Application of Industry 4.0 Concepts for Increasing Reliability of Valves

John-Kenneth Sangolt

Marita Bjorøy

Thomas Erstad

Bachelor’s thesis in Production Engineering & Mechanical Engineering

Bergen, Norway 2019

Høgskulen på Vestlandet

Western Norway University of Applied Sciences

Application of Industry 4.0 Concept for Increasing Reliability of Valves

John-Kenneth Sangolt

Thomas Erstad
Marita Bjorøy

Department of Mechanical- and Marine Engineering
Western Norway University of Applied Sciences
NO-5063 Bergen, Norway

IMM 2019-M51

Marita Bjorøy, Thomas Erstad, John-Kenneth Sangolt

Western Norway University of Applied Sciences
Department of Engineering and Economics
Department of Mechanical and Marine Engineering
Inndalsveien 28,
NO-5063 Bergen, Norge

Norsk tittel:	Implementering av industri 4.0 konsepter for å øke ventil påliteligheten
Author(s), student number:	John-Kenneth Sangolt, 150186 Thomas Erstad, 151217 Marita Bjorøy, 180195
Study program:	Production Engineering & Mechanical Engineering
Date:	May 2019
Report number:	IMM 2019-M51 (Group ID-number: M51)
Supervisor at HVL:	Maneesh Singh
Assigned by:	MRC Global
Contact person:	Simon Jeeves
Number of files delivered digitally:	5/Application of Industry 4.0 Concepts for Increasing Valve Reliability (Bachelor thesis), Attachment 1, Attachment 2, Attachment 3, Attachment 4

Preface

This thesis is a result of a bachelor project written at the Department of Mechanical and Marine Engineering at Western Norway University of Applied Sciences (WNUAS). The authors of this thesis are from both the Industrial Engineering and Mechanical Engineering field of study. The bachelor thesis was carried out in collaborations with MRC Global where Simon Jeeves has been our main contact person. The collaborations between our supervisor Maneesh Singh and guidance given to us by our contact person Simon Jeeves has been much appreciated. This assignment has been a unique experience for learning about reliability-based monitoring and detection of failures using Industry 4.0 concepts.

Marita Bjorøy, Thomas Erstad, John-Kenneth Sangolt

Abstract

The traditional approach in today's oil and gas process industry for verifying valve reliability is simplistic and provides little information regarding valve degradation mechanisms. Therefore, this bachelor thesis discusses new theories and concepts to help increase the reliability of safety critical valves, also known as a safety instrumented system. The thesis first describes the structure, working mechanism function and failure profile of an emergency shutdown ball valve. The failure modes and mechanisms have been taken from OREDA database for topside equipment. This information has been listed and then implemented into a failure tree analysis where the most common causes for each failure mechanism have been identified. Based on the knowledge gathered, detailed research work has been carried out to improve the diagnostics of valves.

In the search for a solution to increase the reliability of emergency shutdown valves it is reasonable to look at industry 4.0 and its concepts. This is a digital revolution which implements concepts such as cyber-physical systems (CPS), industrial internet of things (IIoT) and cloud-based storage. Based on these concepts the thesis looks into the use of valve diagnostic systems for identifying the failure mechanisms of a valve subjected to degradation. In this system, sensors and small computers makes it possible to continuously monitor the valve performance and store this data on cloud-based servers.

An experimental test-rig located at MRC-Global workshop has been used to carry out case studies showing how to detect and locate different failure causes using diagnostic systems. The diagnostic results obtained from simulation of degraded valves were compared against healthy valves to identify "signature patterns".

Finally, the traditional approach for valve reliability verification has been compared against the modern Industrial Internet of Things (IIoT) and Cyber-Physical System (CPS) based diagnostic system. The comparative study shows that the implementation of the industry 4.0 concepts considerably increases the reliability of valves.

Marita Bjorøy, Thomas Erstad, John-Kenneth Sangolt

Sammendrag

Den tradisjonelle tilnærmingen i dagens olje- og gassprosessindustri for å verifisere ventilens pålitelighet er svært forenklet og gir lite informasjon om den faktiske ventiltilstand. I denne bacheloroppgaven diskuteres nye teorier og konsepter for hvordan en kan øke påliteligheten til sikkerhetskritiske ventiler, også kjent som et sikkerhetsinstrumentert system. Oppgaven beskriver først strukturen, arbeidsmekanismen og feilprofilen til en nødavstengningsventil. Feilmodiene og mekanismene er tatt fra OREDA-databasen for toppsideutstyr. Denne informasjonen er oppført og implementert i en feiltreetanalyse der de vanligste årsakene til hver feilmekanisme er identifisert. Basert på den innsamlede kunnskapen, har det blitt utført detaljerte undersøkelser for å forbedre diagnosen av ventiler.

I søket etter en løsning for å øke påliteligheten til nødavstengningsventiler var det rimelig å se på industri 4.0 og dens konsepter. Dette er en digital revolusjon som innebærer at man implementerer begreper som cyber-fysiske systemer, industrielt internett av ting og skybasert lagring. Basert på disse konseptene ble det i denne bacheloroppgaven undersøkt bruken av ventildiagnostiske systemer for å identifisere feilmekanismene til en ventil som er utsatt for nedbrytning. I dette systemet kan sensorer og små datamaskiner kontinuerlig overvåke ventilens ytelse og lagre disse dataene på skybaserte servere.

En eksperimentell testrigg på MRC Global sitt verksted har blitt brukt til å utføre casestudier som viser hvordan man oppdager og lokaliserer ulike feilårsaker ved hjelp av diagnostiske systemer. De diagnostiske resultatene som ble oppnådd fra simulerte degraderte ventiler, ble sammenlignet med friske ventiler for å identifisere "signaturmønstre".

Tilslutt er den tradisjonelle tilnærmingen for ventilpålitelighetsbekreftelse sammenlignet med det moderne IIoT- og CPS-baserte diagnostiske systemet. Den komparative studien viser at implementeringen av industri 4.0 konseptene øker påliteligheten betydelig.

Marita Bjorøy, Thomas Erstad, John-Kenneth Sangolt

Table of Contents

1. Introduction

In this chapter the background, research question, aim and scope of the thesis is given, alongside the assumptions, limitation and abbreviation used.

1.1 Background

In the oil and gas process industry there are a lot of safety instrumented systems (SIS) implemented in order to reduce the risk associated with operations. One type of SIS which is widely used in the industry are safety critical valves, such as emergency shutdown and emergency blow down valves. The importance of maintaining the functions of these valves is vital, since a failure may lead to accidents with severe consequences for life, assets and/or the environment. The normative approach in reassuring valve reliability which is widely adopted in today's industry gives little diagnostic information of the valves performance or condition. It is therefore important to implement new concepts and ideas to improve the diagnostic of such valves to increase their reliability. This thesis will therefore look to the fourth industrial revolution, industry 4.0 for new concepts to use in the search for increased reliability of safety critical valves.

1.2 Research Question

How can concepts of industry 4.0 help in improving the diagnostic of ball valve and actuator assemblies to increase their reliability?

1.3 Aim of the Project

Aim of this thesis is to find methods to improve reliability of ball valve and actuator assemblies using concepts of industry 4.0.

1.4 Scope of Work

The thesis will focus on the following:

- Description of valve actuator assemblies and the different failures of these
- Current practices of identifying these failures
- Introduction to industry 4.0 concepts and a description of sensors
- Identifying failures using modern diagnostic tools

- Introduce approach to understand and interpret diagnostic data in order to identify failures (Case Studies)
- Conclusion and further research

1.5 Limitations

The limitation set in this thesis are:

- The only failures that will be researched is:
  - Blocked exhaust in the Solenoid
  - Actuator leakage
  - High friction on ball valve
- Focusing only on emergency shutdown valve assemblies consisting of:
  - Ball valve, pneumatically driven scotch-yoke actuator and solenoid valve.
- Economical aspect is not considered.

1.6 Structure of Report

The structure of this report is as following:

Chapter 1 – Introduction of project: Research question, aim, scope, background, etc…

Chapter 2 – Background theory: Description of valve actuator assembly and its failures, current practices, an introduction to industry 4.0 and its concepts, a description of sensors and valve diagnostic systems

Chapter 3 – Methods: Information on how theoretical and experimental data is gathered.

Chapter 4 – Results: Interpret data gathered from tests carried out with the use of valve diagnostic systems.

Chapter 5 – Discuss the difference between normative approach and the use of cyber-physical systems

Chapter 6 – Conclusion and discuss further research.

1.7 Abbreviations

The abbreviation used in this thesis are listed below:

AIR – Abnormal Instrument Reading

CPS – Cyber-Physical System

DOP – Delayed Operation

ELP – External Leakage: Process medium

ELU – External Leakage: Utility medium

ESD – Emergency Shutdown

FEE – Front End Electronic

FTA – Fault Tree Analysis

FTC – Fail to Close on Demand

FTO – Fail to Open on Demand

IIOT – Industrial Internet of Things

INL – Internal Leakage

KPI – Key Performance Indicator

LCP – Valve Leakage in Closed Position

MAST – Maximum Allowed Stem Torque

OPC – Open Platform Communication

PST – Partial Stroke Test

ROC – Read Out Controller

SIS – Safety Instrumented System

STD – Structural Deficiency

WNUAS – Western Norway University of Applied Sciences

2. Background Theory

This chapter consists of a description of a valve actuator assembly, failures that may be found in this assembly and the current ways of identifying these failures. It includes an introduction to industry 4.0 and important concepts. In addition, the chapter also explains sensors, the valve diagnostic system and gaps.

2.1 Description of Valve Actuator Assembly and its Key Performance Indicator

A type of valve actuator assembly used in the oil and gas industry is an emergency shutdown valve (ESD). An ESD valve assembly can consist of a ball valve, a scotch yoke actuator and a solenoid valve. The ball valve includes a body, ball seat, ball disc, gasket and stem. The ball disc and ball seat create a tight shutoff when closed. The scotch yoke actuator key components are a supply pressure inlet and pressure chamber, piston, piston rod, scotch yoke and actuator spring. The two components are linked together through the stem.

The scotch yoke actuator utilizes compressed air to operate, the supply pressure is controlled by a solenoid valve. A solenoid is an electromagnetic device which is controlled by electricity. When the solenoid receives an electrical current through the coil, a magnetic field is created within the solenoid which compress the spring and lifts the plunger so that the valve will be open for air to flow through.

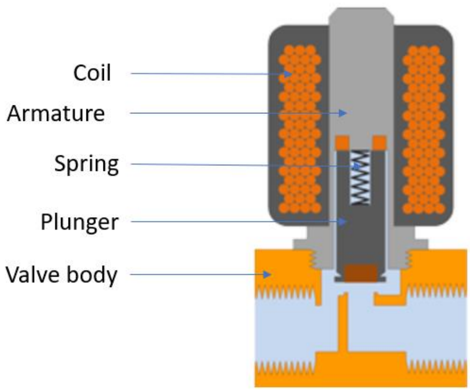


Figure 1 solenoid valve (Tameson, 2019)

The supply pressure goes through the solenoid valve (while open) and into the actuator. Before the valve starts to travel the supply pressure must overcome the actuator spring force (a pneumatic operated scotch yoke actuator has an operation pressure from 3-14 bar). The supply pressure pushes the piston and piston rod into end position while compressing the actuator spring. The scotch yoke being fastened to the piston rod will travel with it, simultaneously turning the stem a quarter-turn and the ball valve into open position. If the solenoid loses the electrical current flowing through the coil the spring within it will decompress and the plunger closes the valve in the solenoid. The tension built up in the actuator spring then presses the piston and piston rod back into start position and the scotch yoke closes the ball valve by turning the stem back a quarter-turn when supply pressure is cut off by the solenoid valve.

While operating a ball valve actuator assembly three different sequences are viewed upon. These sequences are "break to", "run to" and "end to" open/close and are known as key performance indicators (KPI). The most important key performance indicator is the maximum allowed stem torque (MAST). Maximum allowed stem torque is the torque required to deform or shear the stem and it is important that the force in the actuator do not exceed the maximum allowed stem torque.

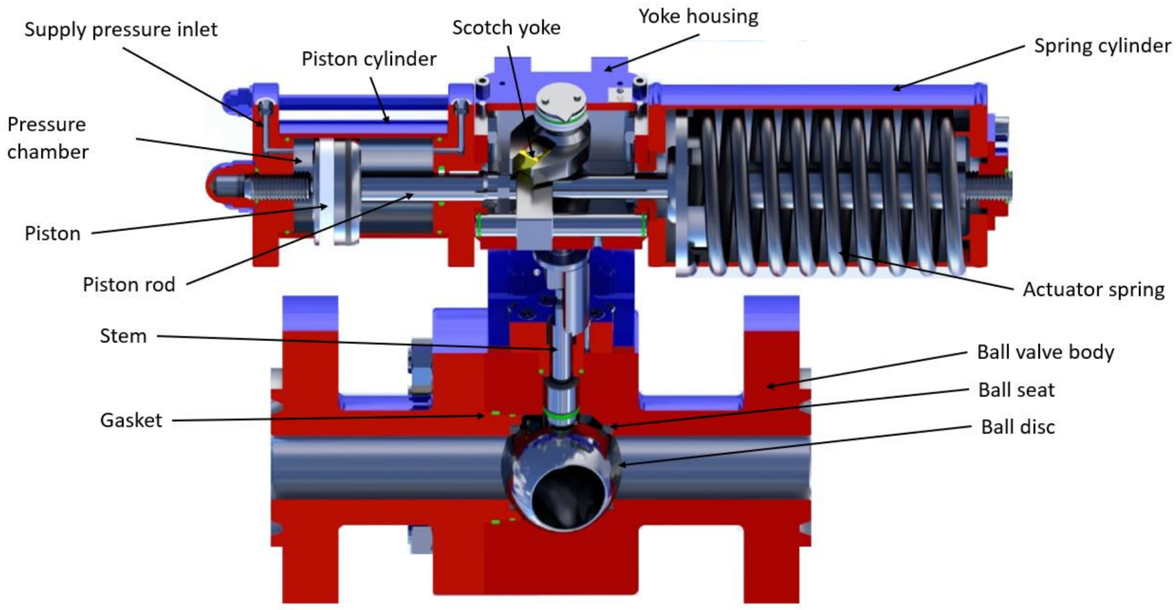


Figure 2 Scotch yoke actuator with ball valve (Paladon, 2018)

2.2 Common Failures

In order to evaluate methods for identifying failures a list of possible failures that may occur on a valve actuator assembly must be compiled. This list is based on the most common failure modes and mechanisms listed in OREDA's database for topside equipment (2009, p. 495-538). The following failures where listed for ESD ball valves:

Table 1 List of common failures for ESD ball valve

Common failure mode	Common failure mechanism
External leakage – Process medium (ELP)	Corrosion Leakage Mechanical failure
Fail to close on demand (FTC)	Blockage/plugged Instrument failure Mechanical failure Sticking
Fail to open on demand (FTO)	Blockage/plugged Instrument failure Mechanical failure
Internal leakage (INL)	Leakage Material failure Mechanical failure
Valve leakage in closed position (LCP)	Leakage Wear
Abnormal instrument readings (AIR)	Blockage/plugged Breakage Corrosion Instrument failure
Delayed operation (DOP)	Mechanical failure No signal/indication/alarm Out of adjustment
Structural deficiency (STD)	Corrosion Instrument failure Material failure External influences
External leakage – utility medium (ELU)	Leakage Mechanical failure

2.3 Fault Tree Analysis

The Fault Tree Analysis (FTA) is based on the common failure modes and mechanism listed in OREDA.

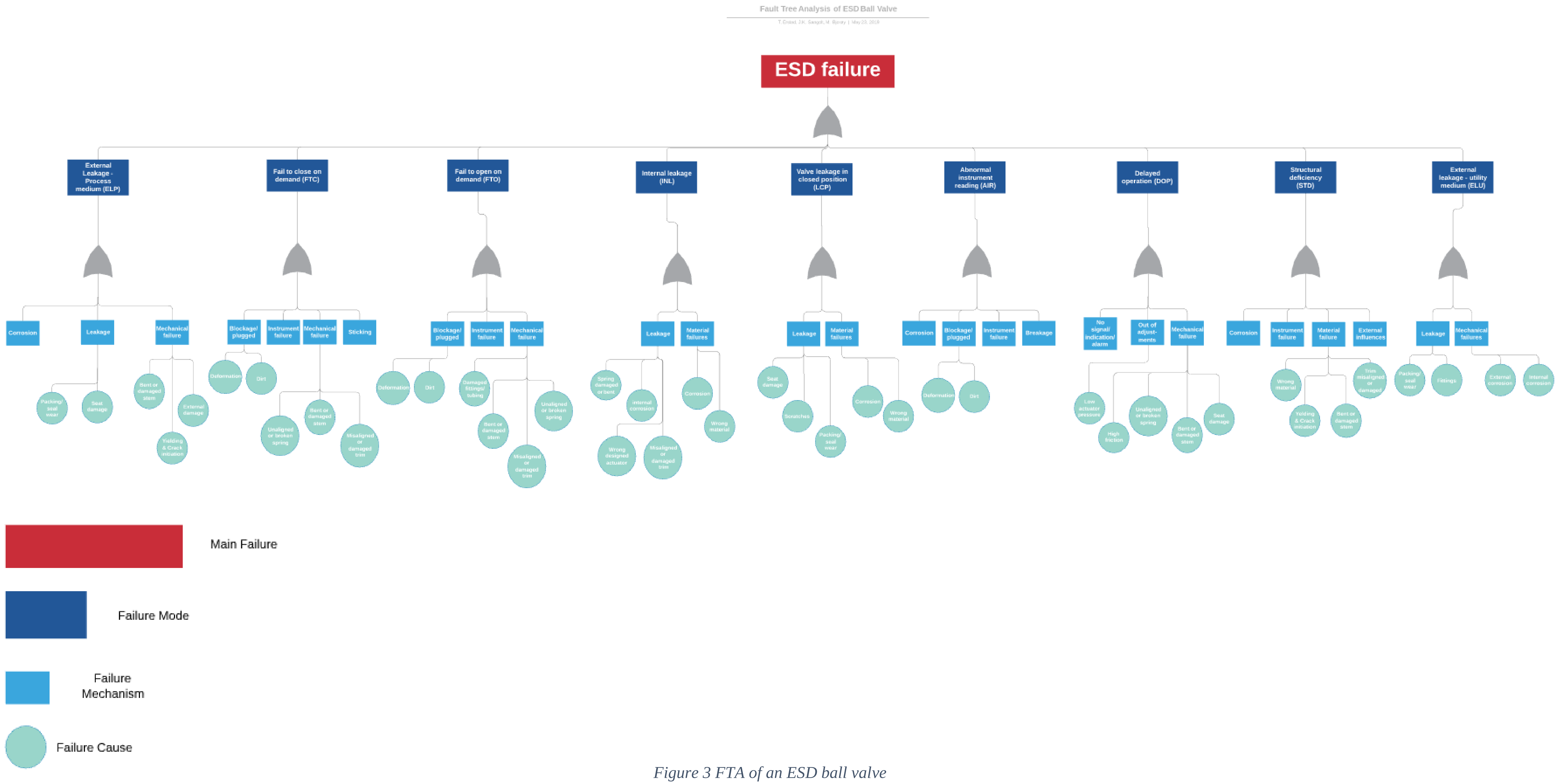


Figure 3 FTA of an ESD ball valve

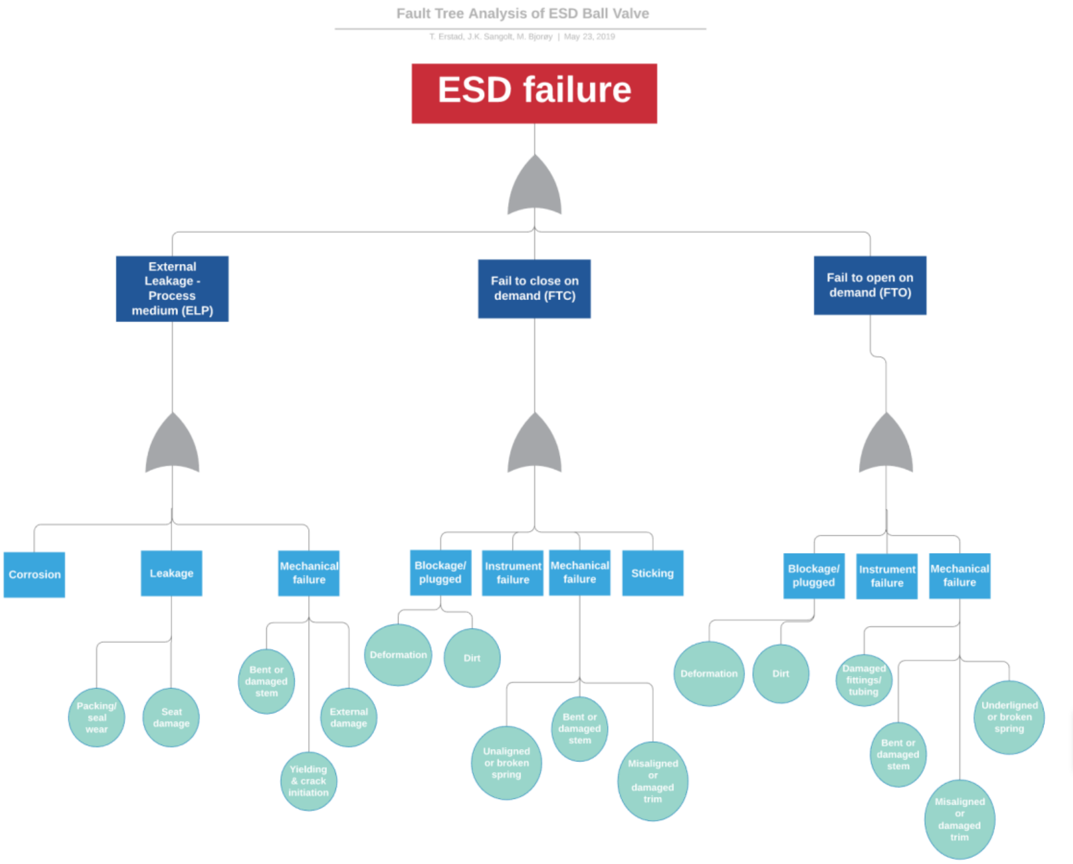


Figure 4 Section one of FTA

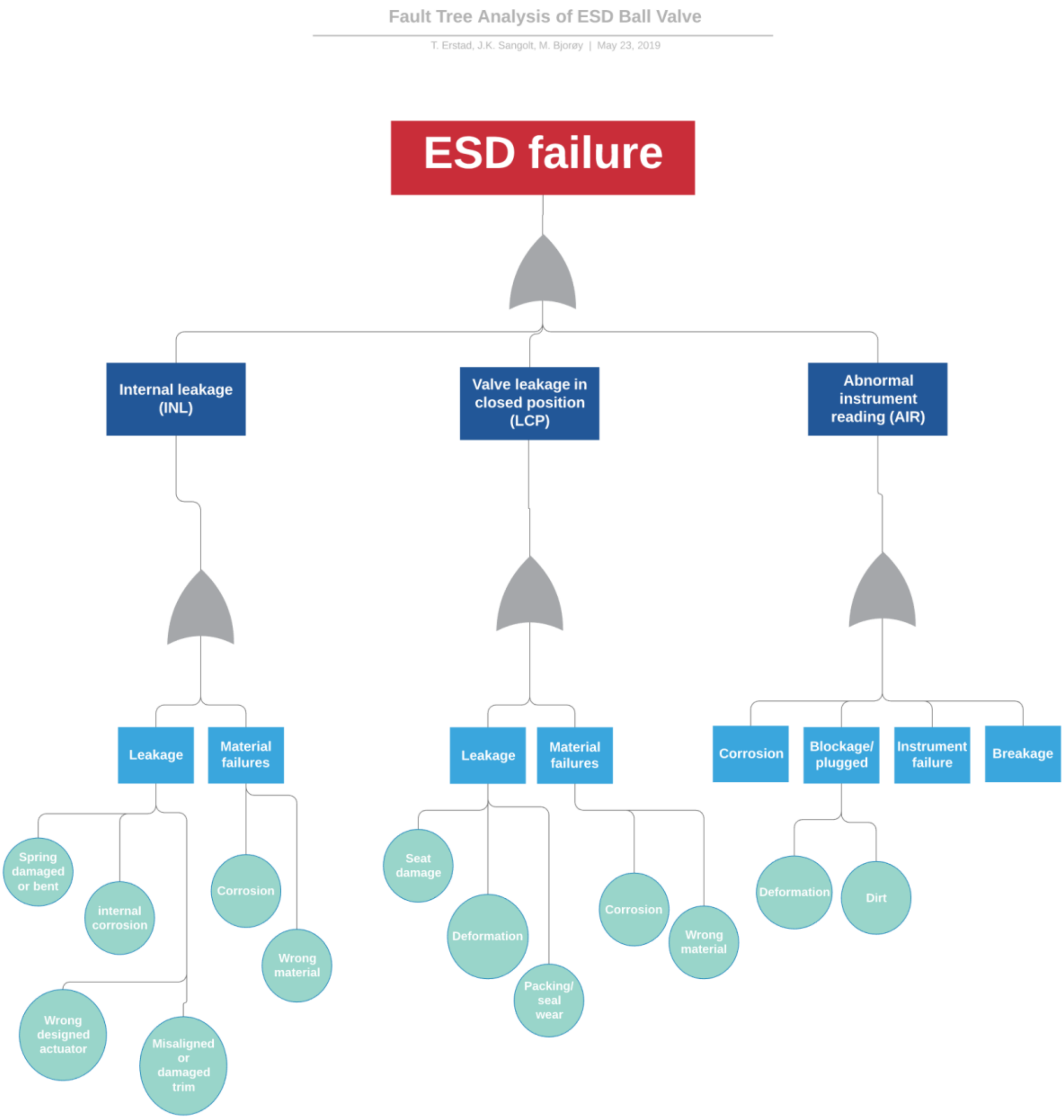


Figure 5 Section two of FTA

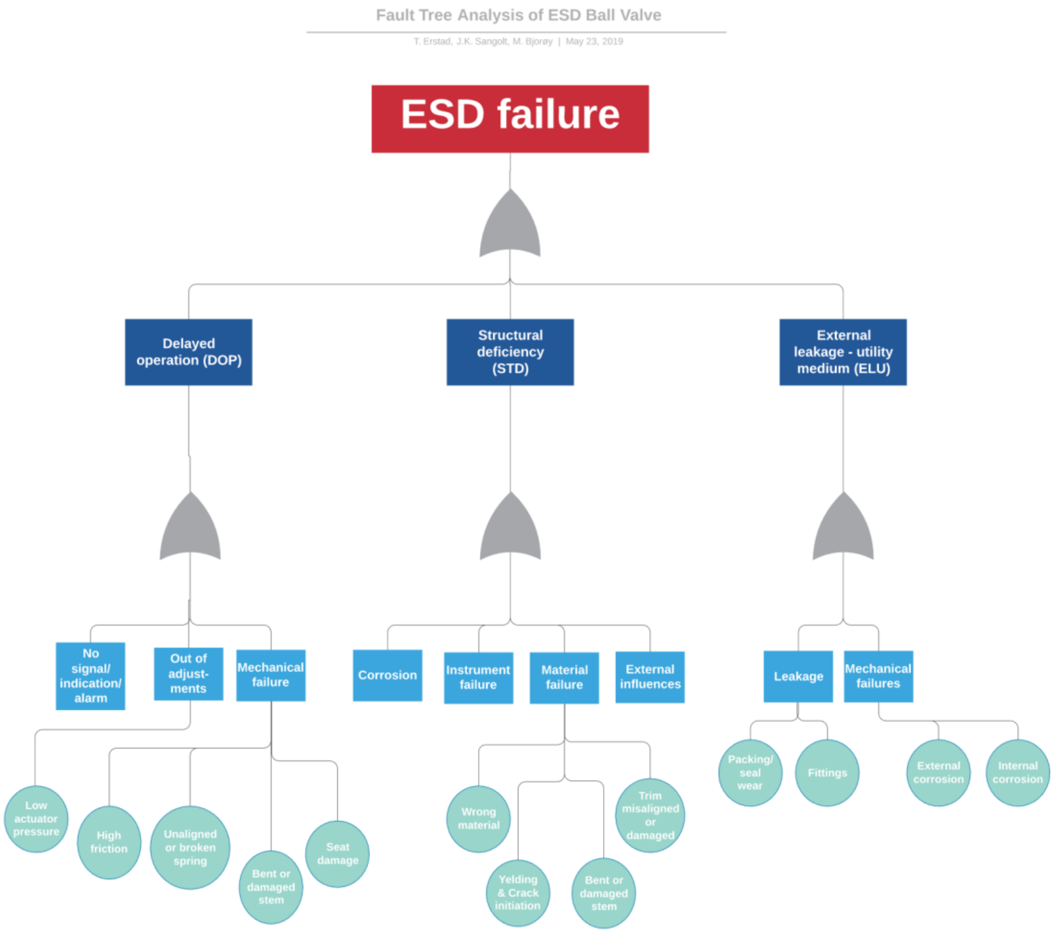


Figure 6 Section three of FTA

2.4 Current practices to identify failures

In order to identify failures on safety instrumented systems (SIS) such as an emergency shutdown valves it is essential to run proof of function tests. According to the standard NOG 070 (Norwegian Oil and Gas Association, 2018, p. 55) should such test be carried out annually, but the time interval may be subjected to change or be delayed if a Partial Stroke Test (PST) has been done. Partial stroke test is when a valve is partially closed and then reopened before fully closed. This gives an indication of valve movement. In this thesis only full proof of function tests will be evaluated and PST will therefore not be described in further detail. Today's normative approach of proof testing is simplistic and provides little information about the valve performance. The test is carried out by one person standing beside the ESD-valve with a stopwatch and confirms the closing time which includes the signal exchange time from ESD logic and solenoid valve. If the closing time is within the time limits the valve is approved, on the other hand if the valve closes too slow it will not be approved and needs to be subject to maintenance. The closing time limits for ESD-valves are 2 seconds per inch of valve size for safety critical valves when closing time is not specified. (PSA, 2010, p.14) Companies may have stricter requirements with closing time limits down to 1 second per inch. The challenge with the normative approach is that the amount of information gathered about valve performance is rather low. The only details are closing time and confirmation about the valve seal. This in turn means that the knowledge about the actual state of degradation on the ESD-valve is very low and therefore the valve reliability is considered to be low. Reliability in this context means the likelihood of the valve working when it is needed.

2.5 Industry 4.0

In the search for a solution to increase the reliability of the safety instrumented systems mentioned above it is reasonable to look at industry 4.0 and its concepts. Industry 4.0 is the name that refer to the fourth industrial revolution which involves digitalization and the application of Cyber Physical Systems (CPS), The Industrial Internet of Things (IIOT), cloud computing, big data and smart objects into the operations. (Gobbo Jr. et al., 2018, p. 374) The concepts of industry 4.0 has been widely accepted and adopted within the manufacturing industry, but with regards to valves it has to this day only been implemented in the nuclear industry (Kelechava, 2016). The implementation of these concepts into the oil and gas process industry may considerably increase the reliability and control of the valve degradation.

Cyber Physical Systems (CPS) is one of the concepts used to define industry 4.0 as mentioned above. These systems provides the use of data access between the physical process and virtual software. “Generally, CPS can be defined as innovative technologies that enable the management of interconnected systems through the integration of their physical and computational environment.” (Pereira & Romero, 2017, p. 1211) In this thesis the CPS mean the communication between the physical process which is the running of the ESD-valve, and data gathered from the different sensors mounted on the assembly. This will be the basis for the method of increasing valve reliability. The different sensors are explained in further detail in section 2.6 and the use of CPS is described further in section 2.7.

Another important concept in industry 4.0 is the Industrial Internet of Things (IIOT). There are many different definitions of what IIOT is, but for this thesis the following definition will be used:

> "A system comprising networked smart object, cyber-physical assets, associated generic information technologies and optional cloud or edge computing platforms , which enable real time, intelligent and autonomous access, collection, communicating and exchange of process, product and/or service information, within the industrial environment,…" (Boyes et al., 2017, p. 3-4)

This concept is important in regard to the reliability of valves because it is important that the information gathered from the CPS is available anytime and from anywhere. The data from CPS will therefore be uploaded using Open Platform Communication (OPC). OPC presents the standards and specification for exchanging of data in the industry, in further detail the communication of real-time plant data between for example control devices from different manufacturers. It is used in order to gather all the data from different sensors in one single cloud database. (OPC, 2019)

The cloud consists of a vast network of remote servers around the globe which are all connected. These may be either private or public. It has many uses, but for this thesis the cloud is used for storing and accessing of data needed to carry out analysis on ESD-valves. The biggest advantage with cloud-based storage is the fact that the data can be accessed from anywhere at any time with internet connection. The servers used are also significantly larger than normal computer storage and therefore gives the opportunity to save more data at one single place.

2.6 Sensors

The sensors used in the CPS makes it is possible to routinely record and monitor the performance of valve actuator assemblies in the oil and gas process industry. The sensors are attached to or nearby the assembly and can provide continuously updated charts of how the status of the assembly is at all times (MRC Global, 2019). Below in figure 7. is an illustration of an ESD-valve with sensor name and location of sensor. Further description of each sensor is presented in section 2.6.1 to 2.6.7.

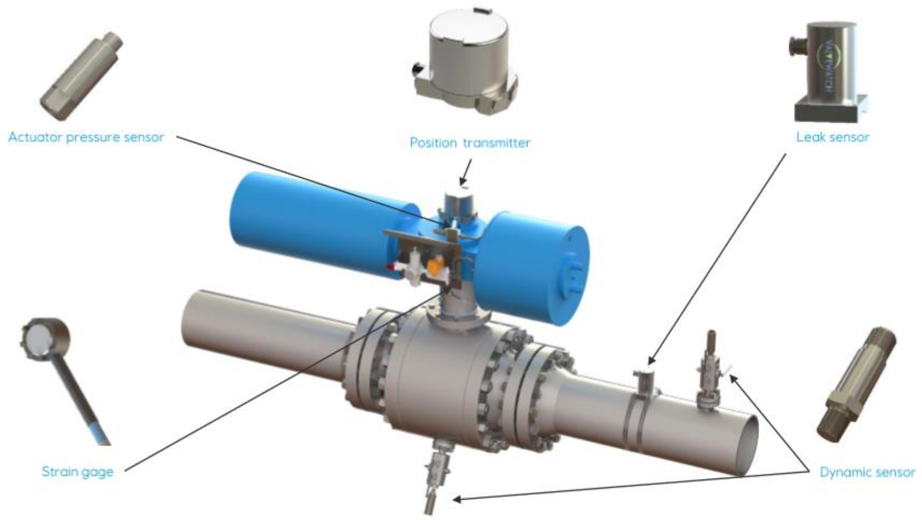


Figure 7 Overview of ESD-valve with sensors (MRC Global, 2019)

2.6.1 Limit Switch

The function of a limit switch is to give a confirmation whether a valve is closed or open. This information provides both visual and remote electrical indications of the position of the valve. This function can help make it possible to detect problems in the valve automation system before they turn in to dangerous and/or costly accidents (MRC Global, 2019).

Figure 8 Limit switch

2.6.2 Pressure Sensor

The function of the pressure sensors is to measure the static pressure and the sensor is mounted in the pressurized area of the solenoid and/or actuator. The limits for the pressure sensor are listed below as shown in attachement 1. (MRC Global, 2019)

Pressure sensor:

- Ranges from 3.5 bar to 700 bars. (51-10,000 psi)
- Frequency response to 3,5 kHz
- mV output
- Operating temp. -40 to +80°C
- Accuracy +/- 0,02% FS
- Overpressure protection at 80 bars

Figure 9 Pressure Sensor (MRC global, 2019)

2.6.3 Strain Sensor

This sensor provides a number that indicates the torque on the stem. This sensor is mounted directly on the yoke and measures the dimensional changes between the valve and the actuator by analyzing the force between them. The limits for the strain gauge are listed below as shown in attachment 4. (MRC Global, 2019)

Strain:

- High strength titanium epoxy
- Torque – ball valve
- ATEX – Ex i
- Output signal in µV
- Accuracy +/- 0,01% FS
- 5000Ω - full bridge

Figure 10 Strain Sensor (MRC Global, 2019)

2.6.4 Dynamic Leak Sensor

This sensor is placed in the cavity in both upstream and downstream positions of the valve and can give indications if there is leakage between them by measuring the difference in pressure. If it detects a leak, then the seal integrity is in question. The limits for the dynamic pressure sensor are given below. (MRC Global, 2019)

Dynamic:

- Range – Up to 10,000 psi
- Type: full bridge
- Resistance - 2000Ω
- Full scale output 10mV/V
- Excitation voltage 1-10 volts

Figure 11 Dynamic Leak Sensor (MRC Global, 2019)

2.6.5 Acoustic Leak Sensor

This sensor also measures leak in the valve. It is mounted on the valve or on the pipe near the valve and when the valve is in closed position the acoustic sensor can indicate if there is a leak in the valve by measuring if there is any difference in pressure across the valve. The limits for the accustic sensor are listed below as shown in attachment 2. (MRC Global, 2019)

Acoustic sensor:

- Min. dP for detectable gas leakage >1 bar
- Min. dP for detectable liquid leakage >3 bar
- Valve/pipe surface temperature -40 to +225°C
- Operating temp. -40 to +150°C
- Flow regimes oil, gas, water, multiphase

Figure 12 Acoustic Leak Sensor (MRC Global, 2019)

2.6.6 Positioner

Positioners are placed on a valve to control which position the valve is in. It may also allow the operator to remotely open or close the valve by either using a pneumatic or electrical signal. In the case of monitoring it is used to compare the position given by the control system to the valve's actual position. (MRC Global, 2019)

2.6.7 Position Transmitter

A position transmitter transforms the physical position (shown on the positioner) of the valve to an electrical signal which gives information or feedback to a computer of what position the valve is in. This is often given in form of percentage open or close. The limits for the position transmitter are listed below as shown in attachment 3. (MRC Global, 2019)

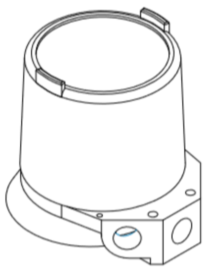


Figure 13 Position transmitter

Position transmitter:

- Signal output Ω
- Potentiometer 10k Ω
- Operating temperature -40 to +85°C
- Position read out

2.7 Identification of failure using diagnostic systems

Using CPS such as a valve diagnostic system to monitor the valve actuator assembly reduces risk by continuously providing a quantitative assessment of the valve performance. The diagnostic system measures and records data at a high data sample rate (up to 4000 measures per second), which gives precise and informative data regarding the integrity and condition of the assembly during every operation (Hale, 2017). A more in-depth explanation of how the valve diagnostic system is set up and the different steps are described in section 2.7.1. The process of identifying the failures is done by looking at the graphs generated by the sensor datapoints. These graphs are then interpreted and qualitatively assessed in order to figure out if there is any ongoing failure mechanism and the location of these. An example of this process will be shown in two case studies in section 4.1-4.2. In addition to this, failures may also be detected by an automation in a software which detect if for example the measured torque is close to the valve MAST (maximum allowed stem torque) value or available torque, so as the safety factor is no longer sufficient. This factor is the ratio between the available and used actuator force and is often determined by suppliers or companies. This automated alarm does not tell you directly what the failure is, only that something is wrong and where to look. Therefore, the graphs will still need to be interpreted in order to locate the failure. The use of diagnostic system also makes it possible to use normal closing operations as a proof of function test instead of scheduling for this to be carried out.

2.7.1 Description of Valve Diagnostic system

The valve diagnostic system consists of sensors that are placed on or near the valve, these sensors are connected to a junction box, which also is called a Front End Electronic (FEE). The function of the FEE is to house the different electrical components and to provide the components with a safety barrier. Further on the FEE is connected to a Read-Out Controller (ROC) that interpret the data samples from all the different sensors and makes them readable. The ROC is connected to the network so that the interpreted data can be uploaded to private database servers, often referred to as the cloud. The stored data in the cloud can then be accessed when needed from either a remote desktop or through the client's maintenance system and get introduced into a diagnostic software. The software uses the data points and makes a real-time graph which can be analyzed. In addition to this the stored data makes it possible to detect trends and could help to predict failures before they even occur. In figure 14 a visual representation of this setup is shown.

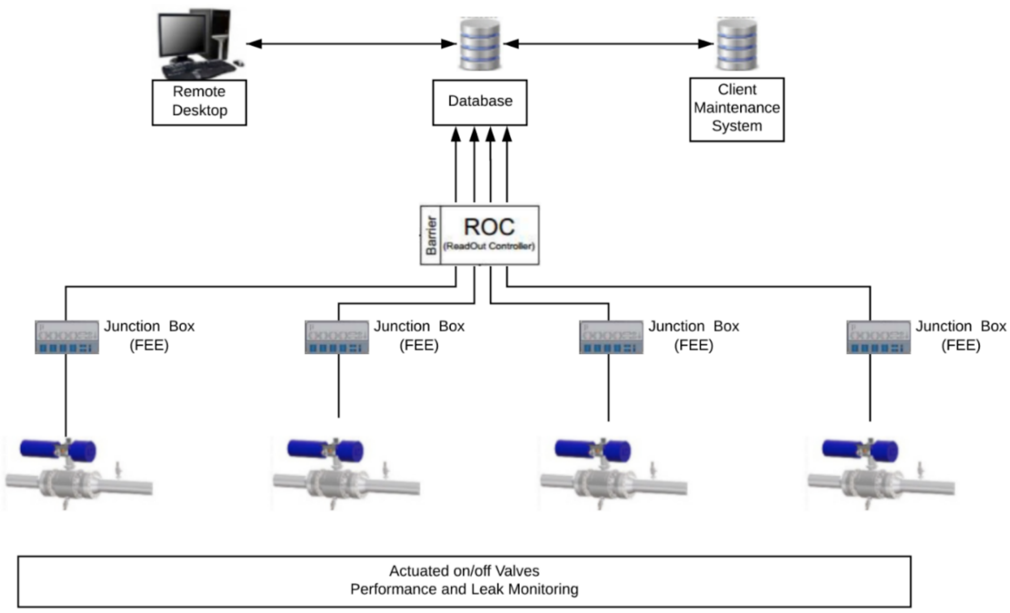


Figure 14 Valve Diagnostic Tool

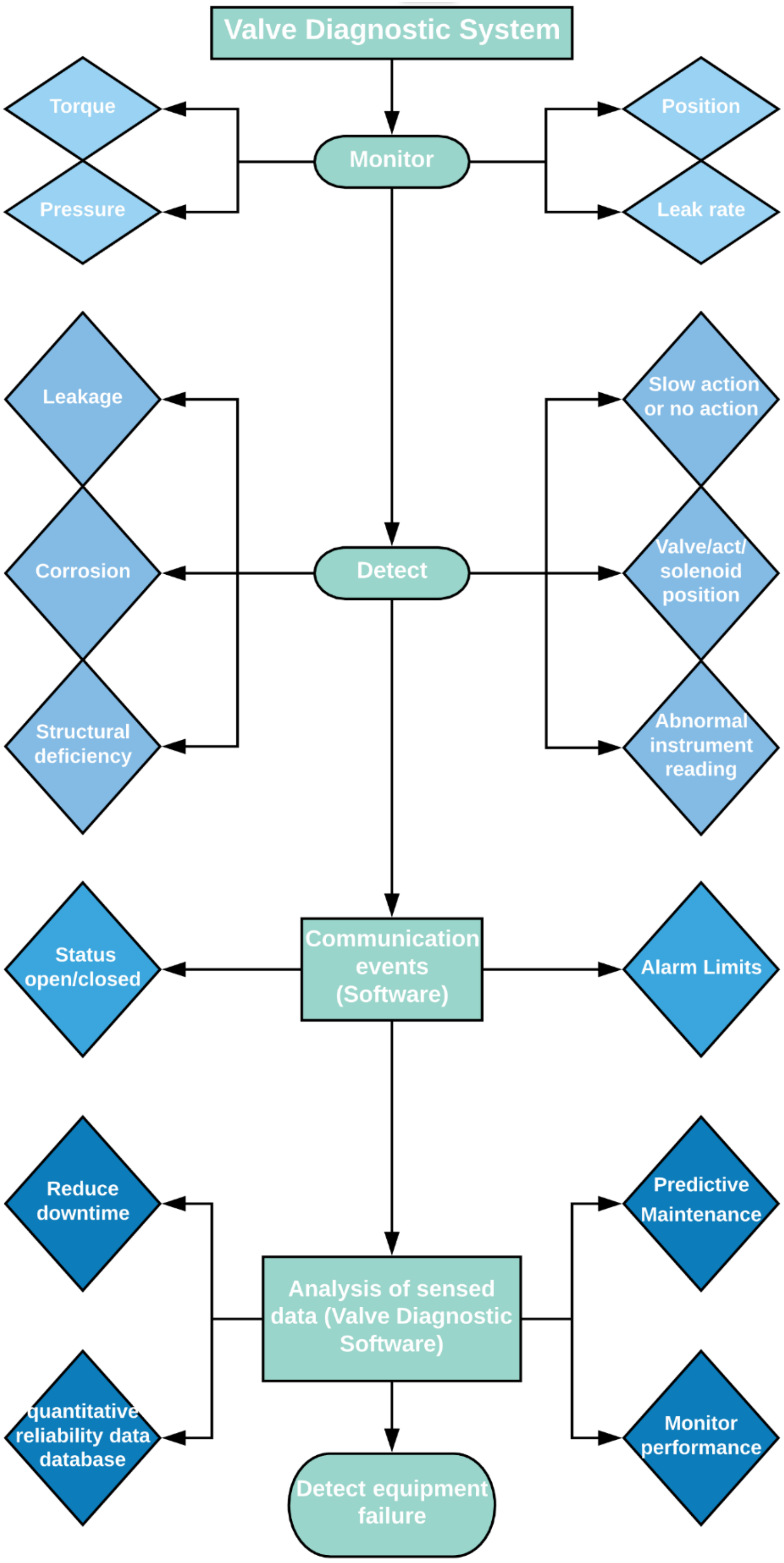


Figure 15 Overview of valve diagnostic system process

Figure 15 in section 2.7.1 shows an overview over the process from monitoring to detecting equipment failure when using a valve diagnostic system. To get a better understanding of the different steps they are described in further detail below and an overview of the failures and which sensor detects them are given in figure 21.

Monitor and detect

As mentioned earlier valve diagnostic system uses sensors attached on or near the valve to monitor the status of the valve. These sensors measure the torque, pressure, position and the leak rate, and by doing so the system can detect, track and monitor the development of the different failure mechanisms/causes that eventually may lead to a failure.

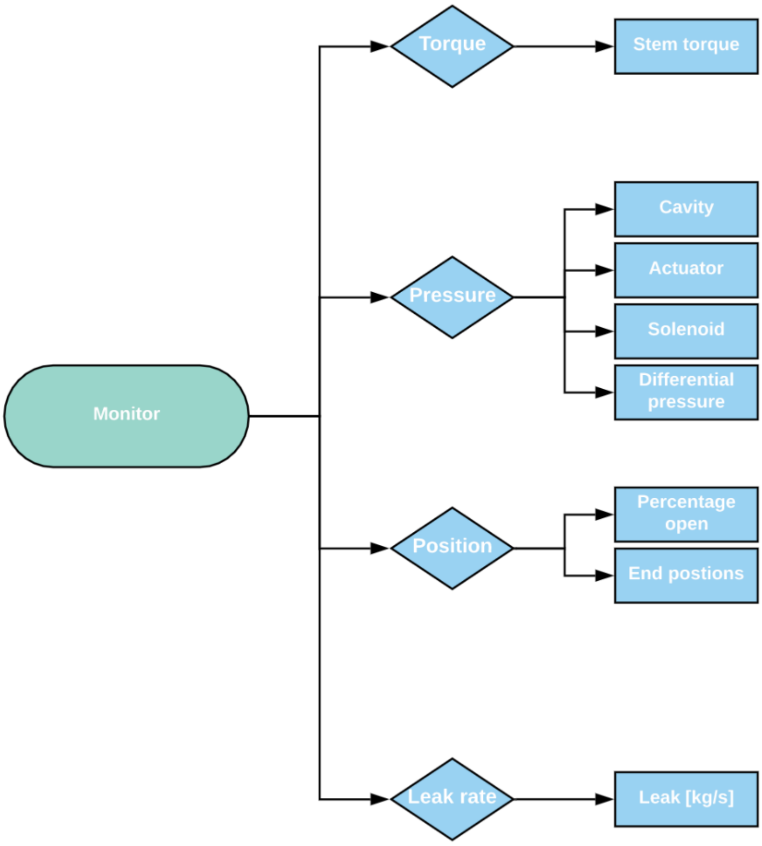


Figure 16 Overview of what a valve diagnostic system can monitor

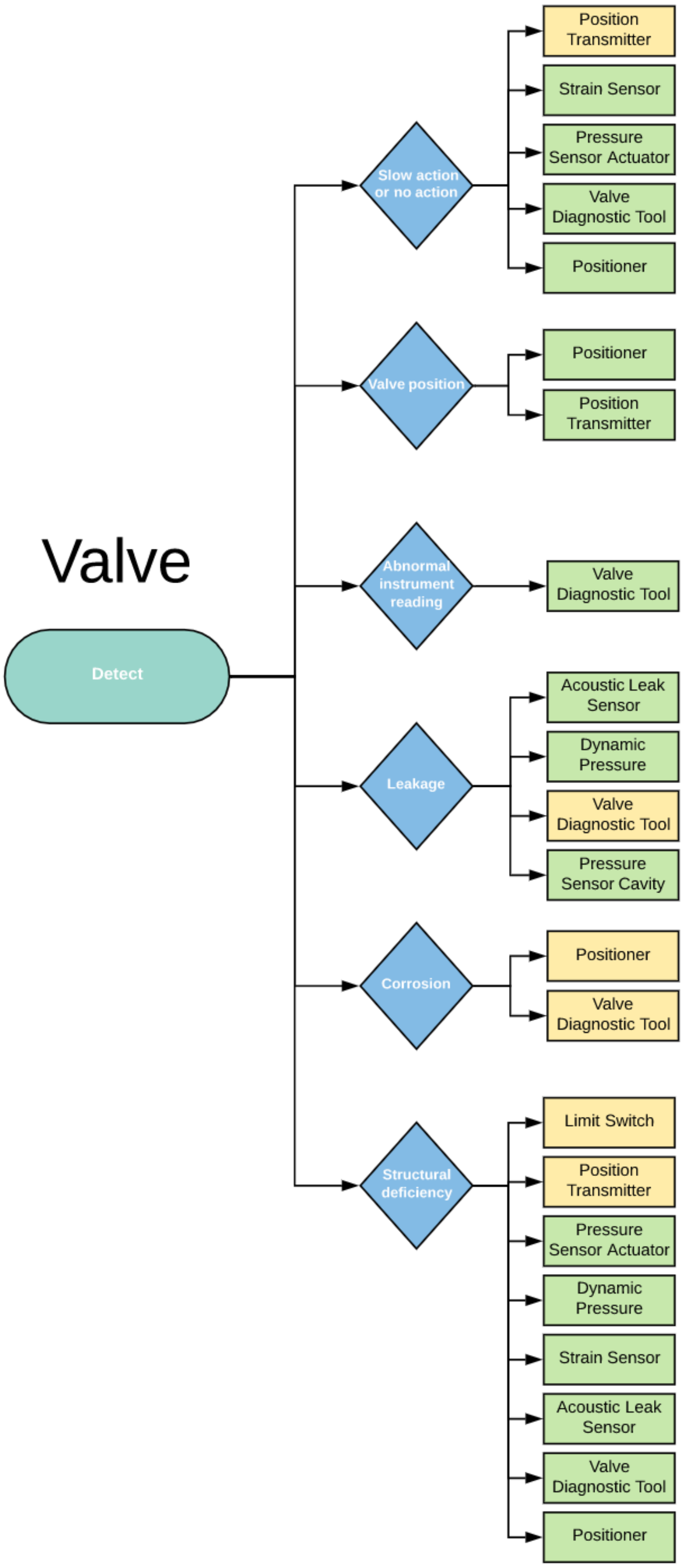


Figure 17 Overview of detected failures on valve and which sensor that detects it.

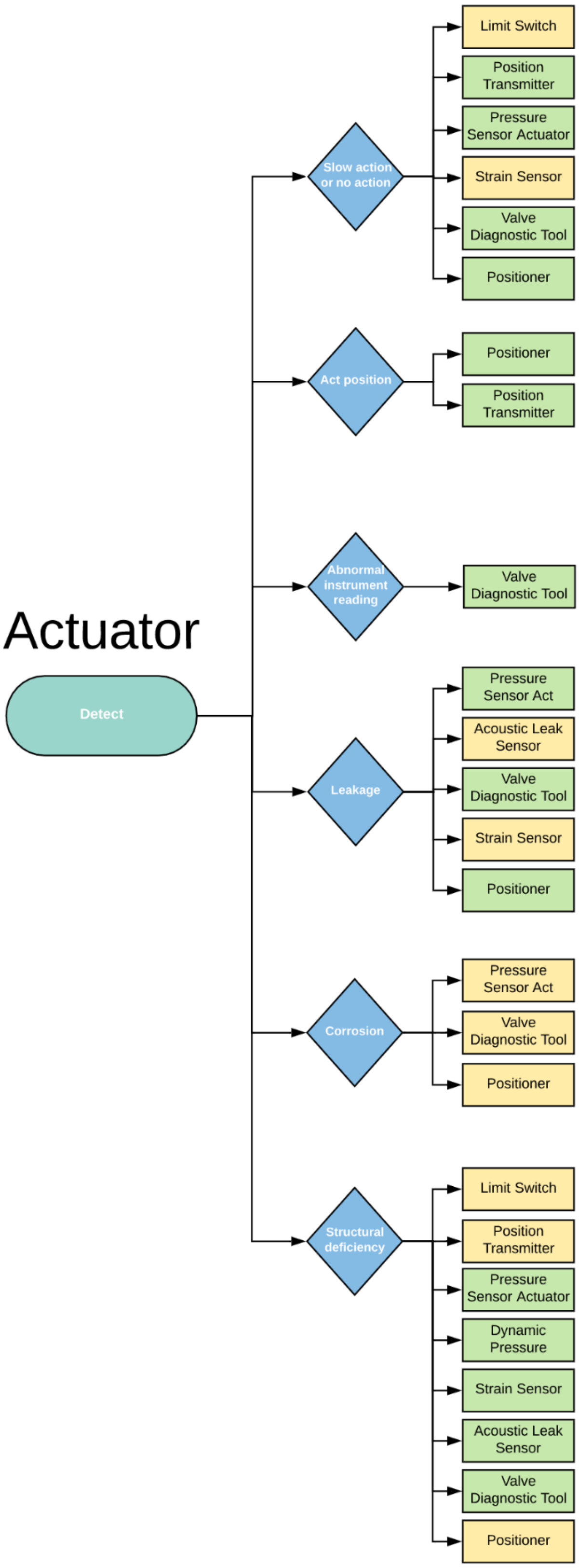


Figure 18 Overview of detected failures on actuator and which sensor that detects it.

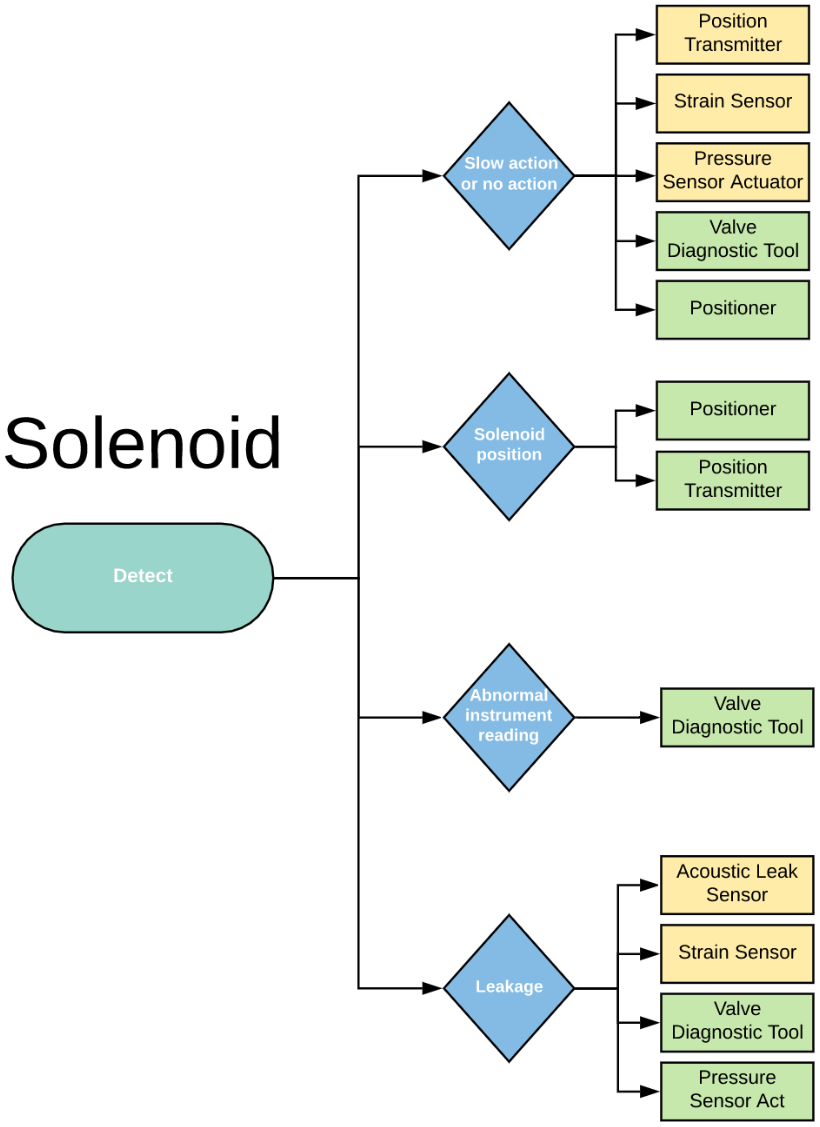


Figure 19 Overview of detected failures on solenoid and which sensor that detects it.

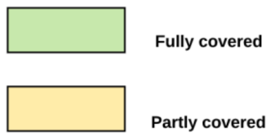


Figure 20 Color code

Failure mode	Part/Fault	Severity	Effect	Visual inspection	Limit Switch	Position Transmitter	Pressure Sensor Actuator	Pressure Sensor Solenoid	Pressure Sensor Cavity	Strain Sensor	Dynamic Leak Sensor	Acoustic Leak Sensor	Process Data (OPC)	VDT (Valve Diagnostic Tool)	Electrical Actuator	Positioner	Total Coverage
	Valve																
STD	External corrosion	2	Will cause problems when maintenance is required	2	0	0	0	0	0	0	0	0	0	0	0	0	0
ELP	External leakage	4	Usually this requires immediate shutdown	2	0	0	0	0	0	0	0	1	0	0	0	0	1
STD	Stem damage, scratches or wear	3	Will cause external leakage over time	1	0	0	1	0	0	1	0	0	0	1	0	1	1
STD	Bent stem	3	Will cause galling and external leakage over time	0	0	0	2	0	0	2	0	0	0	2	1	2	2
INL	Internal leakage valve open	3	Will cause damage to trim, sooner maintenance	0	0	0	0	0	2	0	2	0	0	0	0	0	2
LCP	Internal leakage valve closed	3	Will cause damage to trim, sooner maintenance	0	0	0	0	0	2	0	2	2	0	1	0	0	2
STD	Internal body corrosion/ erosion	3	Will cause damage to body, sooner maintenance	0	0	0	0	0	0	0	0	0	0	0	0	0	0
STD	Internal trim corrosion/erosion	3	Will cause damage to trim, sooner maintenance	0	0	0	0	0	0	0	0	0	0	1	1	1	1
STD	Internal trim misalignement , galling	3	Will cause damage to trim, sooner maintenance	0	0	0	2	0	0	2	0	0	0	2	2	2	2
STD	Internal trim damage	3	Will cause damage to trim, internal leakage	0	1	1	1	0	0	2	2	2	0	1	1	1	2
STD	Low friction, packing/seals worn out	3	Will cause external leakage over time	0	0	0	1	0	0	2	0	0	0	2	2	2	2
DOP/FTC	High friction, scaling etc.	3	Will cause poorer performance, more power needed	0	0	1	2	0	0	2	0	0	0	2	2	2	2
DOP/FTC	Stick-slip effect	2	Will cause poorer performance, more power needed	2	0	1	2	0	0	2	0	0	0	2	1	2	2
	Actuator																
STD	External corrosion	2	Will cause problems when maintenance is required	2	0	0	0	0	0	0	0	0	0	0	0	0	0
ELU	External leakage	3	Will cause poorer performance, more power needed	2	0	0	2	0	0	1	0	1	0	2	1	1	2
STD	Stem damage, scratches or wear	2	Will cause poorer performance, more power needed	1	0	0	1	0	0	2	0	0	0	2	1	1	2
INL	Internal leakage	3	Will cause poorer performance, more power needed	0	0	0	2	0	0	1	0	0	0	2	1	2	2
STD	Internal corrosion - piston actuator	3	Poorer performance, internal valve leakage, actuator leakage	0	0	0	1	0	0	1	0	0	0	1	0	1	1
DOP/FTC	Internal misalignement, galling	3	Will cause poorer performance, more power needed	0	0	0	1	0	0	1	0	0	0	2	1	2	2
FTC	Spring damaged or broken	3	Lack of force, internal valve leakage, sooner maintanance	0	1	1	2	0	0	1	0	0	0	2	2	2	2
DOP/FTC	Spring unlinearity / bent spring	3	Lack of force, internal valve leakage, sooner maintanance	0	0	0	2	0	0	0	0	0	0	2	2	2	2
DOP/FTC	Wrong initial compression	3	Lack of force, internal valve leakage, sooner maintanance	0	0	0	2	0	0	0	0	0	0	2	2	2	2
DOP/FTC	Wrong mechanical connection (wrong travel)	3	Lack of force, internal valve leakage, sooner maintanance	1	1	2	0	0	0	0	0	0	0	2	0	1	2
DOP/FTC	Wrong engineerd / designed actuator	3	Lack of force, internal valve leakage, sooner maintanance	0	0	0	1	0	0	1	0	0	0	2	1	2	2
	Solenoid																
DOP/FTC	Stiction, reduced performance	3	Will cause poorer performance, more power needed	0	0	0	1	1	0	0	0	0	0	2	0	1	2
FTC	Stucked	3	Will cause poorer performance, more power needed	0	1	1	2	2	0	1	0	0	0	2	0	1	2
DOP/FTC	Blocked exaust	3	Will cause poorer performance, more power needed	1	0	1	1	2	0	1	0	0	0	1	0	1	2
ELU	External leakage	3	Will cause poorer performance, more power needed	2	0	0	2	0	0	1	0	1	0	2	0	0	2
INL	Internal leakage	3	Will cause poorer performance, more power needed	0	0	0	2	0	0	1	0	0	0	2	0	0	2

OK	
Follow up	2
Action required	3
Immediate action	4

2	Full coverage of fault
1	Partly coverage of fault
0	Most likely no coverage of fault

Figure 21 Overview of failures and how to detect them on Valve, Actuator and Solenoid

2.8 Gap

There are some failure causes that is undetectable without having for example a visual inspection of the valve. These failures are presented in figure 21 where it can be shown which failures the sensors can or cannot detect. To get a measurement of how a valve diagnostic system performs the Diagnostic Coverage (DC) should be calculated based on figure 21.

As seen in chapter 2.6.1 to 2.6.7 a description of the sensors is presented with the sensor's abilities and limitations. These limitations are important to consider when using the valve diagnostic sensors.

2.8.1 Diagnostic Coverage

Diagnostic coverage of safety functions is important because it gives an overview of how many percent of the failures are detectable and which failures are undetectable. The definition used in this thesis is given below:

> "Diagnostic Coverage (DC) is a measure of the effectiveness of diagnostics, expressed as a percentage (DC_{avg}) of a safety function, and is calculated from assessing both the total dangerous failure rate and the dangerous detected failure rate for each component in the SRP/CS (Safety-related part of a control system)…" (Smith & Simpson, 2016).

The DC can be calculated either for each individual part or for a complete system, when calculating for the whole system it is often referred to as DCavg of all the individual parts. There are several ways to calculate this. The formula used in this thesis can be found below in Formula 1. and is stated in the IEC 61508-2 Annex C.1.

$$DC = \frac{\lambda_{DD}}{\lambda_{(DU+DD)}} = \frac{DD}{DU+DD} = \frac{Number\ of\ failure\ detected\ or\ controlled}{Number\ of\ totale\ failures\ on\ the\ element}$$ Formula 1.

3. Method

3.1 Theoretical method

Data collection in this thesis have mainly been gathered through qualitative methods such as articles published by MRC, ISO/IEC standards and through published articles on ScienceDirect library from WNUAS. Since this is a fairly new subject, there are not a lot of articles in direct link to this thesis, but some links have been drawn from parts of other articles to be used in the thesis.

In addition to the articles some data and information have been collected through non-formal interviews with MRC global and it has also been gathered experimental quantitative data from tests carried out on ESD-valves at MRC global's test rig described below.

3.2 Description of experimental test rig for data collection

The experimental test rig mainly consists of two ESD-valves and one EBD-valve connected with pipelines. The pipes are connected to a water pump which can be used to simulate system pressure. On the valves it is mounted an actuator pressure sensor, stem strain gauge, positioner and a pressure sensor for the system. The test rig-system is run by a fully functional control room setup and a computer using valve diagnostic system to continuously analyze the incoming data. Figure 22 shows an overview of the test rig.

Figure 22 Overview of test-rig

In this thesis it was decided to focus on ESD-valves and the tests was therefore carried out on these. Both ESD-valves in the test rig consists of a solenoid valve, scotch-yoke actuator and a ball valve (described in detail in section 2.1). The difference between these two valves is that valve number one in figure 23 can adjust if the sealing seat should be active or non-active. This is done with air pressure which moves the seat to either be in contact with the ball or not. Figure 23 shows the two ESD-valves used for the flow test in case study 1 and for all tests in case study 2.

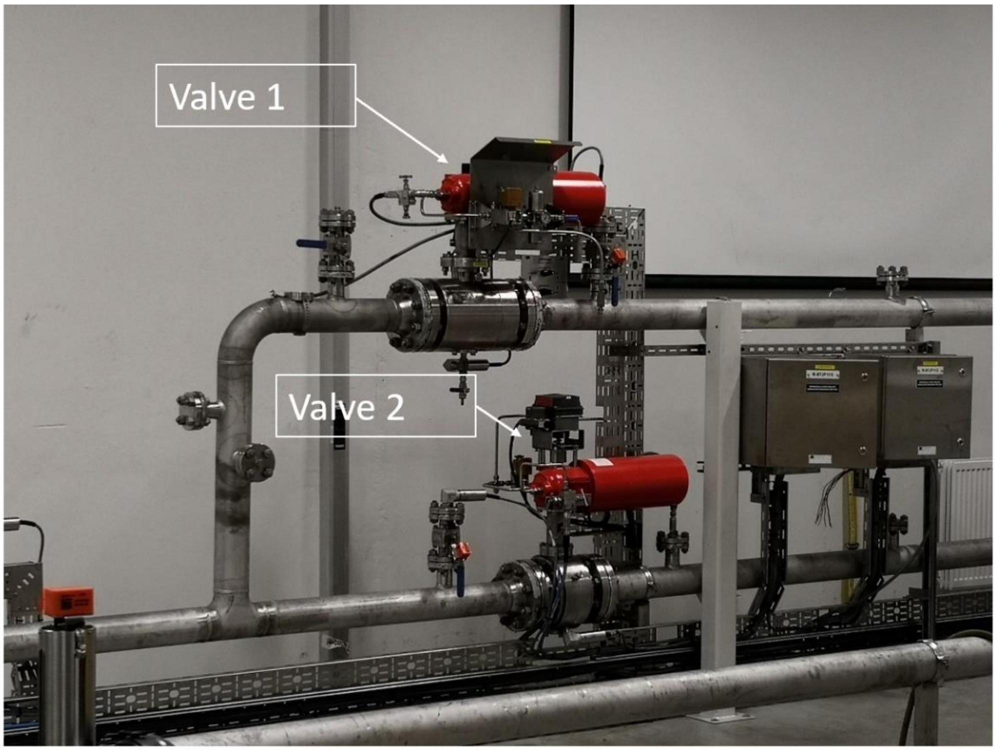


Figure 23 Two ESD-valves used to carry out tests

4. Results

In this chapter two case studies are reviewed in order to see how the Cyber-Physical Systems come into use in detecting failures and monitoring. The first study shows how flow affect different operation parameters and how a failure/degradation may be detected. The second study shows how to both detect and identify failure based on valve diagnostic test data. All the tests analyzed in this thesis is taken on ESD-valves.

4.1 Case study 1

Case study 1 consist of a flow test carried out at the MRC Global test rig and an actuator test carried out at a different location. The first case show how flow affects different parameters and the second case show how to detect failure on an actuator based only on actuator pressure graph.

4.1.1 Flow affection on parameters

Description of test

In this test different system flow is used to see how this affect a ball valve. With the use of valve diagnostic system, we can monitor the pressure in the actuator, stem torque and pressure in pipe.

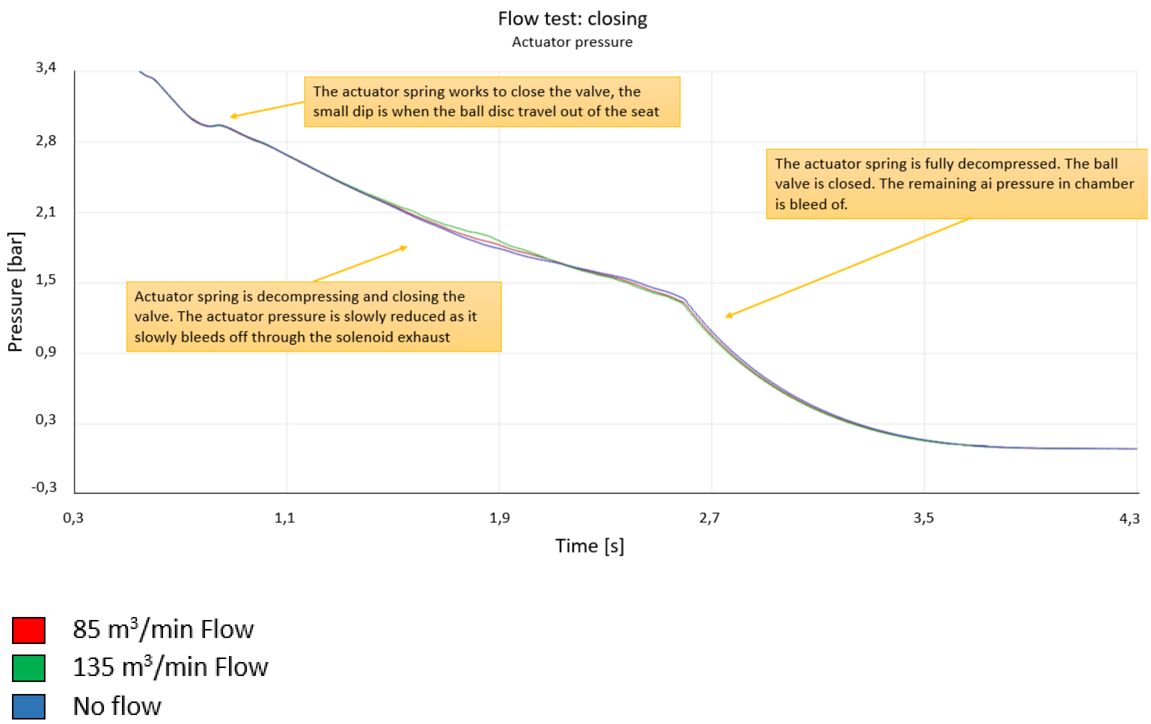


Figure 24 Actuator pressure for flow test

Section 1: Valve Motion Starts 0,3-1,1 second

In this section the key performance indicator (KPI) break to close is shown, which is when the ball valve overcomes the friction force from the seat and starts to turn. This is when the solenoid has lost the electrical current and the pressure in the actuator is released through the solenoid exhaust. The spring will start to decompress and close the valve. The flow does not have any visually impact on the break to close due to low flow rate.

Section 2: Valve in Motion and Closing 1,1-2,7 seconds

In this section the KPI run to close and end to close is shown. Run to close is when the actuator spring is decompressing and continuously closing the valve. While run to close there is some variation in actuator pressure, this indicates that the system flow in pipe has a small impact on the ball valve while closing. The end to close point is when the ball disc has turned 90 degrees and into its seat. The differences in end to close is also small, but shown in end to close the green and red chart pressure is lower than the blue chart, and this indicates that the flow helps the ball valve to fully close as the flow pushes on the ball disc.

Section 3: Valve Closed 2,7-4,3 seconds

In this section the actuator spring is fully decompressed, and the ball valve is closed in its seat. The drop of actuator pressure is the remaining supply pressure which rapidly is released.

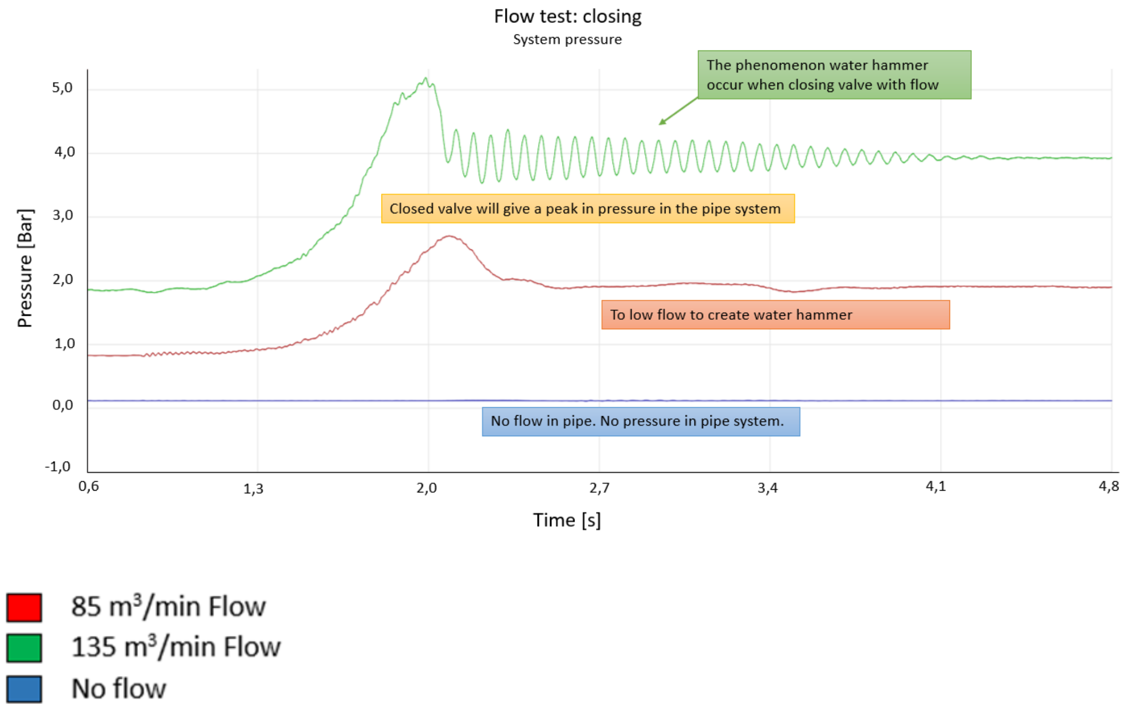


Figure 25 System pressure for flow test

Section 1: Stable System Pressure and Closing Start 0,6-2,0 seconds

In this section the pipe pressure builds up while closing with flow. When the ball valve closes the area through the ball disc will become smaller and smaller the further the valve gets in the process of closing. This will increase the pressure in the pipe. When there is no flow there is no pressure.

Section 2: Valve Closed and Period of Stable Closing Pressure 2,0-4,8 seconds

After the closing peak the pressure stabilizes show in the red chart. Due to higher flow rate in the green chart a water hammer occurs before the pressure becomes stabile. Water hammer is when the flow bounces back and forth making the pressure vary and occurs when flow suddenly stops.

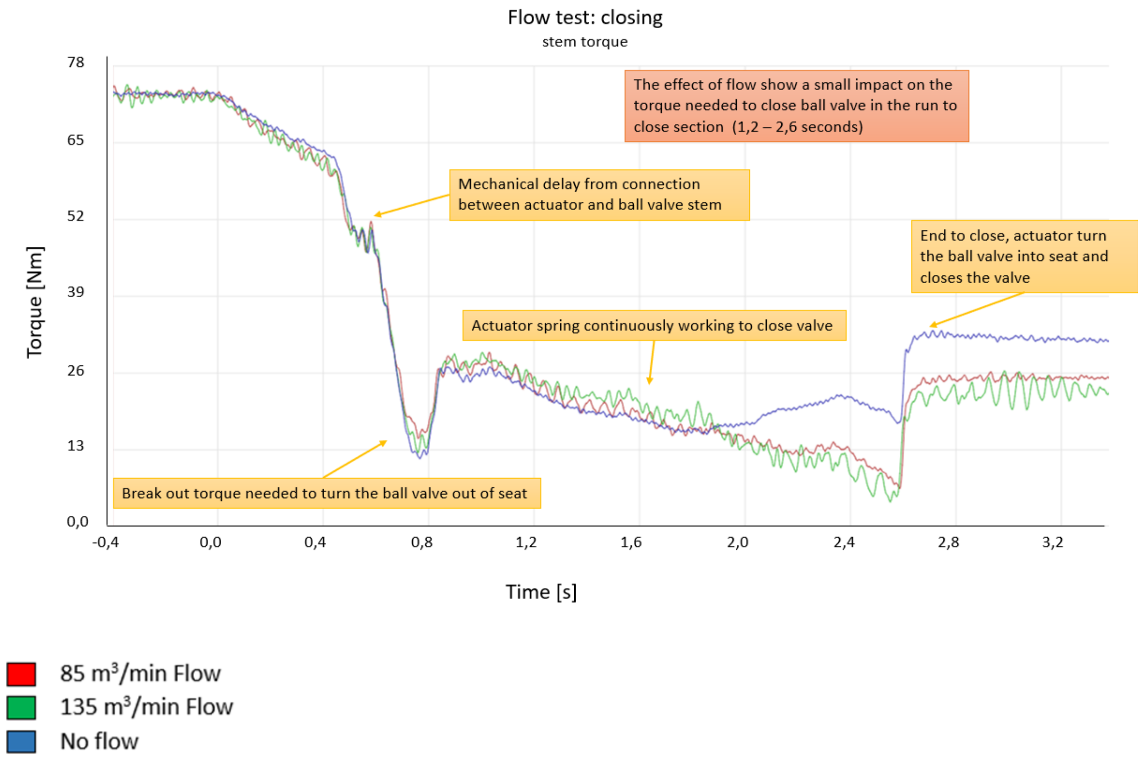


Figure 26 Stem torque for flow test

Section 1: Valve Motion Starts 0,0-1,2 seconds

In this section there are two factors shown, mechanical delay and break to closing. As the actuator spring starts to decompress a mechanical delay will occur as the yoke and stem is mechanically connected. The break to close is also shown which is when the ball disc turns out of the seat. All three charts are quite similar, which indicates that the flow has low or none influence on the torque in this section.

Section 2: Valve in Motion 1,2-2,6 seconds

Shown in the chart the torque needed to run to close will differ as the flow increases. The torque is somewhat equal to the actuator pressure and as the pressure decreases the torque decreases as well. The flow will have some effect on the torque as shown in run to close section. The blue chart uses somewhat lower torque to close because there is no flow in the system.

Section 3: Valve Closing 2,6-3,2 seconds

As the valve goes into end position it is shown that the torque increase as the ball disc hits the seat in all three cases. The difference is close to none in torque while end to close. This would have been easier to see if the chart lines was laid on top of each other.

Conclusion

This test uses sensors to monitor the pipe pressure, actuator pressure and strain gauge. Using these sensors and a valve diagnostic system makes it is possible to detect both abnormal behavior and phenomenon such as water hammer. The flow of water used in this test might help the ball valve to close as it pushes on the ball disc, but it will neither damage nor create abnormal activities. For an offshore or onshore installed ESD valve with a different medium such as oil with gravel, dirt, mud or gas might change the outcome. A change of medium, flow and pressure might end to an FTC (fail to close on demand) and DOP (delayed operation) as shown in fault three analysis (FTA). (figure 4 & 6)

4.1.2 Detection of failure on an actuator

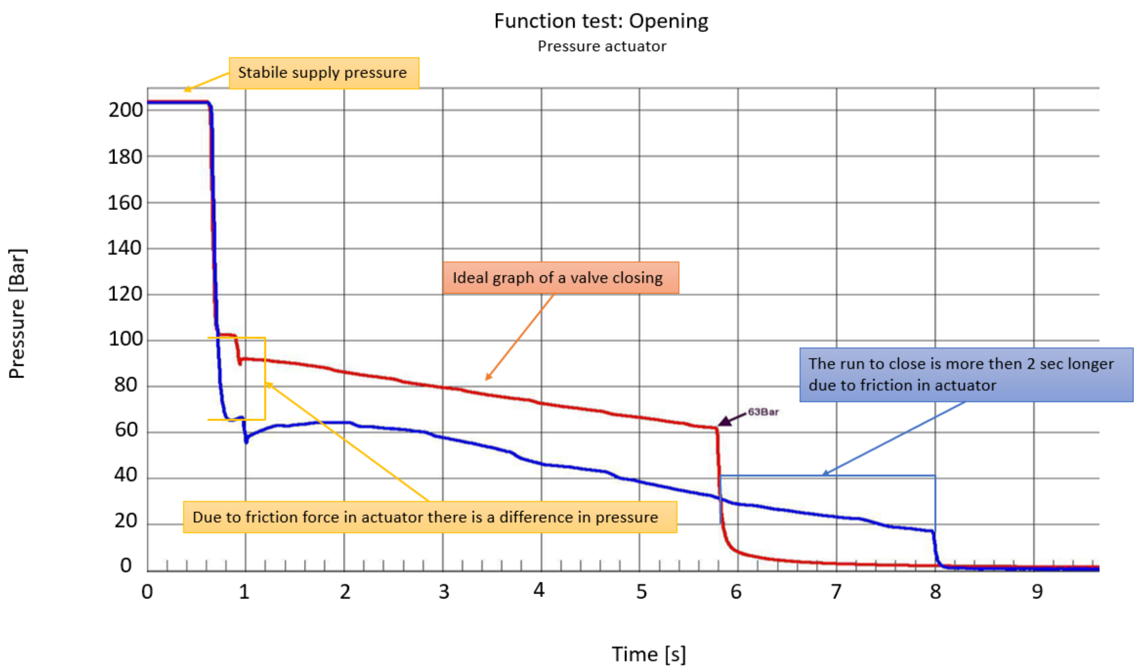


Figure 27 Actuator pressure for an ESD

This test is taken on an ESD where the blue graph shows the old test and the red graph shown a new test taken after repairs. Hence the red chart can be assumed to represent a fully functional valve.

Section 1: Period of Stable Actuator Pressure 0-8 seconds

In this section the pressure in the actuator is stable at 205 bar and this is the supply pressure when the valve sits fully open and has not yet started to move. Here the values of old vs new test are completely the same, this means that the valve is fully open during both tests.

Section 2: Valve Motion Start 8-10 Seconds

In this section it shows that the pressure is dropping rapidly, this is when the actuator is releasing its pressure and the actuator spring comes into action and the closing movement of the valve starts. On both tests there is a bit of a “dip” in the pressure around 8-9 second mark, this is when the actuator spring starts to decompress and runs the valve. On the old test the pressure falls around 40-50 bars lower than the new test before the spring to takes into action. This indicates that the actuator is in need off higher force in order to start the actuator movement (Break to close). Also, the old test’s “dip” is bigger than for the new test which indicates that the actuator takes longer to start moving. On the blue chart it is a small pressure increase after the actuator comes into action, this is probably caused by some extra friction in the motion of the ball valve.

Section 3: Valve in Motion and Closing 10-14 Seconds

This section shows the pressure on both tests slowly declining. A difference is shown after about 13-14 second mark where the new test suddenly has a drastic pressure decrease, this is because the actuator spring has reached the endpoint and valve has then fully closed into the seal. On the old test the pressure keeps declining rather slowly, meaning that it takes a longer time to reach the end position.

Section 4: Valve Closed 14-16 Seconds

The last section shows the old test finally reaching the actuator spring endpoint and fully closes. The difference in closing time between the new test and the old test is about two seconds, which might be the difference between an accident and safe operation.

Test conclusion:

In this test only the sensor for actuator pressure has been used and therefore it is not easy to determine where the failure is located before disassembling the valve and actuator. But it is still possible to detect that something is not as it should be and that there has been some sort of degradation causing a failure mechanism to start occurring. In case study 2 the use of more sensors and the analysis of failure cause will be described.

4.2 Case Study 2

Case study 2 is based on test carried out at the MRC Global test rig. The description of this rig is given in section 3.2.

4.2.1 Solenoid failure detection

Description of test

To illustrate how a valve will react to a blocked exhaust in the solenoid, a adjusteble needle valve was installed. This made it possible to manually adjust the opening of the exhaust of the valve and gives an approximation of how a valve diagnostic system can monitor and detect this type of solenoid failure. All tests were carried out with no system flow, using actuator pressure sensor and strain gauge.

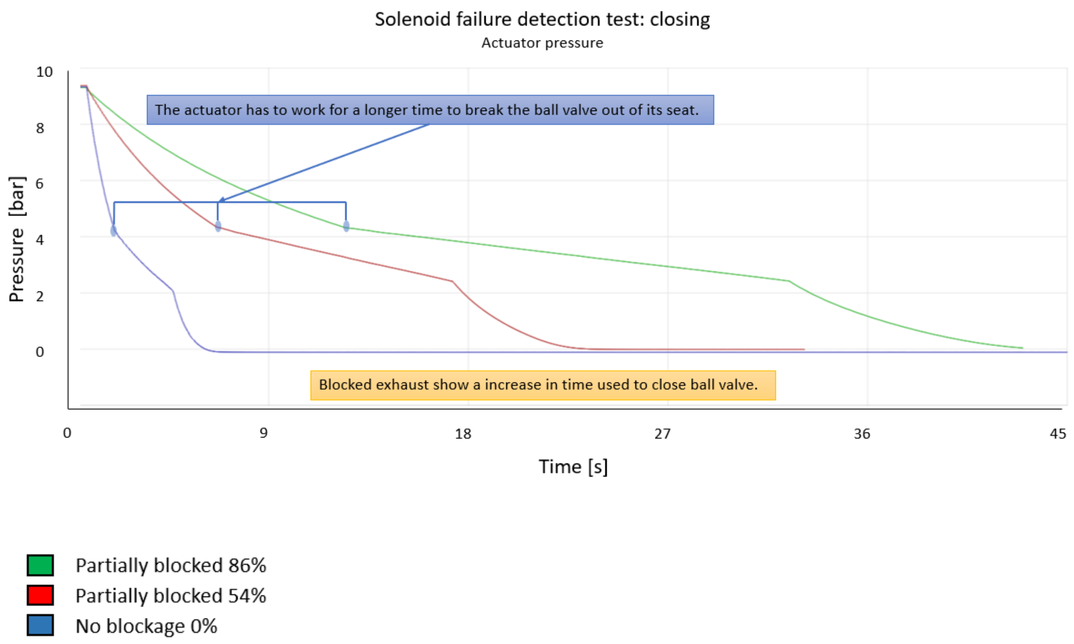


Figure 28 Actuator pressure for solenoid failure detection test

The valve is closing when the solenoid has lost its electrical current and the pressure in the actuator is released throughout the solenoid exhaust.

No blockage 0%

No blockage 0%: This graph shows an normal closing procedure of a valve. With no blockage the pressure in the actuator releases with effectivenes out the solenoid exhaust. The valve starts to close at around 3 seconds and has a closing time of about 7 seconds in total.

Partially blocked 54%

Due to blockage in the solenoid exhaust the air pressure in the actuator will not release as quickly as intended. This results in the piston and the spring moving with a slower pace inside the actuator. Since both the breakout and closing torque are at approximatetly the same actuatore pressure, the force needed is about the same for no blockage as the partly blocked. The difference is that it takes an increased time in order to complete the same steps. Hence the valve starts to move after around 8 seconds and closing time of the valve is increased to about 23 seconds.

Partially blocked 86%

As seen in the graph the closing time of the valve has increased to almost 45 seconds. The reason for this is the same as for the red graph (partially blocked 54%) just with an increased blockage.

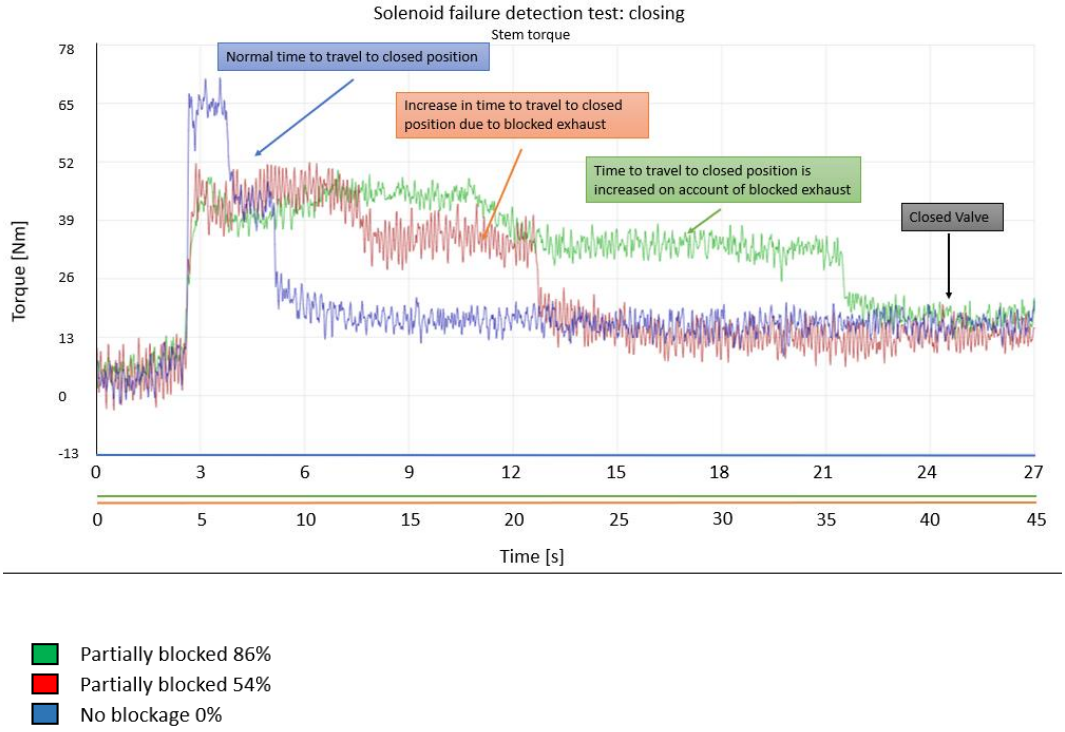


Figure 29 Stem torque for solenoid failure detection test

No blockage 0%

As shown in the graph the torque measured with zero blockage is about 26 nm higher than both of the other tests. The peak of torque occurs due to low counterforce as the supply pressure is rapidly bled of through the exhaust. The three different sections at 3-4 seconds, 4-6 seconds and 6-27 seconds indicates normal activity in both actuator and ball valve.

Partially blocked 54%

To compare the three different tests, the charts is placed on top of each other, hence different timelines which is color coded. Looking at the red chart it is shown that the torque is lower than the blue chart, this is caused by a blockage acting as a counterforce. Every key performance indicator as break to, run to, and end to close takes longer time to achieve due to the blockage on the solenoid exhaust. The actuator spring continuously work and pushes on the piston back into start position.

Partially blocked 86%

The actuator has the same tension and force as in the two other test, but due to blockage the supply pressure in the pressure chamber in the actuator cannot evacuate fast enough resulting in longer tension intervals.

Conclusion of failure

The use of both the pressure and stem torque sensors makes it is possible to identify what and where the failure of the solenoid lies. As shown in figure 21 (DC Overview), a failure of blocked exhaust is detectable by these sensors. In addition to the sensors used in this test, positioner, and position transmitter is also beneficial to strengthen the conclusion. The lengthened torque intervals and increased time to reach same steps in the closing process indicates that the failure is blocked exhaust, which may lead to the failure mode DOP (Delayed Operation) or in worst case scenario Fail to Close on Demand (FTC) as shown in the FTA. (figure 4 & figure 6)

4.2.2 Actuator failure detection

Description for test

This test was carried out by implementing a leakage in the actuator. The tests were done with no leakage, 67% leakage and 80% leakage on the actuator while trying to open the ball valve. All tests were done with no system flow, using actuator pressure sensor and strain gauges.

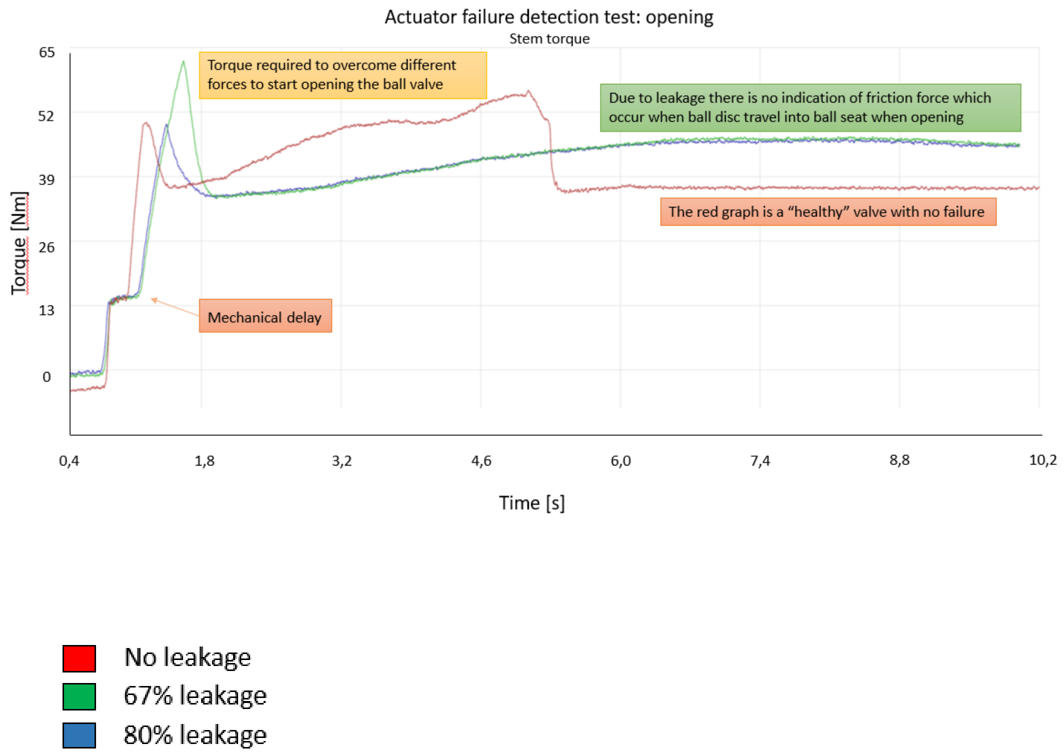


Figure 30 Stem torque for actuator failure detection test

Section 1: Torque Buildup and Valve Motion Starts 0,4-1,8 seconds

In section 1 it is shown a mechanical delay which occur in the valve actuator assembly while the actuator receives the supply pressure and starts to travel. The mechanical delay will cause a point where there is almost no force shown in the chart. The break to open torque in all three cases will be caused by the friction force between the ball disc and ball seat.

Section 2: Valve in Motion and Closing 1,8-6,0 seconds

In the section it is shown that the torque in the red chart has completed both run to open and end to open torque and the valve has travelled to open position. The blue and green chart run to open torque is much longer and continuous throughout this section because of the leakage in the actuator.

Section 3: Valve Closed 6,0-10,2 seconds

The red chart shows a pressure build up at the point where the valve reaches open position. At this point the pressure starts to stabilize. There is no indication of leakage in the red chart line and is considered a "healthy" valve. The blue and green chart is still struggling to overcome the force in the actuator spring and the valve never manages to fully travel to open position. The forces needed from the supply pressure is too low to open the valve due to leakage in the actuator.

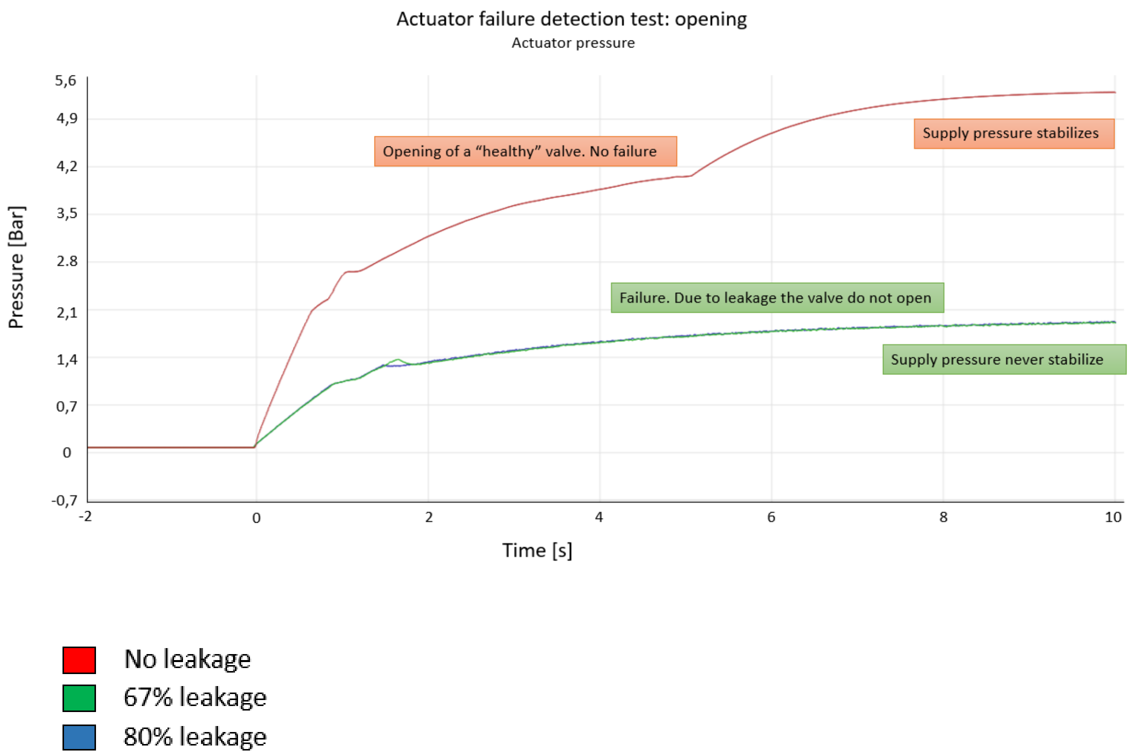


Figure 31 Actuator pressure for actuator failure detection test

Section 1: Pressure Buildup and Valve Motion Starts 0-2 seconds

In this section the break to open pressure is shown. This is the pressure needed to turn the ball valve out of its seat. The red line has sufficient supply pressure and therefor builds up pressure faster. The green and blue line must work for a longer time to get the ball valve out of the ball seat and to start travelling, this because of the leakage in the actuator.

Section 2: Valve in Motion 2-6 seconds

Shown in the chart the green and blue are both in run to open phase throughout the whole section. The red line is in the run to open phase from 2 to approximately 5 seconds. At this point there is a pressure buildup indicating that the valve has started to set into the seat and fully open.

Section 3: Valve Closed 6-10 seconds

In this section the red line has a small pressure build up as the valve has finished to travel and the supply pressure stabilizes. For the green and blue line, the pressure never gets high enough for the valve to travel to open position due to leakage. Shown in chart the run to open pressure is too low.

Conclusion

With the use of pressure and stem torque sensors it is possible to identify what the failure is and where it is located. In addition to the sensors used in this test, visual inspection, acoustic leak and positioner would be beneficial to strengthen the conclusion. The lack of pressure and increased time indicates an external leakage resulting in a FTO (fail to open on demand) shown in the FTA. (figure 4)

4.2.3 Valve failure detection

Description of test:

This test was carried out on a special type of ESD-valve with adjustable sealing seat as described in section 3.2. The test was done in order to see how the valve diagnostic system are able to detect an increase in valve friction. It was carried out by running the test with no seat active, one seat active and two seats active. All tests were done with no system flow, using actuator pressure sensor and strain gauges.

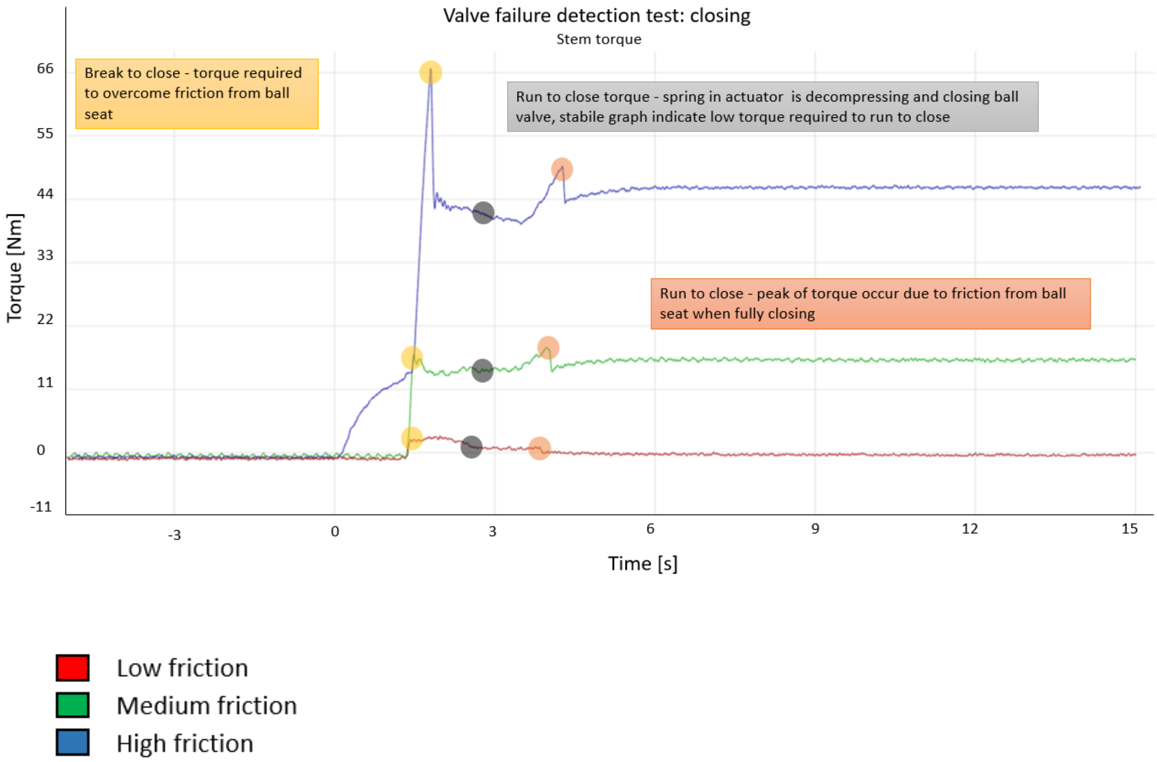


Figure 32 Stem torque for valve failure detection test

Section 1: Torque Buildup and Valve Motion Starts 0-3 seconds

Looking at the low friction graph (red graph) it is possible to see that the breakout (marked in yellow) and closing torque (marked as grey) are rather low and very similar. This is mainly because there is almost no friction with no seat active and most of the extra valve friction often come for the seats.

The medium friction (green graph) is done with one seat active and instantly shows an increase in both breakout and closing torque. It is also possible to see that the breakout torque is higher than the run torque, because of the static friction caused by the seat.

The high friction (blue graph) are when both the seats are active and therefore a drastic increase in torque required to break the ball free and start the motion is shown. It also shows a significantly larger difference between the breakout torque and the run torque compared to the two other cases. This is because the static friction is much higher than the dynamic friction.

Section 2: Valve Closing and Torque stabilizing 3-15 seconds

In this section the low friction graph has a run torque equal to the closing torque, which again is because no seats are active, and the force required to close the valve is therefore the same as to run.

As for the medium friction graph an increase in closing torque is shown. This is because of the increased friction between the ball and the seat when the valve fully closes.

The high friction graph has the same as before a larger increase in torque required to close the valve. This is because the friction increases drastically when having two seats active.

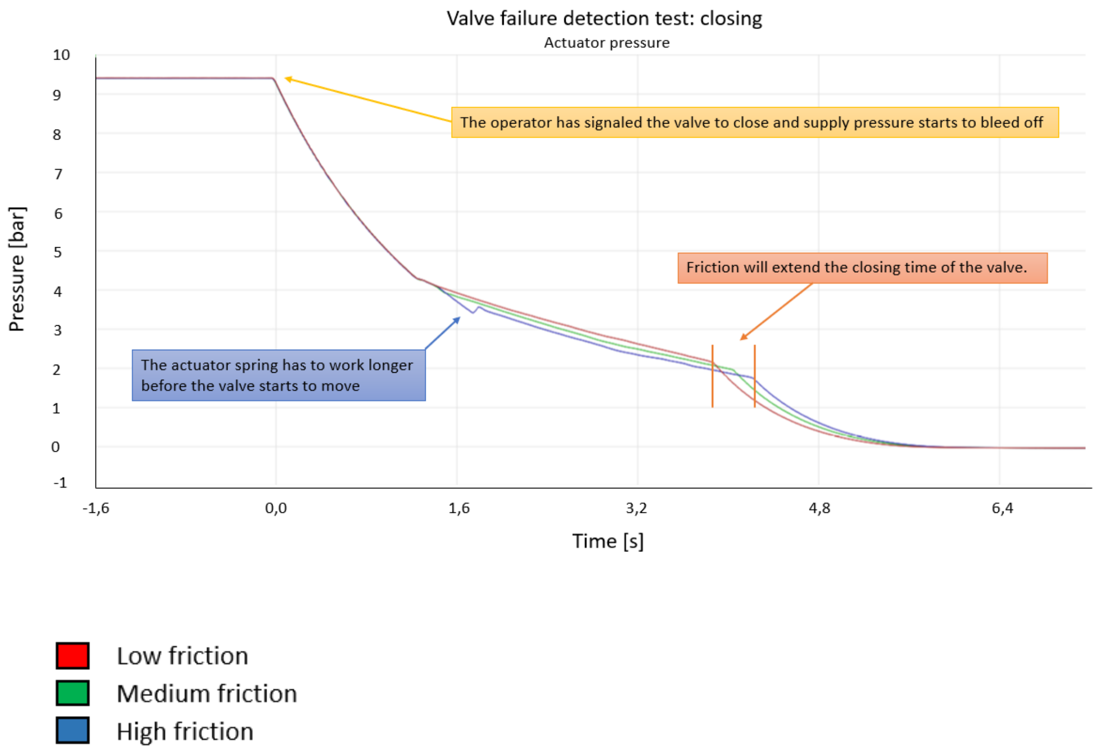


Figure 33 Actuator pressure for valve failure detection test

Section 1: Pressure Drops and Valve Motion Starts 0-2 seconds

In the first section the pressure drop is equal for all the different tests, but at around 1,6 seconds at the point where the valve starts to move a difference is noticeable. In the tests with higher friction it is possible to see a lower pressure and in the case of high friction it is also shown a "dip" because of the increased friction. This again indicates that the torque required is higher as shown in figure 33. Further it is also shown that the run pressure is slightly lowered with the increase in friction, this is also because of the increased torque requirement.

Section: Valve Closing and Pressure drops to Zero 2-6,4 seconds

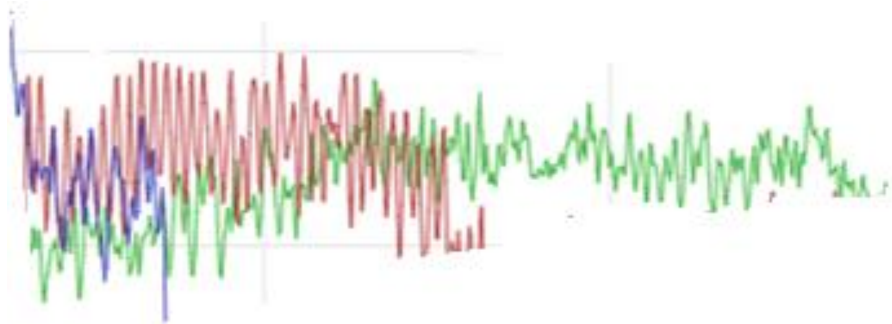
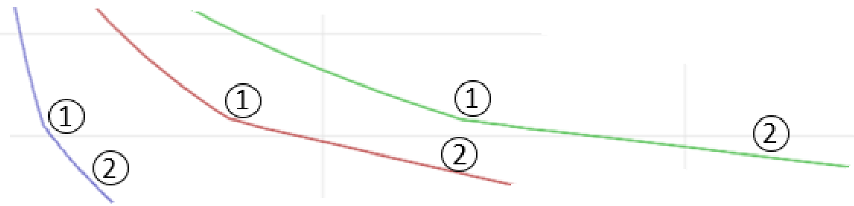
In section 2 a difference is shown in the closing pressure. The increase in torque required for closing the valve fully can also be seen by the increase in time to reach closing point. After, the pressure drops and the valve is fully closed at around 5,5 seconds for all the graphs.

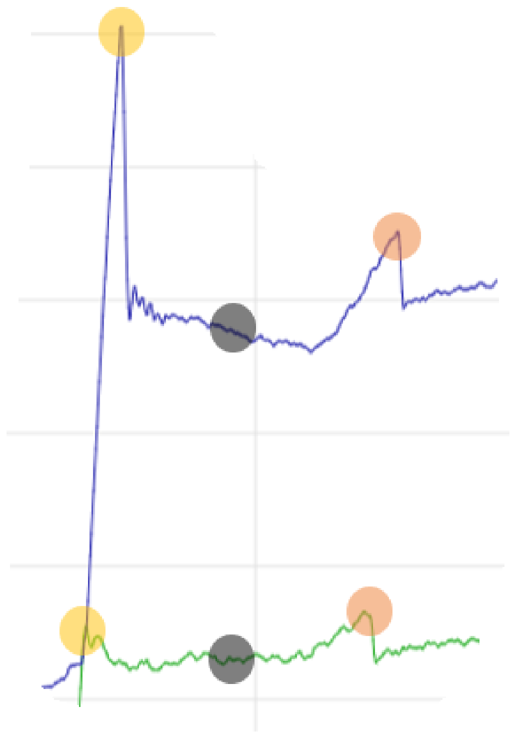
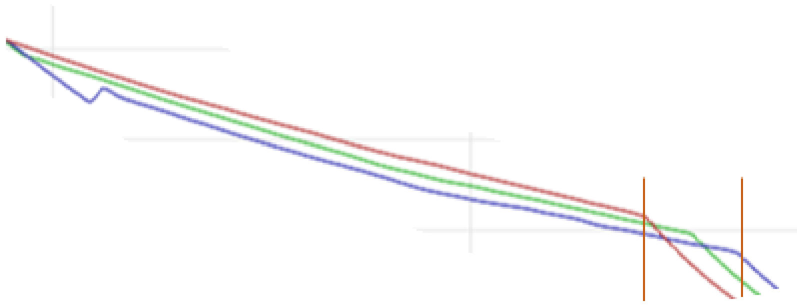
Conclusion of failure

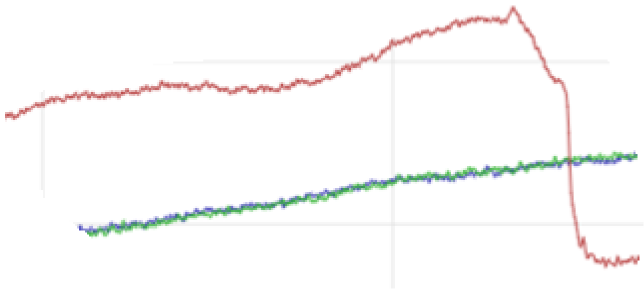
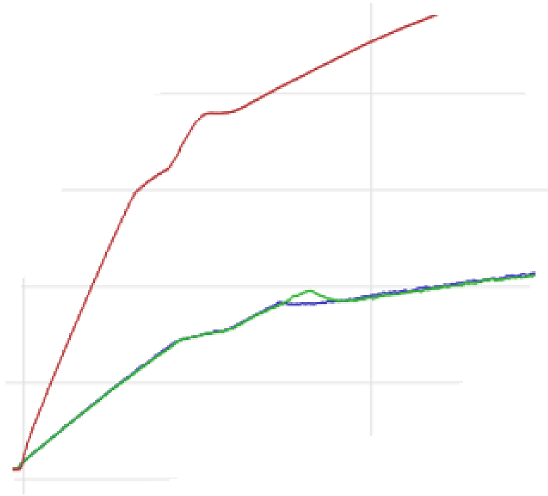
The use of both the pressure and stem torque sensors makes it is possible to identify what and where the failure of this valve is located. As shown in figure 21 (DC), a failure of increased friction is detectable by these sensors. In addition to the sensors used in this test, positioner, and position transmitter is also beneficial to strengthen the conclusion. The increase in torque used and the lengthened and lowered actuator pressure indicates that this failure is due to high friction, which may lead to the failure mode DOP (Delayed Operation) or in worst case to FTC (Fail to Close on Demand). (See figure 4 & 6)

4.2.4 Identification summary of failure causes from case study 2

Table 2 Overview of results from case study 2

Failure cause	Operating parameter	Description of anomaly	Examples	Notes
Blocked Exhaust	Stem Torque	Torque active time stretched		The area of which the force is in affect, is strectched out as seen in the example. This is because the actuator pressure releases slower, meaning the spring needs to work longer. Length of the green graph is 2x longer than the red.
	Actuator Pressure	Pressure drops slower		The time to reach the same point in the closing process takes longer time as shown.

Higher/Increased friction	Stem Torque	Increase in torque value for: Break/Run/End to close force		The torque required to start motion, run the valve and close the valve is increased overall.
	Actuator Pressure	Lower pressure and increased time		The actuator pressure is lower, and the closing point takes longer to reach with an increase in friction.

Actuator leakage	Stem Torque	Torque never builds up to reach the force required to fully open the valve		Because of the actuator pressure being too low, the piston will not have enough force to fully open valve.
	Actuator Pressure	Pressure does not build up and evens out at too low pressure.		The pressure in this test is approximately 2 bars too low for valve to fully open.

5. Discussion

In this chapter the normative approach of today will be compared versus the method with application of industry 4.0 concepts in regard to the valve reliability. The method that provides the best comparison is to look at the diagnostic coverage with the current practices of analysis valve reliability compared to the use of CPS such as valve diagnostic system.

5.1 Comparison of diagnostic coverage

An overview of DC on ESD-valve assemblies is shown in figure 21. The figure shows a total of 29 failures, where 21 of these are fully covered by the diagnostic system and five are partly covered. In this calculation the fully covered failures are numbered as one and the partly covered is numbered as 0,5. Using formula 1. in section 2.8.1 gives the following DC:

$$DC_{avg} = \frac{DD}{DU + DD} = \frac{23{,}5}{29} = 0{,}8103 \approx 0{,}81$$

The DC on an ESD-valve based on current practices and no CPS, then figure 21 shows a total of five fully covered failures and four partly covered, which gives the following DC:

$$DC_{avg} = \frac{DD}{DU + DD} = \frac{7}{29} = 0{,}2413 \approx 0{,}24$$

A coverage of 82% is defined as “Medium” coverage according to IEC 61508-6 (1997, p.50), but compared to the diagnostic coverage of the current practices which is at 24 %, this is a significant increase. Hence it is possible to detect more failures, and this results in an increase of valve reliability.

6. Conclusion and further research

In this chapter the conclusion in regard to the application of industry 4.0 concepts will be drawn and a recommendation for further research is given.

6.1 Conclusion

A large part of the safety instrumented systems in the oil & gas industry are valves such as ESD-valves. As mentioned earlier the importance of these to maintain their function is vital, because they function as safety barriers for prevention of severe accidents. Therefore, the thesis focused on the most common failures from OREDA and how the industry 4.0 concepts such as CPS and IIOT would help increase the detection of these failures. The two case studies carried out during this thesis helps to understand how these concepts will work within the valve reliability verification. As seen in case study 1 the use of valve diagnostic systems monitors the different operating parameters and gives an indication of the valve performance. The second case study shows example of failures and how to detect them and the causes through interpreting valve diagnostic data. By comparing the diagnostic coverage with using a valve diagnostic system against the normative approach of manual proof of function test, the DC will increase by 57%. Based on the case studies and the comparison of DC it can be concluded that the implementation of CPS and IIOT in the form of valve diagnostic systems will considerably increase the reliability and the detection and localization of failures.

6.2 Further Research

For further research it is recommended to look at:

1. How to improve the automated alarms that may be implemented into the valve diagnostic software.
2. Carry out more tests in order to determine what parameters indicates different failure causes.
3. Look at the implementation of more sensors into the valve diagnostic system in order to increase the DC.
4. How the incoming valve diagnostic data should be organized and stored.
5. How the implementation will affect the economical aspect.
6. Create a further link between FTA and overview of sensor coverage

References

1. Boyes, H., Hallaq, B., Cunningham, J., Watson, T. *The industrial internet of things (IIOT): An analysis framework.* Computers in Industry 101, 2018. p. 1-12. <https://doi.org/10.1016/j.compind.2018.04.015 >
2. Gobbo Jr., J.A., Busso, C.M., O. Gobbo, S.C., Carreão, H. (2018) *Making the links among environmental protection, process safety and industry 4.0.* Process Safety and Environmental Protection 117, 2018. p.372-382. <https://doi.org/10.1016/j.psep.2018.05.017 >
3. Hale, S. (2017) *ValveWatch Real Time Valve Monitoring Matures Exactly When Needed* [Internet]. MRC Global. Available from: <http://ebrochure.mrcglobal.com/ValveWatch/html5forpc.html?page=0> [Read: 26.04.2019]
4. IEC 61508-2 (2000). *Requirements for electrical/electronic/programmable electronic safety-related systems.* Functional safety of electrical/electronic/programmable electronic safety related systems. Rev 1. Geneva: The International Electrotechnical Commission (IEC). p. 3-143
5. IEC 61508-6 (1997). *Guidelines on application of part 2 and 3.* Functional safety of electrical/electronic/programmable electronic safety related systems. Rev 4. Geneva: The International Electrotechnical Commission (IEC). p. 1-79.
6. Kelechava, B. (2016) *Valves in smart manufacturing* [Internet]. USA: American National Standards Institute (ANSI). Available from: <https://blog.ansi.org/2016/04/valves-in-smart-manufacturing/> [Read: 26.04.2019]
7. MRC Global (2019) *How it Works* [Internet]. Available: <https://www.mrcglobal.com/Global-Region/Products/ValveWatch/How-It-Works>. [Read: 25.04.2019]
8. OPC (2019) *What is OPC* [internet]. The Industrial Interoperability Standard. Available from: <https://opcfoundation.org/about/what-is-opc/> [Read: 28.04.19]
9. Pereira, A.C., Romero, F. (2017) *A Review of the meaning and the implications of industry 4.0.* Manufacturing Engineering Society International Conference, 2017. p. 1206-1214. DOI: 10.1016/j.promfg.2017.09.032
10. Petroleum Safety Authority Norway (2010) *Requirements for the companies' reporting on barrier performance*. Rev 12. Stavanger: Petroleum Safety Authority Norway (PSA)

11. OREDA (2009) *Offshore reliability data: Volume 1 – Topside equipment.* Høvik: Det Norske Veritas (DNV)

12. Smith, Dr David J., Simpson, Kenneth GL. (2016) *A Straightforward Guide to Functional Safety: IEC 61508 (2010 Edition), IEC 61511 (2015 Edition) & Related Guidance.* The Safety Critical System Handbook, 2016. p.169-186. https://doi.org/10.1016/B978-0-12-805121-4.00009-X

13. The Norwegian Oil Industry Association (2018) *Application of IEC 61508 and IEC 61511 in the Norwegian Petroleum Industry (recommended SIL requirements).* 070/rev 3. Stavanger: Norwegian Oil Industry Association.

Picture references

1. MRC Global (2019) *Acoustic Leak Sensor* [Internet]. Available: <https://www.mrcglobal.com/Global-Region/Products/ValveWatch/Sensors> [Read: 26.04.2019]
2. MRC Global (2019) *Dynamic Leak Sensor* [Internet]. Available: <https://www.mrcglobal.com/Global-Region/Products/ValveWatch/Sensors> [Read: 26.04.2019]
3. MRC Global (2019) *Overview of ESD-valve with sensors*. [Internet] Available: <http://ebrochure.mrcglobal.com/ValveWatch/html5forpc.html?page=0> [Read: 01.05.2019]
4. MRC Global (2019) *Pressure Sensor* [Internet]. Available: <https://www.mrcglobal.com/Global-Region/Products/ValveWatch/Sensors> [Read: 26.04.2019]
5. MRC Global (2019) *Strain Sensor* [Internet]. Available: <https://www.mrcglobal.com/Global-Region/Products/ValveWatch/Sensors> [Read: 26.04.2019]
6. Paladon (2019) *Rotary actuator (Scotch Yoke)* [Internet]. Available: <https://www.google.com/search?q=scotch+yoke+actuator+paladon&safe=off&rlz=1C1NHXL_noNO696NO696&source=lnms&tbm=isch&sa=X&ved=0ahUKEwji0Jbyq5jiAhVohosKHdijCP0Q_AUIDigB&biw=1280&bih=610#imgrc=a6yMVJEMfRsK7M: > [Read: 25.04.2019]
7. Tameson (2019) *Solenoid valve types* [Internet]. Available: <https://tameson.com/solenoid-valve-types.html> [Read: 25.04.2019]

List of Figures

List of Tables

Attachment 1 – Actuator Pressure Sensor Datasheet

MRC Global

Instrument Datasheet
Actuator pressure sensor

VALVEWATCH®

Customer Po: 2214140 & 2214141

TYRA REDEVELOPMENT PROJECT - WHRP

01	16.11.2018	Issued for review	JIG	JOT	AHNE
Rev.	Date	Description	Org'd by	Chk'd by	Appr.
Doc.No.:	DK-TYYY-PIP-DAT-000-10729				

Tag numbers	
Mounted on valve:	Actuator sensor tag
TWEB-ESDV-29001	TWEB-PT-29001
TWEB-ESDV-33001	TWEB-PT-33001
TWBB-ESDV-38021	TWBB-PT-38021
TWBC-ESDV-33001	TWBC-PT-33001
TWBC-ESDV-33001	TWBC-PT-33001
TECB-ESDV-38021	TECB-PT-38021
TECB-ESDV-38011	TECB-PT-38011
TEBB-ESDV-46001	TEBB-PT-46001
TEBB-ESDV-38011	TEBB-PT-38011
TEBB-ESDV-38021	TEBB-PT-38021
TEBB-ESDV-38031	TEBB-PT-38031
TEEB-ESDV-46001	TEEB-PT-46001
TEEB-ESDV-46002	TEEB-PT-46002
TEEB-ESDV-38011	TEEB-PT-38011
TEEB-ESDV-38021	TEEB-PT-38021
TEEB-ESDV-38031	TEEB-PT-38031
TEEB-ESDV-38051	TEEB-PT-38051
TEEB-ESDV-38061	TEEB-PT-38061
TEEB-ESDV-38071	TEEB-PT-38071
TEEB-ESDV-38081	TEEB-PT-38081
TEEB-ESDV-38111	TEEB-PT-38111
TEEB-ESDV-38136	TEEB-PT-38136
TEEB-ESDV-38146	TEEB-PT-38146
TEEB-ESDV-38106	TEEB-PT-38106
TEED-BDV-34014	TEED-PT-34014
TEEC-ESDV-34008	TEEC-PT-34008
TEEB-ESDV-34015	TEEB-PT-34015
TEEE-BDV-38137	TEEE-PT-38137
TEEE-BDV-38147	TEEE-PT-38147

NORSOK	INSTRUMENT DATASHEET P01 **PRESSURE / DIFF. PRESSURE INSTRUMENT ELECTRIC**	

Tag number	: See page 2	Scale Range	: 0-20 bar
Service description	: NA	Set/Alarm Point	: NA
P&ID	: NA	Area	: NA
Line/equipment no.	: NA	P. O. Number	:

1 GENERAL

1.01	Type	: PDCR 5900
1.02	Manufacturer	: GE Druck
1.03	Manufacturer model no	: PDCR59B0-TC-A1-CA-HA-PR-112M5505 0-20Bar SG
1.04	Operating Temp. Limits	: -40 - +80 deg C
1.05	Mounting	: On instrument manifold
1.06	Weight	: 1,03 kg
1.07	Other	: NA

2 INSTRUMENT CHARACTERISTICS

2.01	Calibrated input range	: 0-20barg
2.02	Characteristic	: Linear
2.03	Accuracy	: ± 0,2 % FS
2.04	Repeatability	: NA
2.05	Lower / upper range limits	: 0-20 bar
2.06	Min / max span	: 3,5-20 bar
2.07	Zero adjustment	: NA
2.08	Overpressure protect. to	: 80 bar
2.09	Max static pressure	: 80 bar
2.10	Other	: NA

3 ELEMENT / SENSOR

3.01	Type	: Sealed Gauge
3.02	Material, element (sensor)	: 316L SS
3.03	Material, socket (inlet port)	: 316L SS
3.04	Material, sensor bolts/nuts	: NA
3.05	Process conn. size/type	: NPT 1/2" male
3.06	Sour service spec.	: NA
3.07	Other	: NA

4 HOUSING

4.01	Dimension	: Ø60x97 mm
4.02	Material	: 316L SS
4.03	Cable connection	: Screw termianls
4.04	Cable entry	: M20 female
4.05	Enclosure protection	: IP67
4.06	Ex. classification	: Ex ia IIC T5 Ga
4.07	Protective coating	: NA
4.08	Other	: NA

5 TRANSMITTER

5.01	Indicator	: NA
5.02	Output signal	: 0-100mV at 10V supply
5.03	Communication	: NA
5.04	Supply voltage	: 2,5-12V
5.05	Consumption	: <2mA at 10V
5.06	Load limitation	: NA
5.07	Other	: Output signal 10mV/V supply

6 SWITCH

6.01	Reset; automatic or manual	: NA
6.02	Deadband or differential	: NA
6.03	Alarm at increase/decrease	: NA
6.04	Contact configuration	: NA
6.05	Contact material	: NA
6.06	Contact rating	: NA
6.07	Contact action on alarm	: NA
6.08	Other	: NA

7 CHEMICAL SEAL

7.01	Type	: NA
7.02	Material, upper/lower part	: NA
7.03	Material, bolts / nuts	: NA
7.04	Material, diaphragm	: NA
7.05	Fill fluid	: NA
7.06	Capillary length/diameter	: NA
7.07	Material, capillary/armour	: NA
7.08	Process conn. size/type	: NA
7.09	Other	: NA

8 ACCESSORIES

8.01	Mounting bracket	: NA
8.02	Material, mounting bracket	: NA
8.03	Overpr. protection valve	: NA
8.04	Material, overpr. prot. valve	: NA
8.05	Pulsation damper	: NA
8.06	Material, pulsation damper	: NA
8.07	Other	: NA

9 NOTES

01	16.11.2018	Issued for acceptance	JIG	JOT	ANH	2000298250-A07-DS-0001	3/3
Rev	Date	Issue/description	Prepared	Checked	Approved	Datasheet no.	Page

Attachment 2 – Acoustic Leak Sensor Datasheet

MRC Global

Instrument Datasheet
Leak sensor

VALVEWATCH®

Customer Po: 2214140 & 2214141

TYRA REDEVELOPMENT PROJECT - WHRP

01	16.11.2018	Issued for review	JIG	JOT	AHNE
Rev.	Date	Description	Org'd by	Chk'd by	Appr.
Doc.No.:		DK-TYYY-PIP-DAT-000-10731			

Tag numbers	
Mounted on valve:	Leak sensor tag
TWEB-ESDV-29001	TWEB-ACE-29001
TWEB-ESDV-33001	TWEB-ACE-33001
TWBB-ESDV-38021	TWBB-ACE-38021
TECB-ESDV-38021	TECB-ACE-38021
TECB-ESDV-38011	TECB-ACE-38011
TEBB-ESDV-46001	TEBB-ACE-46001
TEBB-ESDV-38011	TEBB-ACE-38011
TEBB-ESDV-38021	TEBB-ACE-38021
TEBB-ESDV-38031	TEBB-ACE-38031
TEEB-ESDV-46001	TEEB-ACE-46001
TEEB-ESDV-46002	TEEB-ACE-46002
TEEB-ESDV-38011	TEEB-ACE-38011
TEEB-ESDV-38021	TEEB-ACE-38021
TEEB-ESDV-38031	TEEB-ACE-38031
TEEB-ESDV-38051	TEEB-ACE-38051
TEEB-ESDV-38061	TEEB-ACE-38061
TEEB-ESDV-38071	TEEB-ACE-38071
TEEB-ESDV-38081	TEEB-ACE-38081
TEEB-ESDV-38111	TEEB-ACE-38111
TEEB-ESDV-38136	TEEB-ACE-38136
TEEB-ESDV-38146	TEEB-ACE-38146
TEEB-ESDV-38106	TEEB-ACE-38106

NORSOK

INSTRUMENT DATASHEET X01

MISCELLANEOUS INSTRUMENTS

Tag number	: See page 2	Range	: NA
Service description	: NA	Set/Alarm Point	: NA
P&ID	: NA	Area	: NA
Line/equipment no.	: NA	P. O. Number	:

1 GENERAL

1.01 Type	: DSP Leak Monitor
1.02 Manufacturer	: ClampOn AS
1.03 Manufacturer model no	: 930-14211-003
1.04 Operating Temp. Limits	: -40 to +150 deg C
1.05 Operating Press. Limit	: NA
1.06 Complete assembly	: NA
1.07 Mounting	: Clamp to outside of pipe
1.08 Weight	: 3,5 kg
1.09 Other	: NA

2 INSTRUMENT CHARACTERISTICS

2.01 Accuracy	: NA
2.02 Repeatability	: NA
2.03 Other	: NA

3 HOUSING

3.01 Dimensions (ø x h)	: 119 mm x 108 mm
3.02 Enclosure material	: Stainless steel 316L
3.03 Ingress protection	: IP68
3.04 Protective coating	: None
3.05 Cable entry	: 1 off M20 x 1.5 ISO
3.06 Cable gland	: OSCG
3.07 Cable	: Draka RFOU(c) 2pr x 0.75 mm²
3.08 Other	: NA

4 HARDWARE / CERTIFICATION

4.01 Power input(from barrier)	: 12 VDC to 25 VDC(20 VDC typical)
4.02 Power consumption	: 1.5 W (typical) / 2.1 W (maximum)
4.03 Hazardous area	: Zone 0, 1 ,2
4.04 Certification code	: Ex ia IIB T2-T5
4.05 Equipment code	: Ex II 1 G
4.06 EC-type certificate number	: Presafe 17 ATEX 9492X
4.07 Signal output	: RS-485
4.08 RS-485 protocol	: ClampOn proprietary DSP
4.09 RS-485 baud rate	: 19 200 bps
4.10 Other	: NA

5 OPERATION

5.01 Manner of operation	: Real-time measurement
5.02 Technology	: Passive ultrasonic
5.03 Processing	: DSP in sensor unit
5.04 Calibration	: Factory calibrated
5.05 Flow conditions	: Oil / water / gas / multiphase
5.06 Min. detectable leakage	: Liquid: dP >3 bar Gas: dP >1 bar
5.07 MTBF	: >30 years
5.08 Other	: Built-in temperature sensor in sensing tip. Temperature available via OPC

7 NOTES

1 Weight including mounting accessories.
2 ATEX-certified for pipe surface temperature up to +225 °C Temperature class depends on pipe surface temperature. See certificate Presafe 17 ATEX 9492X for details.

3 Operating temperature stated for 15 °C ambient temperature.
4 Leak Monitor supplied with 5 meter cable pre-terminated in sensor, with flying leads for termination in junction box.
5 For use in hazardous area, the sensor has to be powered from an intrinsically safe power barrier according to EC-type examination certificate. Use only an I.S. power barrier supplied or approved by MRC
6 All sensors are calibrated to a master signal at factory.
7 Minimum leakage rate is 0.1 l/min, depending on delta pressure (dP) over the leakage point.

03	20.06.2014	Issued for review	JIG	JOT	ANHE	2000298250-A07-DS-0003	3/3
Rev	Date	Issue/description	Prepared	Checked	Approved	Datasheet no.	Page

Attachment 3 – Position Sensor Datasheet

MRC Global

Instrument Datasheet
Position sensor

VALVEWATCH®

Customer Po: 2214140 & 2214141

TYRA REDEVELOPMENT PROJECT - WHRP

01	16.11.2018	Issued for review	JIG	JOT	AHNE
Rev.	Date	Description	Org'd by	Chk'd by	Appr.
Doc.No.:	DK-TYYY-PIP-DAT-000-10732				

Tag numbers	
Mounted on valve:	Position transmitter tag
TWEB-ESDV-29001	TWEB-ZT-29001
TWEB-ESDV-33001	TWEB-ZT-33001
TWBB-ESDV-38021	TWBB-ZT-38021
TWBC-ESDV-33001	TWBC-ZT-33001
TWBC-ESDV-33001	TWBC-ZT-33001
TECB-ESDV-38021	TECB-ZT-38021
TECB-ESDV-38011	TECB-ZT-38011
TEBB-ESDV-46001	TEBB-ZT-46001
TEBB-ESDV-38011	TEBB-ZT-38011
TEBB-ESDV-38021	TEBB-ZT-38021
TEBB-ESDV-38031	TEBB-ZT-38031
TEEB-ESDV-46001	TEEB-ZT-46001
TEEB-ESDV-46002	TEEB-ZT-46002
TEEB-ESDV-38011	TEEB-ZT-38011
TEEB-ESDV-38021	TEEB-ZT-38021
TEEB-ESDV-38031	TEEB-ZT-38031
TEEB-ESDV-38051	TEEB-ZT-38051
TEEB-ESDV-38061	TEEB-ZT-38061
TEEB-ESDV-38071	TEEB-ZT-38071
TEEB-ESDV-38081	TEEB-ZT-38081
TEEB-ESDV-38111	TEEB-ZT-38111
TEEB-ESDV-38136	TEEB-ZT-38136
TEEB-ESDV-38146	TEEB-ZT-38146
TEEB-ESDV-38106	TEEB-ZT-38106
TEED-BDV-34014	TEED-ZT-34014
TEEC-ESDV-34008	TEEC-ZT-34008
TEEB-ESDV-34015	TEEB-ZT-34015
TEEE-BDV-38137	TEEE-ZT-38137
TEEE-BDV-38147	TEEE-ZT-38147

NORSOK

INSTRUMENT DATASHEET X01

MISCELLANEOUS INSTRUMENTS

Tag number	: See page 2	Range	: NA
Service description	: NA	Set/Alarm Point	: NA
P&ID	: NA	Area	: NA
Line/equipment no.	: NA	P. O. Number	:

1 GENERAL

1.01	Type	: AQ Position monitor
1.02	Manufacturer	: Imtex
1.03	Manufacturer model no	: AQ70S5NR-H
1.04	Operating Temp. Limits	: -40 to +85 deg C
1.05	Operating Press. Limit	: NA
1.06	Complete assembly	: NA
1.07	Mounting	: Actuator - according to NAMUR
1.08	Weight	: 2 kg
1.09	Other	: NA

2 INSTRUMENT CHARACTERISTICS

2.01	Accuracy	: NA
2.02	Repeatability	: NA
2.03	Other	: NA

3 HOUSING

3.01	Dimensions (ø x h)	: 142,5mm x ø120,7mm
3.02	Enclosure material	: Stainless steel 316L
3.03	Ingress protection	: IP66/67
3.04	Protective coating	: None
3.05	Cable entry	: 2 off M20 x 1.5 ISO
3.06	Cable gland	: Hawke 501/453
3.07	Cable	: Draka RFOU(c) 2pr x 0.75 mm²
3.08	Other	: NA

4 HARDWARE / CERTIFICATION

4.01	Hazardous area	Zone 0, 1 ,2
4.02	Certification code	Ex ia IIC T6
4.03	Equipment code	: Ex II 2 G
4.04	EC-type certificate number	: Sira 10ATEX2060X
4.05	Signal output	: Ohm
4.06	Other	: NA
		:

5 OPERATION

5.01	Manner of operation	: Position read out
5.02	Technology	: Potentiomenter, 10k Ohm
5.03	Processing	: NA

7 NOTES

Imtex Type AQ CF3M (316L) Stainless Steel Position Monitor
with 4-20mA Transmitter (Solid State/Non-Contact)
A190036 10k Ohm Potentiometer
2 P&F NJ2-V3-N Proximity Sensors
2 x M20 Conduit Entry, IP66/67, Open / Closed Visual Indicator

01	20.06.2014	Issued for review	JIG	JOT	ANHE	2000298250-A07-DS-0003	3/3
Rev	Date	Issue/description	Prepared	Checked	Approved	Datasheet no.	Page

Attachment 4 – Strain Gauge Datasheet

MRC Global

Instrument Datasheet
Strain gage sensor

VALVEWATCH®

Customer Po: 2214140 & 2214141

TYRA REDEVELOPMENT PROJECT - WHRP

01	16.11.2018	Issued for review	JIG	JOT	AHNE
Rev.	Date	Description	Org'd by	Chk'd by	Appr.
Doc.No.:	DK-TYYY-PIP-DAT-000-10730				

Tag numbers	
Mounted on valve:	Strain gage sensor tag
TWEB-ESDV-29001	TWEB-STT-29001
TWEB-ESDV-33001	TWEB-STT-33001
TWBB-ESDV-38021	TWBB-STT-38021
TECB-ESDV-38021	TECB-STT-38021
TECB-ESDV-38011	TECB-STT-38011
TEBB-ESDV-46001	TEBB-STT-46001
TEBB-ESDV-38011	TEBB-STT-38011
TEBB-ESDV-38021	TEBB-STT-38021
TEBB-ESDV-38031	TEBB-STT-38031
TEEB-ESDV-46001	TEEB-STT-46001
TEEB-ESDV-46002	TEEB-STT-46002
TEEB-ESDV-38011	TEEB-STT-38011
TEEB-ESDV-38021	TEEB-STT-38021
TEEB-ESDV-38031	TEEB-STT-38031
TEEB-ESDV-38051	TEEB-STT-38051
TEEB-ESDV-38061	TEEB-STT-38061
TEEB-ESDV-38071	TEEB-STT-38071
TEEB-ESDV-38081	TEEB-STT-38081
TEEB-ESDV-38111	TEEB-STT-38111
TEEB-ESDV-38136	TEEB-STT-38136
TEEB-ESDV-38146	TEEB-STT-38146
TEEB-ESDV-38106	TEEB-STT-38106

NORSOK	INSTRUMENT DATASHEET X01 **MISCELLANEOUS INSTRUMENTS**	

Tag number	:	See page 2	Range	:	N/A
Service description	:	N/A	Set/Alarm Point	:	N/A
P&ID	:	N/A	Area	:	N/A
Line/equipment no.	:	N/A	P. O. Number	:	NA

1 GENERAL

1.01	Type	:	Strain gage
1.02	Manufacturer	:	MRC Solberg & Andersen AS
1.03	Manufacturer model no	:	4-53100-KT-5000SA-15M
1.04	Operating Temp. Limits	:	N/A
1.05	Operating Press. Limit	:	NA
1.06	Complete assembly	:	Sensor with flying lead
1.07	Mounting	:	Glued to Valve yoke
1.08	Weight	:	0.675 kg w/cable
1.09	Other	:	4-wire

2 INSTRUMENT CHARACTERISTICS

2.01	Accuracy	:	+/- 0.01% FS
2.02	Repeatability	:	NA
2.03	Characteristic	:	Linear
2.04	Output signal	:	µV
2.05	Excitation Voltage	:	3V
2.06	Other	:	See Note 5.01

3 Housing

3.01	Material	:	316SS
3.02	Ex classification	:	Ex ia IIC T4 Ga

4 Electrical

4.01	Connection	:	Moulded sensor with flying lead
4.02	Cable	:	LSHF 2 Pair 24AWG Low Smoke Halogen Free cable
4.03	Wire termiations		Green= signal + Yellow= signal - Brown= EXC + White= EXC -
4.04	Cable Length	:	15 m
4.05	Strain Gage	:	5000Ω - full bridge

5 NOTES

5.01 Output signal is µV.
Excitation Voltage is 3V and output signal will be given as µV based on applied force.

01	16.11.2018	Issued for acceptance	JIG	JOT	ANH	2000298250-A07-DS-0002	3/3
Rev	Date	Issue/description	Prepared	Checked	Approved	Datasheet no.	Page