FMEA DURING PROJECT FEED TO ENSURE HIGH AVAILABILITY VSD SYSTEM AS USE CASE

Paper No. PCIC Europe EUR23_28

Axel Rauber
ABB Switzerland Ltd
Austrasse
CH-5300 Turgi
Switzerland

Brenden Harkness
Chevron Services Norway AS
Aker Solutions Fornebu
Snarøyveien 20
NO-1360 Fornebu
Norway

Abstract – For highest availability a Systems Engineering approach is utilized to ensure that the equipment & system integration meets the requirement for the end-user, whilst working within what is deliverable by engineering contractor & equipment manufacturer.

To mitigate the risk of unplanned process interruptions a project specific "Failure Mode Effects Analysis" can be implemented during the "Front End Engineering Design" stage, it is offered to ensure optimized system engineering & integration. The FMEA is done together with the end-user, engineering contractor & equipment manufacturer.

The FMEA leads to updates of the equipment specifications & system design, with less recycle or late design changes. It will also provide valuable information regarding the maintenance philosophy and activities for the equipment, ensuring efficient maintenance practices via condition monitoring and target equipment maintenance.

The FMEA process and the requirements for the review team are defined together demonstrating how the output is used to address component/failure risk being carried over to operations. A current project for delivery of high power VSD systems is utilized as the case study.

Index Terms – FMEA, FMECA, Adjustable Speed Drive, ASD System, Availability, Reliability, Redundancy.

I. INTRODUCTION

A. Impact of large ASD into current industrial applications and design

Adjustable speed drives (ASD) have been available in the market for decades and have a proven track record in critical, high-power applications. In addition to the acceptance of the electrical driver technology, the trend towards ASD systems (ASDS) in industrial high-power applications is driven by a combination of efficiency, cost-effectiveness, control, and environmental considerations. For example:

1. Electrical drivers are more efficient and cost-effective than gas or steam turbines.
2. Electrical drivers offer greater control and flexibility over the system, allowing for better management of the load and increased precision in the output. This is particularly important in applications such as chemical manufacturing, where precise control over the process is essential.
3. By utilizing electric drivers, it is possible to achieve the decarbonization of value chains. This is particularly significant, as it aligns with the carbon neutrality commitments made by both countries and companies.

In high-power applications, the use of electrical drivers instead of mechanical drivers requires a deeper understanding of the technology to effectively adapt it to project requirements, versus the current technology i.e., gas turbines as prime movers. As a result, owners cannot simply view the ASD as a "black box" and must be willing to engage with the technology. This includes understanding the ASD configuration, auxiliary options, system and component spare part philosophy, maintenance requirements and procedures, which are critical to ensuring continuous operation for many years, particularly in remote areas where personnel may not be readily available. By doing so, owners can maximize the benefits of using electrical drivers in their projects while minimizing the risk of unplanned downtime and other issues.

B. Combination of ASD with hermetically sealed compressors

The project in question has combined the ASDS with a hermetically sealed compressor, resulting in improved efficiency and additional benefits. These compressors are known for their high reliability and low maintenance requirements, as the sealed design eliminates the need for auxiliary equipment including seal gas and lubrication systems. Also being hermetically sealed the compressor reduce the gas release risk if installed topsides, or in this case can be deployed Subsea. As a result, production efficiency is maintained at a higher level due to reduced compressor downtime, making it an ideal choice for various industrial and commercial applications.

C. What is FMEA / FMECA (overview)

Failure Mode and Effect Criticality Analysis (FMECA) was established in the 1960's, by the United States of America (USA) National Aeronautics and Space Administration (NASA) to assist in the design of equipment and systems in space programs of that time and is still used today. The FMECA process is utilized across various industries including the Oil and Gas industry. The FMECA process is widely utilized in the Technology Qualification Process (TQP) in the Subsea sector of the Oil and Gas Industry, with the American Petroleum Institute developing recommended practices; API 17Q Recommended Practice on Subsea Equipment Qualification and API 17N Recommended Practice on Subsea Production System Reliability, Technical Risk and Integrity Management and [1] IEC 60812 Analysis techniques for system reliability – Procedure for failure mode and effect analysis (FMEA) provides guidance to the industry sector.

What is a FMECA? A FMECA is best explained in two parts; first the Failure Mode and Effect Analysis which is defined as "*a systematic procedure for the analysis of a system to identify the potential failure modes, their causes and effects on system performance"* [1] IEC 60812 Analysis techniques for system reliability – Procedure for failure mode and effect analysis (FMEA). The second is the Failure Criticality, which is defined as the *"combination of severity of an effect and the frequency of its occurrence or other attributes of a failure as a measure of the need for addressing and mitigation"* [1] IEC 60812 Analysis techniques for system reliability – Procedure for failure mode and effect analysis (FMEA).

II. PROJECT SCHEDULE CONSIDERATION (WHEN)

During the standard project phases in the Oil and Gas industry, specifications for equipment are created during the Front-End Engineering Design (FEED). During early Detailed Design, these specifications are then issued to equipment suppliers for the tendering process, subsequent bid clarifications, and equipment supplier selection.

When introducing the FMEA process into the workflow it is essential to ensure that the FMEA analysis is completed in a timely manner. This means that the selection of the equipment supplier needs to be made early enough to allow for sufficient time for the FMEA process to be completed, to enable the updating of equipment specification to reflect what is required prior to issue of contract; or the project allows for sufficient budget and schedule flexibility to the change of the equipment requisition post contract award. For the reference project the equipment supplier has been selected during FEED. For example, in a typical project workflow, the selection of the equipment supplier may be made during the Detailed Design phase. However, with the introduction of FMEA, the selection of the supplier may need to be made during the FEED phase to allow sufficient time for the FMEA process to be completed and the relevant specifications to be updated. Due to the complexity of the FMEA, it is not feasible to do it with several vendors in parallel and so a vendor needs to be pre-selected prior to the normal phased award of Detailed Design.

If the FMEA is done after the PO has been placed, as is usually the case, there are several implications. Firstly, the FMEA process will be limited by the equipment supplier's budget and schedule, which could impact the number of failure cases that can be analyzed (for example 20 more-or-less high-level scenarios). This could result in a less comprehensive analysis, which could lead to unidentified failure modes and potentially higher risks during the project execution. Secondly, any changes identified through the FMEA process could impact the project schedule and cost due to changes in design, or internal equipment selection.

To mitigate these risks, it is important to establish clear communication between the client, design contractor and equipment supplier about the depth of analysis required for the FMEA process, along with its potential implications of cost and schedule. The scope of the FMEA should be clearly defined in the PO, including the number of failure cases to be analyzed and any potential design changes that may result. The supplier should provide a clear timeline for the FMEA process and any subsequent design changes highlighted, to ensure that they can meet the project schedule.

III. DRIVERS / MOTIVATION FOR THE FMEA (WHY)

Overall, FMEA can provide a range of valuable insights into potential equipment failures and their impacts, informing decisions around equipment selection, maintenance, and repair to improve overall reliability and reduce risks "de-risk".

1) Assist or provide input into product selection: FMEA can help provide insight into potential failure modes of different equipment options being considered during the FEED phase. By evaluating the potential risks associated with each option, FMEA can assist the selection process and help identify the most reliable and cost-effective equipment for the project. The FMEA considers the final ASD technology and elements.

2) Define equipment failure modes: FMEA is primarily used to identify potential failure modes of equipment or systems, including how they might fail, when they might fail, and the potential consequences of those failures. By defining these failure modes, engineers and project teams can better understand the potential risks and develop strategies to mitigate or eliminate them.

3) Understand impact of failures to the wider system/s: FMEA can help to understand the impact of equipment failures on the broader system or process in which they operate. By considering the potential consequences of equipment failures on the overall system, FMEA can help identify critical equipment and inform decisions around redundancy and backup systems. Performing an FMEA during the development phase of a product is a crucial step to ensure safety and reliability. By focusing on potential failure modes and their effects, manufacturers can identify and address potential issues before the product is released to the market. In this case, the focus is not on system availability but on safety and product reliability, which are critical aspects of any product. The FMEA on a project can therefore help the manufacturer to understand the consequences of trips for critical processes. By identifying potential failure modes and their effects, the manufacturer and design team can assess the impact of different types of failures on the process and develop strategies to mitigate these impacts.

4) Understand the equipment design: FMEA can provide insights into the design of equipment, identifying potential weaknesses or areas for improvement. By analyzing potential failure modes and their causes, FMEA can influence design decisions to improve equipment reliability and reduce the likelihood of failure. The FMEA process can help the end user understand the standard ASD offering, as well as possible options and potential for customization. This can help the end user make more informed decisions about the equipment they need and ensure that the equipment meets their specific needs and requirements, however customization can introduce risk. Project-specific solutions lack the operating hours and experience of standard options, which may lead to disturbances during commissioning and maintenance and in the worst case, nuisance trips of the plant. The uniqueness and complexity of these solutions have inherent risk of limited manufacturers support. Therefore, it is important to carefully consider the trade-offs between customization and standard options. When considering customization, manufacturers and end users should carefully evaluate the potential benefits and risks.

Customization may be necessary to meet specific needs or requirements, but it is important to ensure that the equipment remains reliable and operates as intended. This may require additional testing and validation, as well as ongoing monitoring and maintenance to ensure that the customized equipment continues to function correctly. In some cases, it may be possible to incorporate customization into the standard offering, which can help mitigate the risks associated with project-specific solutions. Manufacturers can work with end users to identify common customization needs and develop options that can easily be incorporated into the standard offering. This can help reduce the risks associated with customization while still providing the flexibility needed to meet specific needs and requirements.

Further, the FMEA provides an opportunity to consider tie-in and utility requirements and other interfaces. In fact, one of the key benefits of a FMEA is that it helps to identify potential failure modes and their effects, which should include failures related to tie-in and utility requirements and other interfaces. Identifying these potential failure modes early in the development process can help manufacturers and end users take steps to mitigate these risks. For example, they may choose to develop alternative interfaces or backup systems to ensure continuity of operations in the event of a failure.

5) Increase equipment fluency for project engineers and operations personnel: FMEA can provide project engineers and operations personnel with a deeper understanding of the equipment being analyzed. By identifying potential failure modes and their causes, FMEA can increase the fluency of these personnel with the equipment, allowing them to better understand its operation and potential risks.

As part of the FMEA process, relevant team members of the supplier, contractor and client teams are engaged. The supplier's engineers will provide the technical detail of the equipment design including the systems, subsystems, and components. The contractor and client team will provide the necessary engineering requirements of the project. As part of the client team, relevant operations and maintenance personnel should attend, as these participates will provide a wider understanding on the operational system impact of the equipment and current maintenance practices of the company. With the contractor and client personnel participating in the FMEA, it will provide a wider understanding of the supplier's equipment, the equipment options available and considerations required in implementing the equipment into to project design, to fit the project functional *requirements.*

6) Establish a reliability Model: FMEA can inform the development of reliability models, which can be used to predict the likelihood of equipment failures with informed decisions around maintenance and repair. By understanding potential failure modes and their causes, FMEA can help to develop accurate reliability models, which can improve the overall reliability of equipment and reduce downtime. Reliability models are based on assumptions about the likelihood of failure and the causes of failure, which can be informed by FMEA. By using FMEA to identify potential failure modes and their causes, manufacturers and end users can develop more accurate reliability models that reflect the specific risks associated with their equipment.

In addition, FMEA provides an auditable trail of reliability assumptions. This means that manufacturers and end users can trace the development of their reliability models back to the specific risks identified during the FMEA process. This can help ensure that reliability models are based on sound assumptions and can be used to make informed decisions around maintenance and repair.

Furthermore, the FMEA process can tie in possible condition monitoring and process performance, efficiency, and production impact upon loss of ASD. By understanding the potential failure modes and their impacts on the equipment, manufacturers and end users can develop effective condition monitoring strategies that can help detect and prevent equipment failures before they occur. This can improve the reliability of the equipment and reduce the impact of downtime on production efficiency.

7) Understand impact into operations: FMEA can help to understand the potential impact of equipment failures on operations, including production downtime, product quality issues and safety risks. By understanding the potential consequences of equipment failures, FMEA can influence decisions around equipment selection, redundancy, and maintenance.

Here are some specific points related to understanding the impact of equipment failures on operations that can be addressed through FMEA.

Base and optional equipment spare part consideration (→ FMEA outcome) which could be worked into cost/benefit trade-offs analysis: By considering the potential failure modes and their consequences during the FMEA process, manufacturers and end users can make informed decisions around equipment spares holding. This includes considering the base and optional equipment spares required to maintain operations in the event of equipment failure, which can be worked into cost/benefit trade-offs analysis.

8) Understanding of manufacturer recommended preventative maintenance practices: FMEA can help to identify potential failure modes and inform decisions around preventative maintenance practices. By understanding the specific risks associated with their equipment, manufacturers and end users can develop effective preventative maintenance strategies that can help to reduce the likelihood of equipment failures.

9) Building information (know-how capture and development): FMEA can help to capture and develop "know-how" related to equipment reliability and maintenance. By documenting the specific failure modes and their causes, manufacturers and end users can build a database of information that can be useful in future equipment development and maintenance practices.

10) Planned maintenance vs breakdown / troubleshooting: FMEA can help to influence decisions around planned maintenance vs. breakdown/troubleshooting. By understanding the specific risks associated with their equipment, manufacturers and end users can develop effective maintenance strategies that can help to reduce the likelihood of breakdowns and troubleshooting requirements.

11) Training and competency: FMEA can help to identify training and competency requirements for equipment operators and maintenance personnel. By understanding the specific failure modes and their causes, manufacturers and end users can develop effective training programs that can help to reduce the likelihood of equipment failures.

12) Vendor support: FMEA can inform decisions around vendor support requirements. By understanding the specific risks associated with their equipment, manufacturers and end users can determine the specific support requirements they will need from their vendors, *including warranty, service, and spare parts support.*

13) Control methods: FMEA can define the development of control methods to mitigate or eliminate potential failure modes. By identifying the potential causes of failures, FMEA can help develop strategies to prevent or mitigate those failures, improving the overall reliability of equipment.

14) Control system interface: The FMEA can help identify potential failure modes related to the control system interface.

15) Operator interface: Like the control system interface, FMEA can help identify potential failure modes related to the operator interface, such as the possibility of incorrect button presses or misunderstandings of display information. Control methods can be developed to minimize the risk of operator interface-related failures, such as implementing intuitive interfaces with clear labels and minimizing the number of steps required for operators to complete tasks.

16) Control system architecture: FMEA can help identify potential failure modes related to the control system architecture, such as the possibility of a single point of failure. Control methods can be developed to minimize the risk of control system architecture-related failures, such as implementing redundant components or backup systems.

17) Cyber Security: FMEA can help identify potential failure modes related to cyber security, such as the possibility of a cyber-attack or unauthorized access to sensitive information.

18) Wider system impact (cost versus reliability): FMEA can help to understand the wider system impact of equipment failures, including the costs associated with downtime and repair. By evaluating the cost versus reliability trade-offs of different equipment options, FMEA can inform decisions around redundancy and design margins, ensuring that equipment is both reliable and cost-effective.

With efficiency in production being pushed further into project design requirements, Reliability, Availability and Maintainability (RAM) modelling is being widely used by projects to drive design and to meet the project production efficiency targets. RAM modelling provides clarity of understanding regarding failure of equipment and systems in production and allows for running of numerous scenarios to assist with drive decisions of project capital expenditure (CAPEX) versus operation expenditure (OPEX). To improve the RAM modelling, the reliability of equipment needs to be well understood and the FMEA process applied on equipment to achieve it.

19) Safety implications: FMEA can also help to identify safety risks associated with equipment failures, including risks to personnel and the environment. By identifying potential safety risks, FMEA can inform decisions around safety controls and equipment design, ensuring that safety risks are minimized.

IV. EXECUTION OF THE PROJECT SPECIFIC FMEA (HOW)

[1] IEC 60812 provides guidelines for the application of FMEA, including the FMECA variant. This standard specifies the process for planning, performing, documenting, and maintaining FMEA and it provides a common language and methodology for organizations to use when conducting FMEA. The standard outlines the following steps in the FMEA process:

1. Define the scope and objectives of the FMEA
2. Identify the system or product to be analysed
3. Identify the functions and potential failure modes of the system or product
4. Determine the severity of the potential failure modes
5. Identify the causes of the potential failure modes
6. Determine the likelihood of the potential failure modes occurring
7. Determine the current detection methods and their effectiveness
8. Determine the risk priority number (RPN) for each potential failure mode
9. Identify and implement corrective actions to reduce the RPN for high-priority failure modes
10. Monitor the effectiveness of the corrective actions and update the FMEA as necessary

[1] Provides guidance on the Failure Modes and Effects Analysis (FMEA) process, which can be applied to a wide range of systems and processes, including hardware, software, and human actions. The standard emphasizes that the FMEA process should be tailored to meet the specific objectives of the analysis and should be applied in a manner that is appropriate to the complexity and criticality of the system being analyzed. The FMEA process outlined in [1] involves identifying potential failure modes and their effects, assessing the likelihood and severity of those effects, and prioritizing them for further analysis and mitigation. The standard also provides guidance on how to document and communicate the results of the FMEA analysis, including recommended formats for FMEA reports.

To tailor the FMEA process to a specific project, a range of inputs and information may be required, including site-specific information, requirements, and restrictions. Other factors that may need to be considered include whether the system or process is manned or unmanned, the mean time to repair, equipment availability requirements. Site-specific information can be critical to identifying potential failure modes and their effects. This might include factors such as environmental conditions, operational constraints and safety considerations that are unique to the project location. Knowing whether a system or process is manned or unmanned can be important for FMEA, as it can affect how quickly and effectively a failure can be addressed. Similarly, understanding the mean time to repair and equipment availability requirements can help inform decisions around prioritizing and mitigating potential failure modes. In some cases it may be necessary to consider redundancy solutions for systems, sub-systems, or components. This can help to ensure that critical functions are maintained in the event of a failure but can also add complexity and cost to the system design.

V. WHO IS PERFORMING THE FMEA

The FMEA process typically involves a cross-functional team of experts who can provide inputs from a range of perspectives. The exact composition of the team may vary depending on the nature and complexity of the system or process being analyzed, but it may include the following roles:

1. Facilitator: A person who coordinates the FMEA process and ensures that the team stays on track.

2. Subject Matter Experts (SMEs – Equipment Supplier): Individuals who have in-depth knowledge of the system or process being analyzed and can provide technical input on potential failure modes and their effects.
3. Design Engineers (Design Contractor): Individuals who have responsibility for the design and development of the system and can provide input on design changes that may mitigate potential failure modes.
4. Quality Engineers (Optional): Individuals who have expertise in quality control and assurance and can help identify potential failure modes and their effects.
5. Discipline Engineers (Client / End User): Individuals who have expertise in process design and optimization and can provide input on potential failure modes that may arise during operation.
6. Operators and Maintenance Personnel (Client / End User): Individuals who have direct experience with operating and maintaining the system and can provide input on potential failure modes and their effects in real-world scenarios.
7. Safety and Environmental Experts (Optional): Individuals who have expertise in safety and environmental compliance and can help identify potential hazards and risks associated with failure modes.

Involving the right people from different stakeholders is crucial for the success of the FMEA process. End users, equipment suppliers, Engineering, Procurement and Construction (EPC) contractors, and consultants may each have unique perspectives and insights that can contribute to the identification and mitigation of potential failure modes. End users can provide input on how the system or process will be used in real-world scenarios, as well as any specific requirements or constraints that may affect the analysis. Equipment vendors can provide technical input on the equipment being used and any known failure modes or issues that may be specific to the equipment, while drawing on Field Service support experience. EPC contractors can provide input on how the system or process will be constructed and installed, as well as any specific requirements or restrictions that may affect the analysis. Consultants can provide specialized expertise in areas such as safety, environmental compliance, or regulatory requirements, as well as an objective perspective on the analysis and potential mitigation strategies. By involving the right people from different stakeholder groups, the FMEA process can benefit from a wider range of expertise and perspectives, which can help ensure that potential failure modes are identified and mitigated effectively.

VI. FACILITATION OF FMEA WORKSHOP (WHERE)

While a face-to-face format is preferred, remote FMEA sessions can also be effective using virtual collaboration tools. Performing a FMEA at the equipment supplier's facility can be advantageous in many ways, particularly for complex equipment. It allows the FMEA team to have direct access to the product and its components, observe its functionality and operation, and identify potential failure modes that might not be evident from documentation and diagrams. In addition, the equipment supplier's staff can provide valuable insight and expertise regarding the product's design, functionality, and maintenance requirements. This can help the FMEA team identify and mitigate potential failures more effectively and efficiently. Overall performing a FMEA in a face-to-face format at the vendor's facility is recommended, it is also possible to conduct a FMEA remotely. The key is to ensure that all necessary competencies are available.

VII. CASE STUDY OF FMEA DURING PROJECT EXECUTION

A. Project introduction

The project involves implementing a subsea compression station, that will be powered and controlled from a semi-submersible facility. This semi-submersible facility, in turn, will be powered by a submarine power cable, that stretches over 100 km. It is important noting that the semi-submersible facility will be unmanned and controlled remotely from an onshore facility located on an island, close to the mainland. By situating compressors in close proximity to the wellheads on the seafloor, it is possible to achieve greater recovery of gas from the existing reservoir, while reducing both capital expenditure and lifecycle operating costs when compared to traditional offshore manned compression facilities. Specifically, in this project, the main motor and compressor will be positioned at a depth of approximately 1400 meters beneath the water's surface.

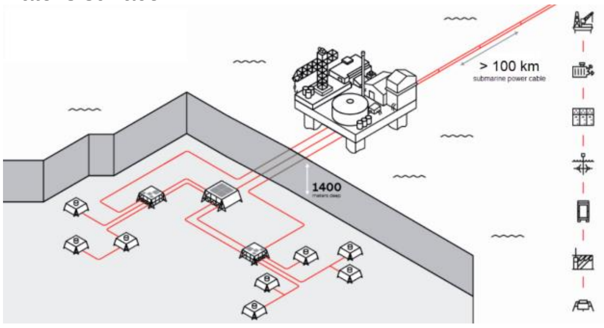

Fig. 1 Compressor station – overview

In this project, the fixed shaft electric motor / compressor combination relies on an adjustable-speed solution that does not require a gearbox. An ASD located on the platform generates an adjustable frequency input to the motor of over 100Hz, which allows the compressor to be driven from 3000 rpm to over 7000 rpm. The ability to drive the compressor over this large range of speed enables an expanded operating envelope that surpasses that of a conventional gas turbine-driven gas compressor. In this case, due to the long step-out distance, a step-up / step-down transformer arrangement in combination with a filter is required to ensure stability and reduce losses over the subsea power cable.

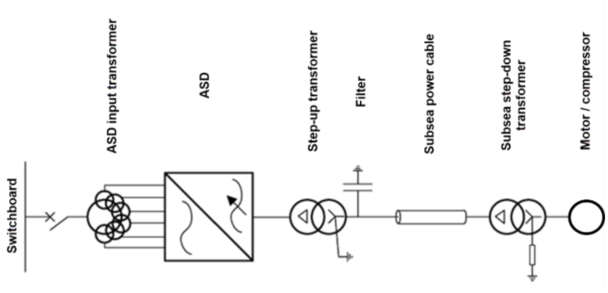

Fig. 2 ASD system overview

B. Selection of technology

In general, the focus of technology selection in this context is on the ASD, as noted in sources [2] and [3]. However, selecting the appropriate technology and equipment supplier can be challenging due to the numerous inputs and requirements that must be taken into account. These include the following considerations related to:

1. Safety
2. Reliability, availability, and maintainability
3. CAPEX and OPEX
4. Network integration
5. Physical size

Various safety functions are available for power electronics converters, such as functional safety and arc fault protection, which are topology-independent and covered in [4]. However, it's worth noting that press-pack type devices, which are installed in a stack under pressure having a robust ceramic housing, provide arc flash safety.

To assess reliability, metrics such as Mean Time Between Failure (MTBF) must be used with care and should not be compared across different technologies or solutions from various equipment suppliers. There is no equipment supplier independent comparison, as there are no common rules to obtain these numbers. The MTBF only accounts for statistical failures. Further, considering field experience, less than 10% of the ASD system failures are related to statistical failures. As stated in [2] proper system engineering and a high maturity of equipment lead to high availability. When considering redundancy options, it can be challenging to compare technologies because low-voltage component-based ASD topologies like multi-level converters (MMC) or cascaded H-bridge (CHB) converters require redundancy in the power part to meet expected availability, whereas simple topologies that use high-voltage semiconductors may not offer redundancy in the power part but are comparable in terms of reliability. Further, supply power loss ride-through capability is to be studied. What is the expected behavior during a network disturbance scenario? As these functionalities, handling supply network disturbances are not topology independent and based on control algorithms, they differ between vendors. More information can be found in [5], [6], [7] and [8].

Cost and efficiency are also important factors in technology selection. While some technologies may have a lower upfront cost, they may not be as efficient and may result in higher operating costs over the longer term. On the other hand, more expensive technologies may have higher efficiency and lower operating costs, with either technology providing the required operational uptime. It is important to evaluate the total cost of ownership and the required production efficiency of the driven equipment over the expected lifetime of the equipment to make an informed decision.

The network integration requirements for power factor and harmonic distortion are to be considered, which may require the inclusion of additional equipment, increasing cost, footprint, drive string reliability, upstream power distribution system stability, leading to increased overall system complexity.

Finally, physical size is another consideration in the technology selection. Different technologies may have different physical footprints, and it is important to evaluate them based on the space available for installation.

The selection of technology and vendor for this project has been primarily based on the system's maturity, with a focus on a comparable configuration that was installed in 2015 and has over 5 years of operational experience. In the example project, VSI technology was chosen due to the use of a high-speed induction motor for applications less than 15 MW. The long step-out, which includes step-up and step-down transformers and subsea cable, in combination with the high motor frequency, requires a specialized control algorithm. The ASD that was chosen relies on a simple topology that utilizes high-voltage components, resulting in a minimized part count and does not feature redundancy in the power part. Single-point-of failures cannot be avoided in an ASD, regardless of the topology. For instance, if the main controller fails or there's water leakage, the system will trip. According to [3], an ASD with a requirement to operate for years without any scheduled or unscheduled shutdowns needs redundancy at the macro level, such as a redundant converter or complete ASD. Redundant ASD solutions are provided for petrochemical facilities with supercritical services such as propane dehydrogenation (PDH) plants, where steam or gas turbines have been traditionally used.

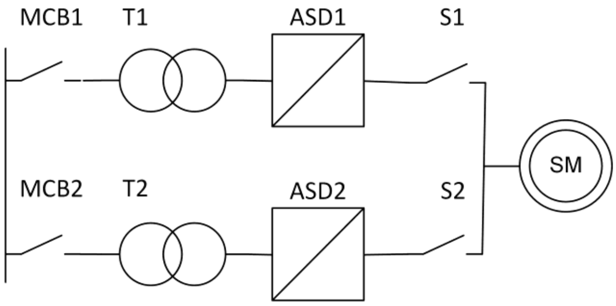

Fig. 3 Overview of a redundant ASD system (incl. redundant input transformers)

As presented in [9], these systems can be designed with one "hot standby" ASD to switch over in less than a couple of hundred milliseconds, so that the process remains healthy in case one ASD fails. Due to space restrictions on the semi-submersible facility, macro-level redundancy was not feasible for this project, which highlights the importance of the FMEA for the critical process.

The ASD is equipped with a water-cooling system, complemented by a water-to-air heat exchanger, that helps to dissipate most of the heat losses of the power part not absorbed by the water directly. This configuration allows for a completely sealed ASD cabinet that can withstand harsh environmental conditions and high ambient temperatures. In fact, less than 2% of the total ASD losses are released into the room via the cabinet. This not only reduces the load on the air-conditioning system but also eliminates the dependency of the ASD operation on it.

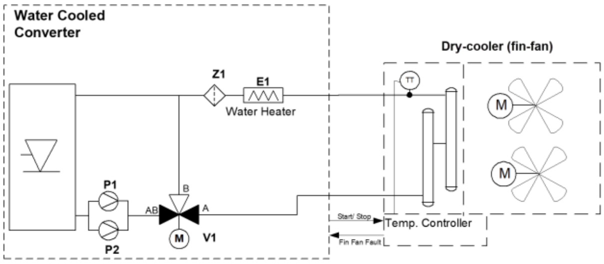

Fig. 4 ASD single-loop dry-cooler arrangement

To mitigate potential risks, the decision was made to restrict the use of only de-ionized water within the electrical room. This necessitates the use of an external heat exchanger, for which a dry cooler, also known as a fin-fan cooler has been chosen. The arrangement is presented in Fig. 3. This type of heat exchanger is designed to cool fluids, such as the de-ionized water in this system without the need for plant- or seawater. The cooling process for the example project works by using a fan to draw air over a series of tubes containing the fluid to be cooled. As the air flows over the tubes, it absorbs heat from the fluid, which is then dissipated into the surrounding environment. The system selection, considering trade-offs, is part of the discussions in the FMEA workshop, depending on the utility system availability, or environmental constraints the design is optimized. E.g., if an external cooling medium was available, the design may have utilized liquid to liquid heat exchanger over air cooled fin-fan coolers.

C. FMEA process

An FMEA has been performed on each system component (transformers, ASD, motor, dry-cooler, overriding controller …) of the platform. The focus is on the ASD.

1) Preparation – determine the FMEA ratings: An agreement was reached on the simplified rating presented in TABLE I, II and III.

TABLE I
SEVERITY COEFFICIENTS

Severity of Effect	Exemplary criteria: Severity of Effect on Product	#
Hazardous w/o warning	"Very high severity ranking when a potential failure mode affects safe system operating and/or involves noncompliance with regulations without warning For repair action requiring long repair duration. No spares, and/or shipment onshore required. Early detection or warning not possible. Time scale > 7 days incl. logistics"	10
Very high w/o warning	System inoperable with loss of primary function. Repair offshore possible. Operational spares typically available. Early detection or warning not possible. Time scale < 7 days incl. logistics"	8
Medium w/ warning and trip to FCS required	System inoperable with loss of primary function. Repair offshore possible. Operational spares typically available. Early detection or warning possible. Mode of failure generally can be confirmed prior to going offshore. Time scale < 3 days incl. logistics MTTR = 1 days (mean time to repair) MTTP = 2 day (mean time to prepare)"	7
Medium w/ warning and trip to FCS not required	System inoperable with loss of primary function but can be convened and restarted from remote. Early detection or warning possible. Mode of failure generally can be confirmed from remote. System can be restarted from remote. Time scale < 1 days incl. logistics"	6
Low	System operable. Comfort/convenience operable at reduced level of performance. Customer's dissatisfaction. Loss of redundancy.	5
Minor	Fit & Finish item does not conform. Defect noticed by average customer.	3
None	No effect. The rank is "1" and not "0"	1

TABLE II
OCCURRENCE COEFFICIENTS

Likelihood of Cause	Exemplary criteria: Occurrence of Causes	#
Very High	New technology / material. No valuable history. Poor experience from past, from other products. Cause is a fact. Several times during 25 years	10
High	Known technology but failure is likely with new design (shape, size, arrangement …), new application, or change in duty operating conditions. > 1 occurrence during 25 years	8
Moderate	Occasional failures associated with similar designs (similar material type, thickness, tolerance…) or in design simulation and testing. Known technology by competitors. 1 occurrence during 25 years	5
Low	Isolated failures associated with almost identical design (e.g. the same material, thickness or other futures) or in design simulation and testing. Known technology. May occur during 25 years	3
Very Low	Failure cause or failure mode cannot occur because it is fully prevented through design solutions (e.g., proven design standard, best practice, or common material, etc.). Unlikely to happen during 25 years	1

TABLE III
DETECTION COEFFICIENTS

Likelihood of Detect.	Exemplary criteria: Likelihood of Detection	#
Almost Impossible	No current design control; Cannot detect or is not analyzed or not likely to detect at any stage or Virtual Analysis is not correlated with to expected actual operating conditions.	10
Low	Only design review or analysis or simple calculations or detection after design freeze	8
Moderate	Product validation (reliability testing, development or validation tests) with fail / pass testing (e.g., Acceptance criteria for performance, function checks…). Detected during prototyping / assembling of prototype.	5
Very High	Product validation (reliability testing, development or validation tests) with test to limit (e.g., until leak, crack ...) or degradation testing (e.g., data trends, before/after ...); Virtual Analysis (e.g., CAE, FEA) is highly correlated with actual results.	3
Almost Certain	Failure is detected / prevented by applying proved the same solutions in other product under relevant conditions.	1

The greyed-out ratings were not applied for this project FMEA.

2) Preparation – availability of technical documentation: Following documents had been made available well before the analysis:

- Electrical drawings (schematics)
- Electrical part list
- Overview of
  - Power hardware
  - Control HW
  - Auxiliary power distribution
  - Water-cooling system (PI&D)
- Definition of standard spare parts kits and parts lists
- Vendor standard maintenance schedule

Everybody involved was expected to be familiar with the information. Oversized printouts of the overview documents were available in the room.

3) Preparation – Identification of failure cases: For an FMEA on an adjustable speed drive with a bill of materials consisting of approximately 1000 parts/components, it is necessary to group parts and limit the level of detail. Grouping is done based on their function and potential failure modes. This will help limit the number of failure cases that need to be analyzed. For example, could printed circuit board assemblies (PCBA) be grouped together; but was not done here as the agreement was to analyze all components on the electrical part list. Mechanical components are grouped together, and some are neglected like busbars, screws …

4) Preparation – Prefilling of FMEA table: The vendor prefilled the document as shown in TABLE IV.

TABLE IV
FMEA TABLE (ASD EXAMPLE)

Failure case	(Ident. / Running number)	X
System	Water-cooling unit	X
Subsystem	Water circuit	X
Component	Pump; 15KW;380-415V	X
Function	Cooling pump	X
Failure Mode	Leakage (sealing)	X
Detection	Pump redundancy lost Alarm	X
Potential Local Effect(s) of Failure	Switch-over to redundant pump	X
Potential Global Effect(s) of Failure	Drive continues to operate. Loss of redundancy.	X
SEV – Severity	5	X
Potential Causes / Mechanisms	Component defect	X
OCC – Occurrence	3	X
Current Process / Design Control	Qualification of a 3rd party equipment for industrial use. Testing by supplier and converter routine testing.	X
DET – Detection	5	X
Criticality	5 x 3 = 15 (SEV x OCC)	X
RPN – Risk Priority Number	5 x 3 x 5 = 75 (SEV x OCC x DET)	X
Recommended Actions	Consider Spare part (not part of the standard package). Consider canned motor/pump for improved reliability.	
Resp. & Target Completion Date	End-user to adapt project specification accordingly	
Actions Taken	Canned motor/pump	Action Result
SEV	5	
OCC	<3	
DET	5	
RPN	<75	

(X) vendor to prefill or at least prepare for discussion

5) Agreement and definition of actions: During the joint analysis, the end-user, vendor, and EPC worked together to identify and evaluate potential failure modes in the system and their effects. A common understanding of these failure modes has been established and appropriate actions to prevent or mitigate them defined. It was agreed that availability of data can be assumed. As the platform is unmanned remote connectivity was compulsory. Further, the data must be made available to the vendor to support condition monitoring, enabling the possibility to uncover trends before alarm levels are reached. For each failure case the following actions were considered:

- Options: Are there any standard or engineered options to mitigate technical risks?
- Highly engineered solutions have not been considered due to the risk associated with their one-time implementation, including effective testing, commissioning, and long maintenance.
- Additional testing during factory acceptance testing.
- Project specific maintenance schedule considering failure modes identified.
- Updated spare parts: For example, many components, that are very unlikely to fail but are single-point-of-failures were added to be held at the end-user's facility for shortest lead time.
- Additional training for operations / maintenance personnel.
- Definition of contractual service response time remote and onsite.
- Review of firmware settings during engineering and before commissioning to avoid nuisance trips.

System testing (e.g., combined, string, full-load testing) was not considered. In general, the effort, costs and risks associated with such a test does not justify the very limited possible insights. It would also mean additional stress, because all equipment needs to be shipped, installed and commissioned at the testing site. Moreover, after the test, stress for the equipment due to de-commissioning and re-packing should not be underestimated.

Below some examples of items which cannot be verified during full load or combined testing:

- Mechanical string, as the foundation and shaft line is different
- Network harmonic behavior due to different grid parameters
- Interfaces to the overriding system are typically not available
- Thermal test of large transformer, as thermal stability is only reached after eight to ten hours
- Noise due to the different environment

Testing on a digital twin was not discussed as the capabilities and availability of the equipment used can be very limited. Therefore, real-time simulations were not discussed to confirm SW settings and performance for this project. Today, solutions are available and are requested for critical large ASD applications, for example if the commissioning time is to be minimized for "brown field" (e.g., ASD system replacing a gas turbine). Using a simulation twin in place of a real drivetrain system avoids excessive set-up and pre-tuning time and costs. It mitigates risk as any faults merely halt the simulation twin, thereby avoiding any damage that could be inflicted if real equipment is used. A real-time simulation represents the closest replica and behavior to the project system.

6) Monitor the effectiveness of the corrective actions: The project equipment is not yet installed on the platform. Monitoring the effectiveness of the corrective actions will be possible once the system is commissioned.

VIII. CONCLUSION

New technologies are being adopted to increase operational efficiency and reduce carbon footprint. However, these technologies come with risks not necessarily at the component level, more at the system or process level. With the trend of considering new technology even for critical applications in remote locations such as unmanned platforms and the need for uninterrupted operation for many years, investing in risk mitigation for new solutions is essential. Failure Modes and Effects Analysis (FMEA) provides an effective framework for end-users, vendors, and possibly EPC and consultants to interact and consider process requirements and component limitations simultaneously.

VI. REFERENCES

[1] IEC 60812 Analysis techniques for system reliability – Procedure for failure mode and effect analysis (FMEA)

[2] A. Rauber, Peter den Bakker, "Adjustable Speed Drive System Comparison VSI and LCI for High Power Applications", PCIC United States 2018.

[3] P. Wikström, L. Terens, H. Kobi, "Reliability, Availability and Maintainability (RAM) of High Power Variable Speed Drive Systems (VSDS)", IEEE Paper No PCIC – 98-16.

[4] IEC 62477-2 Ed.1 Safety Requirements for Power Electronic Converter Systems and Equipment - Part 2: Power Electronic Converters from 1000 V a.c. or 1500 V d.c. up to 36 kV a.c. or 54 kV d.c

[5] T. Wymann, Sture Van de moortel, P. Jörg, "Power Loss Ride-Through in a Variable Speed System, PCIC Europe 2014.

[6] T. Besselmann, P. Jörg, Terje Knutsen, Tor Olav Stava, Sture Van de moortel, "Partial Torque Ride Through with Model Predictive Control", PCIC Europe 2016.

[7] T. Besselmann; A. Cortinovis; S. Van de moortel; A.-M. Ditlefsen; M. Mercangöz; H. Fretheim; P. Jöerg; E. Lunde; T. Knutsen; T. O. Stava, "Increasing the Robustness of Large Electric Driven Compressor Systems During Voltage Dips", IEEE Transactions on Industry Applications, accepted for publication.

[8] A. Cortinovis, M. Mercangöz, T. Besselmann, A.-M. Ditlefsen, T. O. Stava, S. Van de moortel, E. Lunde, "Enabling voltage dip ride-throughs of large electric driven gas compressors", Journal of Process Control, accepted for publication.

[9] S. Mouty, A. Rauber, "Improving VSD System Availability by Using Fully Redundant Power Converters", PCIC Europe EUR22-18 2022

II. VITA

Axel Rauber graduated from the Staatliche Studienakademie Baden-Württemberg, Mannheim, Germany in 2001 with a degree in electrical engineering – Diplom-Ingenieur (BA). In 2001 he started his professional career at ABB System Drives and is currently employed as a global product manager. He is responsible for VSI and LCI based products for high power applications. He has authored three previous papers.
axel.rauber@ch.abb.com

Brenden Harkness completed an Instrument & Electrical Apprenticeship in 1999 and an Advanced Diploma in Industrial Automation. By working in the mineral refining, power generation, water treatment and extensively in the offshore oil & gas industry has gained a wide range of experience. He has been working for Chevron since 2006 in various roles and currently works as an Operations Advisor on the Jansz-Io Compression Project
harknessb@chevron.com