox or Fire & Gas Systems, the supplier usually proposes their recommended alarm and shutdown functions which are then incorporated into the overall package. This exercise to integrate the package is performed by OEMs and is usually supplemented by an internal HAZOP or risk assessment exercise.

Lately, the adoption of the popular IEC61508 and IEC61511 within the industry has influenced the design of the Safety Instrument Systems (SIS). The standard requires the risk of an instrumented safeguarding function be quantified. Internal risk assessments and HAZOPs are being supplemented by formal Process Hazard Analysis (PHA) or Layers of Protection Analysis (LOPA) to determine SIL (Safety Integrity Level) for each safeguarding function.

One of the major drawbacks of the quantification of SIL through these exercises e.g. HAZOP, PHA, LOPA etc. is that it is not mandatory to consider impacts of spurious trip as a result of false positive detection or instrumentation failure. Another important consideration that in these SIL determination exercises, the operational and maintenance practices that are used to determine the probability of occurrence and consequences are determined by the OEMs themselves without the input of any of the end-users. This results in a generic SIL rather than an actual SIL. An actual SIL which is higher would then result in a more robust design with a 2oo3 configuration. An actual SIL which is lower could result in the instrumented shutdown being sufficient as an alarm, leading towards higher availability.

Implementing Instrumented Shutdown Functions

Adopting the IEC61508 and IEC61511 standards further requires appropriate selection of the instrumentation, logic solver and final element in tandem with its SIL. This leads towards selection of more ‘reliable’ instrumentation, logic solvers and final elements available in the market to be used within the package. OEMs and packagers have begun to respond to these standards which can be seen from many SIL rated control systems and instruments being offered for newer turbomachinery packages. All of this generally relates to a higher safety confidence factor of the packaged equipment to end-user with regards to safety of the equipment.

The vast majority of safeguarding functions within a turbomachinery train usually end up with a generic SIL of up to SIL2. Most instrumentation sensors in the market e.g. transmitters and switches can easily meet SIL1 and SIL2 requirements in a 1oo1 configuration. While adopting those meets good governance in terms of conforming to reliability standards, it is to be noted that a 1oo1 configuration is not robust against spurious trips as will be demonstrated in the following chapter.

To further meet SIL requirements, the instrumentation marketplace has resulted in an influx of new generation instrumentation sensors with a variety of inherent diagnostics being employed in newer turbomachinery packages. A more reliable detector is able to flag itself to indicate poor functionality and that further maintenance is required. For an instrument used in a shutdown function particularly a 1oo1 function, this would mean an automatic shutdown to cater for its rectification.

Furthermore, there is not much allowable customization on OEM packages when it comes to having options such as choice of instrumentation and control systems brands or models that the end-users are familiar with or having additional instrumentations with voting that allows for increased availability of a turbomachinery trains.

The obvious benefit of having a ‘standard’ design and philosophy from the OEM generally results in a faster lead times and delivery of these packages without much customization to suit various end-users. The drawback however, is that it does not consider the application and practices of the end-user which could determine if the risk, safeguards and design could be too conservative and over-engineered or vice versa.

INSTRUMENTATION FAULTS AND ROBUST DESIGN ISSUES

All spurious trips are inevitably caused by a false positive detection by an instrument, faulty instrumentation or some human error that eventually leads to an instrument initiating a shutdown of a turbomachinery train.

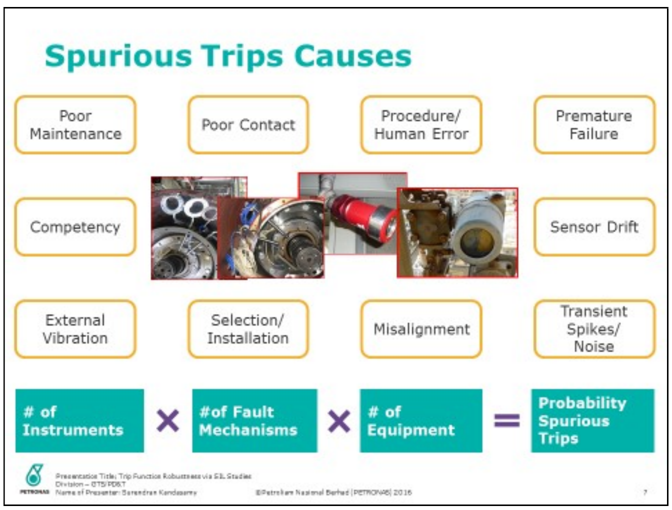

Figure 1: Instrument Fault mechanisms that could result in spurious trips.

As can be seen in figure 1, there are at least 10 possible fault mechanisms that could cause a false positive detection of an instrument which ultimately results in a spurious trip. This demonstrates that despite the best efforts of maintaining any instrument with a 1-out-of-1 (1oo1) trip configuration within a package, there are just too many possibilities that could lead to a spurious trip caused by the instrument. Instrumentation and Control Systems like all electronic devices, can and will present issues from time to time despite the best maintenance efforts.

For end-users, there are various challenges with regards to addressing instrumentation robustness within turbomachinery packages at both the purchasing and operational stages.

Procurement Stages

In the procurement and design engineering stages of a new turbomachinery train, there is far too little requirements or specifications imposed with regards to the availability requirements of the instrumentation and control system design. Even if specifications were made available, as previously discussed, most instrumentation and control schemes in turbomachinery packages come with ‘standard’ packaged designs once the OEM has been selected.

The emphasis of selection and future discussions is predominantly concentrated on the mechanical equipment rather than the robustness of the control systems design. Instrument and Control systems design discussions usually revolve around the implementation of the ‘standard’ package and its integration into the overall facilities Distributed Control System (DCS) and Safety Instrumented System (SIS). Furthermore, there is very limited appetite at this stage to evaluate instrument and control systems design for robustness as it will involve customization which eventually leads to longer lead delivery times and potential variation orders.

For older turbomachinery trains, control system obsolescence is another challenge where instrumentation and control systems have to be refreshed. Usually these upgrades are handled as a project and managed by the OEMs. The choice of upgrade and the new control system and accompanying logic is also deemed ‘standard’ by the OEM of the turbomachinery train. In these upgrades, generally there are a host of new additional safeguarding and diagnostic functions that are not familiar to the end-user which will be offered as default. These often are ~~often~~ not properly understood and will pose threats towards spurious trips if not uncovered and thoroughly discussed with the OEM. Usually, the complexity to physically change out the control system and the urgency to complete the task within a limited time frame supersedes the discussion on robustness.

Operational Stages

Once the turbomachinery train is operational, a sudden trip results in frenetic call to action on the operation crew to stabilize the production facility and on the maintenance crew to evaluate the authenticity of the trip to be spurious or genuine. Should it be a spurious trip, the remedial action to determine the cause and isolate the faulty instrumentation must be taken swiftly in order to resume production. In the case of a single equipment train, further pressure is applied on the maintenance and operations crew to urgently restart the unit, which may not permit a thorough evaluation of the root cause of the fault mechanism. This may subsequently lead to multiple restarts and spurious trip cycles in a short span of time before an effective resolution on the root cause and a proper corrective action is taken. There has been many instances where the maintenance crew would be dumbfounded to find a reasonable explanation or identify the root cause of the fault mechanism of the instrument. Questions on the effectiveness of the instrumentation, maintenance activities, mechanical integrity and even operational practices will continue to linger long after the unit has been restarted.

As the emphasis tends to focus on the specific instrument, most root-cause analysis studies of spurious trip incidents results in recommendations on improving maintenance practices and increasing maintenance frequency with regards to these instrumentation. This increases operational expenditure of the facility and may reduce the probability of occurrence but will never eliminate the risk of spurious trip as demonstrated by Figure 1. Evaluating the necessity of the trip function or potential design changes to the trip function is rarely undertaken as it will be a time consuming affair and usually unsuccessful in nature due to the risks involved especially if the OEM does not sanction the change.

Given that it is very common to have instruments to trip in a 1oo1 or 1oo2 configuration, the probability of spurious trips for that particular equipment naturally increases. This is where PETRONAS has embarked on a systematic approach to attempt to influence instrumented safeguarding designs within turbomachinery packages with the equipment OEMs in a comprehensive and collaborative manner.

INSTRUMENT – MACHINERY ROBUSTNESS IMPROVEMENT STUDY

The PETRONAS Group Technical Solutions Instrument and Control engineering team has embarked on an exercise towards improving the robustness against spurious trips in currently operational critical turbomachinery units with a study called i-MRI (Instrumented - Machinery Robustness Improvement). The guiding principle behind this study is to ensure that no single instrument fault should result in a trip of the unit. Permanent participation in the study usually involves the instrument, mechanical and the process/operations engineer. At the later stages when evaluating the recommendations, the OEMs design engineers are brought in. The study involves a 5 step process as listed below.

1. Identifying all 1oo1 Instrument trips within the package and other potentially not-robustly designed trip functions.
2. Evaluating the trip function against applicable standards, operational practices and its current design.
3. Proposing a suitable recommendation based on the internally assessed risks.
4. Review all proposed recommendations with equipment OEM to finalize solutions.
5. Engineer and implement finalized solutions.

A pre-curser to Step 1 would be a data and document gathering exercise. The commonly required documentation for this exercise are:

1. Cause and Effect Diagrams
2. Process & Instrumentation Diagrams
3. Wiring diagrams and I/O assignments
4. Logic Diagrams or actual offline software logic

5. Instrument datasheets
6. Previous trip incident reports.

With turbomachinery packages, documentation gathering has to be comprehensive and their interconnections well understood as the trip functions may come from various external sources e.g. Fire and Gas Systems, Anti-Surge Control Systems, Machinery Protection Systems and the process plant main Safety Instrumented Systems which can all command a trip to the package's Logic Solver.

In Step 1, the engineer scans, extracts and compiles the non-robust functions that would be of interest to be evaluated into a list that can be edited, commented, filtered and sorted. This step would be made easier if native files of the original Cause and Effect Matrices were made available. For ease of discussions, the trip functions should be organized by sub-systems for ease of discussion e.g. dry gas seals, fuel systems, bearing vibration and temperature, fire and gas, air systems, etc.

Step 2 and Step 3 are usually done in tandem with the participation of the multi-disciplinary engineers. Poring over the available documentation, operational and maintenance practices, equipment and process behavior, the team focuses to arrive at a particular solution. The challenge would be to derive simple, minimally complex, cost effective solutions that address the instrument robustness problem whilst maintaining equipment reliability with identified risks reduced to ALARP (As Low as Reasonably Practicable). The proposed recommendations, assumptions and justifications made are all documented.

In order to achieve some structure when evaluating each trip function, a series of common questions are developed to guide the discussions as stated below in Table 4.

Question	**Answer**	**Proposed Recommendation**
Can the trip occur based on the operating condition?	No	Remove trip function
Is the trip function redundant? Can the failure of the trip instrument to detect result in another instrument to initiate a trip?	Yes	Consider downgrading either one of the trips to alarm or combining the individual trip functions through voting of the instruments.
Are there other instruments performing the same function?	Yes	Vote with other instrumentation
Can another instrument be added into the equipment easily?	Yes	Add additional hardware
Can a time delay before the trip tolerated?	Yes	Implement time delay

Table 4: Questionnaire on evaluating robustness of instrumented trip functions.

Despite the desire to achieve robustness, a caveat that is necessary when conducting this exercise is to avoid overly complicated design solutions that would require complex logic modifications or algorithms to detect faults. The preference is to utilize the existing fault detection capabilities of the system to arrive at the most robust solution. Solutions should be simple, easily understood by end-users, OEMs and system integrators.

Another important consideration is to accept that not all trip functions would be able to be improved through robustness. Some functions are proprietary in nature to which the end user would have limited knowledge of the design basis hence unable to reasonably justify any form of robust solutions. In other instances, where additional instrumentation could be justified, equipment design constraints would not possibly allow for additional instrument to be added into the loop.

In step 4 of this exercise, all previously proposed recommendations are reviewed with the equipment OEM. PETRONAS considers this as an important step with regards to good governance and managing risks when proposing changes. Furthermore, it is an effort to enhance collaboration with the equipment OEMs through engaging in technical discussion to further understand the design basis of each trip function, explain the robustness philosophy and deliberate risks associated with proposed recommendations. From PETRONAS's experience, this has not always resulted in resistance from OEMs as would be expected. The effort to convince OEMs on proposed design changes can be challenging as it involves customization of an established 'standard' design principles but the intent and suggestions have been well received and thoroughly deliberated. On occasions, the results have involved in transferring of the risks to the end-user and in some occasions, it has resulted in OEMs internally reviewing their own 'standard' controls design to meet higher availability demands from end-users. The outcome of this step is a finalized recommended solutions that is ready to be engineered and implemented.

In step 5, the solutions are engineered and implemented by the end-user. It is advised that the engineered solutions particularly involving the logic modifications in the main equipment's logic solver or hardware installation on any proprietary equipment be reviewed by the OEM.

CASE STUDY

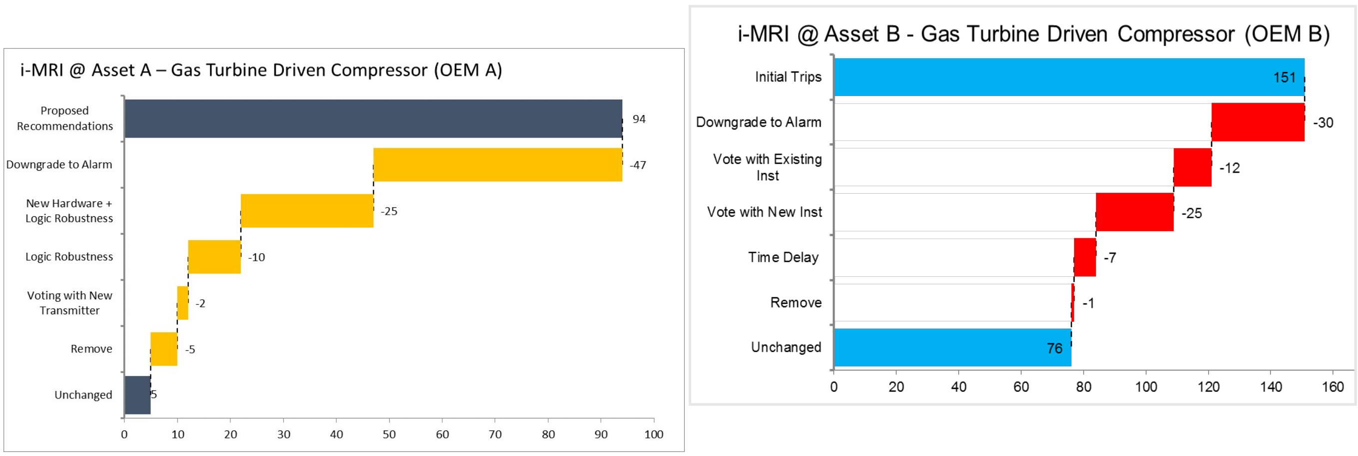

Figure 2: Trip Robustness Improvement Exercise Results

As seen in Figure 2, the exercise has successfully produced reasonably effective results at 2 different assets within PETRONAS Operating Units utilizing turbomachinery from 2 separate OEMs.

Asset A is a Gas Turbine driven Compressor in a Petrochemical facility with a single train where a spurious trip effectively results in a total process shutdown due to insufficient circulation throughout the process. Asset B is a Gas Turbine driven Compressor in a Gas compressing facility whereby a spurious trip results in a loss of product delivery to customers affecting both profitability and reputation of the organization.

The figure 2 illustrates that in both cases, the accepted engineered resolution was in excess of 50% from the original cause and effect matrix. This translates to complete avoidance in the future from potential spurious trips from any instrumentation faults where the recommendations were implemented.

The fact that these resolutions were driven through collaboration with the OEMs does demonstrate the potential of robustness improvements along with OEMs. Further analyzing the results, the absolute number of recommendations that involved additional hardware was optimized. This translates to minimized complexity and costs involved to execute the recommendations to both the end-users and the OEM.

For any standalone facility, this proactive exercise would greatly improve the availability of their critical turbomachinery equipment especially if the risks of spurious operation is not tolerable. For a corporation like PETRONAS, where there is a huge turbomachinery fleet, the benefit of this exercise are multi-fold and extends beyond improving the availability of the unit under evaluation. In the example of Asset B, the one-time executed exercise was applicable for 5 identical trains in the same facility.

Gradually, performing this exercise for various trains by different OEMs, some design similarities and differences begin to emerge. This exposure to various designs provides the landscape for standardization and adopting best practices for the fleet. With better understanding of each OEMs design philosophies, the central engineering teams is now able to provide much better specifications for future turbomachinery equipment that would provide higher availability at the onset. It is also expected that over time, OEMs begin to understand the safeguarding philosophies of the organization to either collaborate directly and/or to develop custom solutions. Alternatively, OEMs can also expand their portfolio to offer solutions meeting different availability needs of different clients.

Collaborative design exercises and standardization promotes mutual benefits and long term relationships between OEMs and end-users towards ensuring better reliability and availability of the fleet. It enhances capability development and encourages multi-discipline engineering cohesiveness through deeper understanding of operational practices, process related constraints and equipment design. This also helps end-users and OEMs move ahead to carve out relevant maintenance strategies and services support to further enhance equipment availability.

COMMON FINDINGS AND RESOLUTIONS

Post evaluation after conducting the machinery robustness study on several turbomachinery trains some of the common improvements are summarized below:

Instrument Trip Functions	Resolutions
Limit Switch position mismatch on Process Valves	Implement as PERMISSIVE to start and as Alarm during operation
Bearing Temperature High-High	Option 1: Downgrade to alarm if Condition Performance Monitoring program is employed. Option 2: 2oo2 Voting between sensors in each bearing.
Switch based Trips	Change to transmitter or convert any existing transmitter in the measuring circuit to perform the trip function.
Door Limit Switch Trips	Implement as PERMISSIVE to start and as Alarm during operation. Evaluate entry requirements, site facility access controls, permit to work, confined space entry protocols, physical lock and potential mitigations.
Instrument Fault trips	Downgrade to high priority alarm on instrument faults if remedial action can be taken to intervene.
Non-redundant system I/O module fault trips	Evaluate I/O assignments in each module and downgrade to alarm where I/O loss is not critical and manageable for short term operation while faulty I/O is replaced.
Diagnostic fault trips for critical instrumentation e.g. Fuel Gas Control Valves	Option 1: Increasing scan time, increasing tolerance of mismatch, time delays before initiating the trip. Option 2: Downgrade to high priority alarm on instrument faults if remedial action can be taken to intervene.

Table 3: Sample of typical recommendations for instrument trip function robustness.

These common recommendations are made with appropriate risk assessments and a clear understanding of the appropriate increased operational vigilance that is required to monitor the performance of the equipment effectively. The recent technological advancement with data analytics has led to a flurry of advancements and efforts being made towards early identification of potential equipment failure and other issues with turbomachinery trains. This can only have a positive effect towards overall availability of the train as it helps improve the detection of faulty or misoperating instrumentation as well promoting increased vigilance of the operating unit. Effectiveness and utilization of such diagnostic tools and early warning systems should be used in tandem as a basis to justify improving the robustness of instruments used to trip the equipment, particularly if downgrading the trip function from trip to alarm is considered.

CONCLUSIONS

Turbomachinery trains are undoubtedly very critical equipment in the oil and gas process industry. In most cases spurious trips are generally not very tolerable as they bring along major opportunity loss, increased maintenance costs due to increased wear and tear of mechanical components and reputational loss in some instances when being unable to meet delivery commitments. Furthermore, the recent trends towards longer operation time needed between maintenance intervals further places importance of robustness of turbomachinery equipment against spurious trips.

In view of this and based on current evidence, much more emphasis is required in the robustness of the Instrument and Controls systems design in turbomachinery trains. In the past, the onus was always placed on the OEMs to deliver robustness of the delivered instrumentation packages. As risk is relative from an end-users perspective, the ‘standard’ one solution fits all approach by OEMs and packages for their fleet worldwide is too rigid an approach and cannot satisfy various end-users.

From this user’s perspective, it is time where a collaborative landscape should be enabled that allows end-users to actively participate alongside the OEMs, instrumentation and system suppliers to shape the instrumentation and controls design of turbomachinery packages. This would allow some degree of flexibility in engineering to achieve various levels of robustness at various price levels to meet different availability requirements of different end-users.

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ABBREVIATIONS

OEM	Original Equipment Manufacturer
HAZOP	Hazard and Operability Study
PHA	Process Hazard Analysis
LOPA	Layers of Protection Analysis
SIL	Safety Integrity Level
1oo1	One out of One (Instrument Voting Configuration)
1oo2	One out of Two (Instrument Voting Configuration)
2oo2	Two out of Two (Instrument Voting Configuration)
2oo3	Two out of Three (Instrument Voting Configuration)
DCS	Distributed Control Systems
ALARP	As Low As Reasonably Practicable

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