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MASTER'S THESIS

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Abstract

Subsea implies unmanned work, harsh environmental conditions for the equipment operation and access difficulties in case maintenance or repair is necessary. Therefore operational conditions of subsea equipment should be monitored. Condition monitoring practice is widely used at onshore and offshore production facilities.

Conditional monitoring of subsea assets is quite a fresh area. The way how the signal from the subsea sensor is transferred topside to the computer screen differs from the common practices.

The main aim of this thesis report is to review condition monitoring techniques which are used in today's subsea installations and propose reliable design of condition monitoring system for the subsea plant. Condition monitoring methods like vibration monitoring, sand monitoring for wellhead equipment and subsea separators, leakage detection, corrosion, erosion, water quality and process parameter monitoring are studied in this paper. Afterwards the design of conditional monitoring system is proposed including main subsea and topside equipment which participate in signal transfer from subsea sensor to the topside automation system. Design has to be reliable so that it would work under different circumstances. Moreover topside control system should incorporate condition monitoring functionality for more effective maintenance planning.

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Acronyms and abbreviations

ALD – Acoustic Leak Detection

CAPEX - CAPital EXpenditures

CN – Control Network

CP – Communication Processor

CPM – Condition and Performance Monitoring

CPU – Central Processing Unit

DAS – Distributed Acoustic Sensing

DCS – Distributed Control System

dP – differential Pressure

DSL – Digital Subscriber Line

DSP - Digital Signal Processing

DTS – Distributed Thermal Sensing

EPCU – Electric Power and Communication Unit

ER – Electrical Resistance

ES – Engineering Station

FFT – Fast Fourier Transform

HMI – Human Machine Interface

HSE – Human, Safety, Environment

HV – High Voltage

HVCB – High Voltage Circuit Breaker

IMS – Information Management System

IO – Input/Output

IWIS – Intelligent Well Interface Standardization

LIF – Laser Induced Fluorescence

LSCM – Low-Speed Copper Modem

MBLPC – Mass Balance with Line Pack Compensation

MCB – Mini Circuit Breaker

MCM – Machinery Condition Monitoring

MCM – Manifold Control Module

MCS – Master Control System

MDIS – MCS-DCS Interface Standardization

MMF – Magneto Motive Force

MSM – Modular Switchgear Monitoring

MTBF – Mean Time Between Failures

MTTF – Mean Time To Failure

NDT – Non-Destructive Testing

NORSOK - NORsk SOkkels Konkurranseposisjon (norwegian)

O&G – Oil and Gas

OS – Operator Station

PEC – Pulsed Eddy Currents

PSL – Pressure Safety Low

ROV – Remotely Operated Vehicle

RTD – Resistance Temperature Detector

SAM – Sand Erosion Monitoring

SAS – Safety and Automation System

SCM – Subsea Control Module

SCU – Subsea Control Unit

SDA – Subsea Distribution Assembly

SDU – Subsea Distribution Unit

SEM – Subsea Electronic Module

SIIS – Subsea Instrumentation Interface Standardization

Slb – Slumberger

SN – Server Network

SPC – Subsea Processing Collaboration

SPCU – Subsea Power and Communication Unit

TCP/IP – Transmission Control Protocol/Internet Protocol

TUTU – Topside Umbilical Termination Unit

UiS – University in Stavanger

UPS - Uninterruptible Power Supply

UTA – Umbilical Termination Assembly

VSCM – Variable-Speed Copper Modem

VSD – Variable Speed Drive

WROV – Work Class ROV

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1. Introduction

Chapter is going to describe subsea environment and which challenges equipment is going to be exposed to. Introduction includes as well problem description, scope of work, goals, methodology and delimitations of the master's thesis.

1.1 Problem description and background

People need recourses especially oil and gas to satisfy their basic daily needs, like, heating of houses, food cooking, driving a car and so on. Annually oil and gas production from already discovered fields decreases. New technologies which improve the oil recovery make production more effective however the production peak of oil and gas is in the past. People are seeking new oil and gas recourses in the remote areas or at deep sea. Subsea environment has a certain characteristics which creates difficulties for oil and gas production:

- **Seawater darkness**. The sun light cannot penetrate deep enough as most of the light is absorbed by the sea water. At 150 m depth 99% of solar radiation is absorbed, after reaching 200 m the light stops penetrating causing complete darkness. All maintenance activities which are carried out with the help of ROV should have sufficient lighting to provide a good overview for the operator. At the same time sea water absorbs almost all electromagnetic frequencies: they cannot penetrate deep enough. That is why sound is used as a wireless data carrier: "*sound waves can carry information much further than electromagnetic waves underwater*" (the Maritime Foundation, 2008).
- **High pressure at the seabed**. According to the Maritime Foundation (2008) "*every 10 meters of depth is equivalent to approximately one extra atmosphere. This means that, at full ocean depth, anything which cannot stand the pressure (including a person) must be housed in something that will withstand 1,100 times atmospheric pressure, or approximately 11,000 tons per square meter.*" Therefore equipment should be designed in a way so that it can withstand such enormous pressure.
- **Low temperature of the deep water**. Sun heats up only the top layer of the sea water and within this layer water (approximately up to 500 m) is mixed by wind and wave forces. Further layers of the sea water are horizontal with an equal density. There is no mixing between the layers and average temperature here is 0-3°C. That is why at the seabed there is a very low temperature. Low temperature which is still above the water

freezing point and high pressure causes the risk of unwanted hydrate formation in flowlines and transport pipelines.

- **Water saltiness**. Seawater contain in average 3% of salt, i.e. 1 kg of sweater contains around 35 g of salt. Salt in the sea water speeds up the oxidation of the metal as it attracts water and accelerates capabilities of water to transfer electrons from one substance to another which leads to corrosion. Corrosion for subsea industry is one of the major issues as it damages subsea equipment. Underwater pipelines also suffer from corrosion. Electric heating of flowlines is often used to avoid hydrate formation. However electrically charged pipelines increases the risk of corrosion.
- Among the other features of subsea environment are **water currents** and **earthquakes** which are also present at the seabed.

Underwater environment differs from onshore, that is why people are in the process of developing new solutions and technologies which can withstand harsh environment, high pressure, low temperatures and unmanned operations. Subsea technology is one of such examples. It deals with the oil and gas recovery at the sea bottom, i.e. all preliminary oil and gas recovery and processing are made at the seabed and afterwards oil and gas are pumped to the nearest production facility through the pipeline. Subsea processing brings many advantages: reduced CAPEX due to absence of topside, more effective and efficient exploration of oil and gas, increase of the inner pressure of the brownfields, opportunity oil and gas exploration in deep water fields and field with the long tie-back distance.

Equipment installation and maintenance at the sea bottom is very expensive: ones it is installed, inspection and maintenance cost increases exponentially. Any possible problems with subsea equipment, production shutdowns are unwanted and need to be avoided. **Condition monitoring and management of the subsea production installation** is one of the possibilities which helps to keep oil and gas production ongoing and to avoid time and money lost for the companies.

Conditional monitoring includes acquiring the data from the different subsea sensors which are installed together with other equipment at the seabed, analyzing this information at the topside facility and plan the maintenance activities. Any small deviation of pressure may alert maintenance engineer that some part of the equipment needs to be changed. Necessary spare part and services should be ordered and included in the plan for the next maintenance activities for subsea installation.

There is no constant access to the subsea facilities. Information about what is happening underwater, at what conditions oil and gas processing is ongoing and what is the status of the most critical equipment can be obtained only by means of conditional monitoring and management.

Subsea conditional monitoring is a very profitable area for both technology supplier and a customer. Good conditional monitoring system saves lots of money for the oil and gas operators as it provides information which helps to create an effective maintenance plan. Imagine if a faulty equipment parts would not be changed on time at subsea plant, this could lead to the production shutdown which in-turn causes production downtime, underwater repair expenditures which cost a lots of money.

However not all conditional monitoring methods which is used onshore are applicable for subsea installation. **Therefore the problem of this thesis is to identify, make a survey and evaluation of available technologies and suggest a conditional monitoring system design for subsea plant.**

1.2 Scope and objectives

The scope of thesis is to review available conditional monitoring practices applicable for subsea industry, investigate how they are used in the real live with the subsea equipment, which faults can be detected with the help of these techniques.

The main objective of the thesis is to suggest reliable condition monitoring system design of the subsea processing plant based on the research data. It is going to be done through the following activities:

- Survey and review of the available onshore maintenance practices
- Survey and review of the available technologies for condition monitoring of subsea equipment
- Overview of subsea equipment which is used in subsea oil and gas processing and relevant failure modes
- Overview of available standards for subsea condition monitoring system design
- Formulation of reliable basic design of condition monitoring system including topside integration.

1.3 Delimitations

The following delimitations apply for this thesis:

- During the design of condition monitoring system for subsea plant subsea the main focus is set to subsea control and electrical system; hydraulic supply is briefly mentioned in Chapter 4.2.1
- Effects of underwater currents and seismic activity are not taken into the account during the system design
- The system design is based on ISO, IEC and NORSOK standards
- Amount of available literature and sources is limited to UiS library services.

1.4 Methodology

The master's thesis is based on the following research methods:

1. Literature research. This method was selected because:
    a. It allows familiarizing and understanding conditional monitoring methods used by other researchers
    b. It gives opportunity to learn advantages which can be included into the design and disadvantages which needs to be avoided
    c. It opens other areas which might be forgotten, gives ideas for the thesis and makes it more multilateral
    d. It increases the credibility of the thesis.
2. Interview method. Engineers from oil and gas industry (operators working with remote monitoring of subsea wells, experts from subsea and automation service companies) were questioned to investigate more details about the subsea field equipment, to confirm the findings from literature research and to get familiarized with the better industrial practices (if available).
3. Discussions with university supervisor. Feedback and advices helped to make work process more effective.
4. Siemens internal documentation is another source of information.

1.5 Structure of the report

The thesis has a following structure:

Chapter 1 **Introduction**	Chapter includes problem description and common practices, scope of work, goals, methodology and delimitations of the master's thesis.
Chapter 2 **State of the art**	Chapter describes common maintenance practices for topside and condition monitoring methods which are applicable for subsea industry and equipment which they can be used with. Overview of available suppliers which provide instrumentation and subsea survey was made. In the second part of chapter subsea plant equipment and failure modes of subsea processing and power supply equipment were listed.
Chapter 3 **Methodology**	Chapter describes methods which selected to create a design of reliable condition monitoring system for subsea plant and main design considerations including relevant standards, HSE (Health, Safety, Environment), human factors, etc.
Chapter 4 **Case study**	Chapter describes the design of condition monitoring system for subsea plant, including subsea and topside parts, electrical supply of subsea plant and Safety Automation System (SAS). Chapter also tells us about how to obtain design reliability and how to use condition monitoring system together with maintenance planning. At the end there are mentioned some of today's challenges related to subsea conditional monitoring.
Chapter 5 **Conclusive remarks and future work**	Chapter provides conclusive remarks of the master's thesis and describes some suggestions regarding the work which is found to be important for subsea conditional monitoring and topside control system development.

2. State of the art

In this chapter we are going to review different condition monitoring practices which are used in subsea industry. Then we are going to look at available topside solutions for condition monitoring, typical subsystems and equipment of subsea processing plant and failure modes of some electrical and process equipment for subsea.

2.1 Periodic and condition-based maintenance

Periodic maintenance schedules maintenance tasks when a certain amount of equipment operational hours has elapsed (Figure 2.1). This number of hours for machine's "healthy" operation is based on the Mean Time To Failure (MTTF). According to thefreedictionary.com MTTF is "*a measure of reliability of a piece of equipment, giving the average time before the first failure*". MTTF is based on statistical measurements. Figure 2.1 shows examples of how the periodic maintenance can be planned based on MTTF:

- Maintenance plan #1: *T*(maintenance) < 50% of MTTF.

  Too early for corrective maintenance. Most likely within this time equipment will not reach the state when maintenance actions will be necessary. So any maintenance planned during this time will not improve equipment performance, it will just cost money and time for the company.
- Maintenance plan #2: *T*(maintenance) = 50% of MTTF.

  The best time for the corrective maintenance: not too early and not too late, probability that equipment can fail is almost zero. 50% of MTTF is the time that is usually been recommended to carry out the maintenance activities to avoid equipment failures.
- Maintenance plan #3: 50% of MTTF < *T*(maintenance) < MTTF.

  If maintenance is going to be executed during this time then there is a probability that equipment may fail (shaded portion of the graph).
- Maintenance plan #4: *T*(maintenance) = MTTF.

  Too late for corrective maintenance. The probability that equipment may fail is 50% which is very high.

Therefore the best time to carry out maintenance activities is 50% of MTTF. MTTF is a purely statistical data, which means that MTTF is available only for a specific type of machinery or machinery system and equipment load. In reality every plant is unique and has a different process systems and equipment which need to perform a certain type of operations which might not have exact statistical data available. For example, if exactly the same type of pump on one plant is used for water handling, and on the other plant it is used for handling abrasive slurries. Statistical MTTF would be the same, but not practical one even though used pump type is the same in both cases. Pump which handles abrasive slurries would require maintenance service more often than the one which treats water. Such issues are resolved by another maintenance practice called predictive or condition-based maintenance.

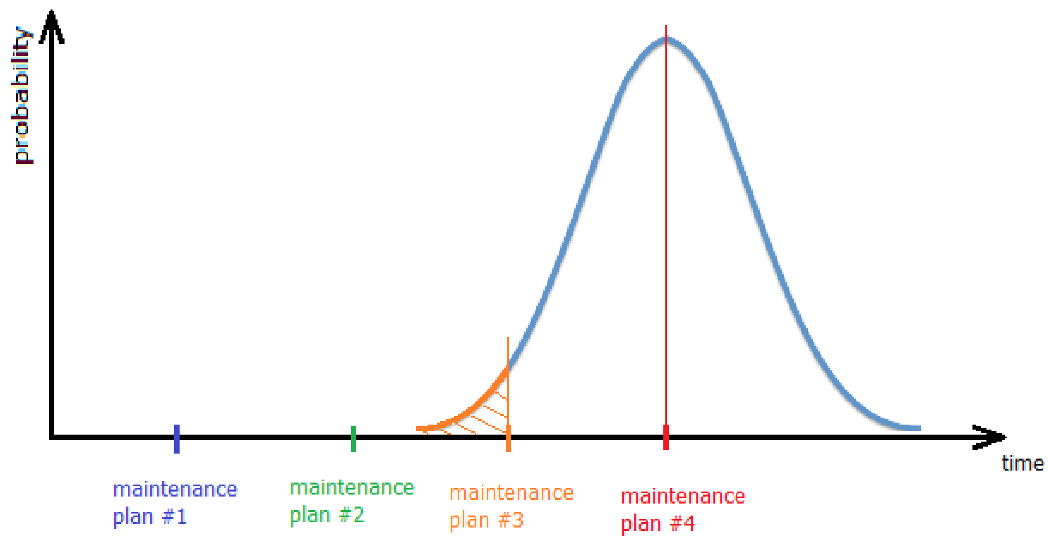


Figure 2.1 Periodic maintenance

Predictive maintenance helps to identify the best time for any maintenance related service; it reduces machines failures, limits unnecessary cost for the maintenance and eliminates production downtime, time and money loss. "*Regular monitoring of the actual mechanical condition, operating efficiency, and other indicators of the operating condition of the machine-trains and process systems will provide the data required to ensure the maximum interval between repairs*" (Mobley, 1990, p.6).

The very simple and clear essence of condition-based maintenance (or *condition monitoring*) consists of three actions: collect the measurements from sensors, compare current and past readings and predict the condition of equipment (Rao, 1996, p.8). In other words condition monitoring approach aims to see how equipment performance changes within the time, predict when it may fail and plan the maintenance based on the collected data from the sensors or visual inspection. To understand this approach a simple example can be considered: the car driver checks from time to time the amount of engine oil available in his car. By monitoring the oil level he can simply evaluate an oil consumption of the engine: he looks at the current oil level in engine, evaluates whether it is sufficient or not, if not he needs to add some more oil. In oil and gas industry different instrumentation solutions (e.g. combination of vibration, corrosion, process monitoring sensors) combined with automation system are used for monitoring purposes. This is a quick, easy and effective way to evaluate equipment performance and plan the maintenance activities. Figure 2.2 shows an example of failure development trend of a system component. In the beginning the component is functioning properly, the trend shows the constant performance. Then we see the three scenarios (Markeset, 2012):

1. *Instantaneous failure*: suddenly component performance converges to zero without any warning. In this case condition-based maintenance will not be useful, as it is not possible to see component degradation in time; <u>only</u> periodic maintenance in this case could help to avoid component failure.
2. *Fast degradation process*: performance of the component slows downs gradually. The condition-based maintenance is applicable here, especially if the component is critical. Maintenance engineer receives an early-warning from the system so that he can start planning the maintenance.
3. *Slow degradation process*: performance of the component slowly converges to zero giving a good time for the maintenance personnel to plan and carry out the maintenance. Both periodic and conditioned-based maintenance can be used in this case.

There are several methods available for conditional monitoring. The most common non-distractive condition monitoring methods which are used onshore and offshore are:

- Vibration monitoring
- Process parameter monitoring
- Thermography
- Tribology
- Visual inspection.

Condition monitoring program should be selected individually for every plant. There is no effective solution which is available and which would suit every industry or factory. The optimal solution for mechanical machinery usually based on vibration monitoring, however for electrical equipment thermographic or infrared scanning is necessary (Mobley, 1990, p.45). It is very common to combine different condition monitoring techniques. For example, vibration and process parameter monitoring can be selected as a basis because it allows automated data management, trending, analyzing and reporting from the single location – operator station in control room at offshore platform or onshore facility. At the same time secondary condition monitoring techniques can be used like visual inspection, and tribology. The term "*secondary*" in this case means to carry out these services periodically, in addition to primary ones and by the professional vendor company. Visual inspection can be useful to detect leaks, loose mountings, structural cracks; tribology can be used in case there is known chronic problem in the plant machinery; otherwise these methods are not cost-effective (Mobley, 1990, pp.43-46).

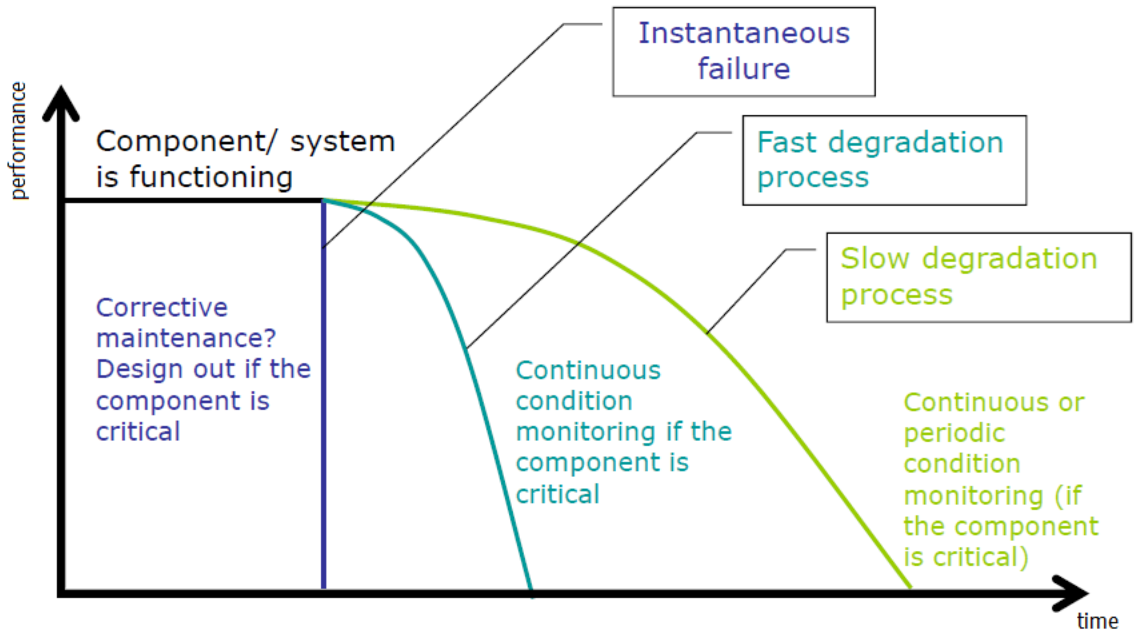


Figure 2.2 Example of failure development trend (Markeset, 2012)

In order to select the right predictive maintenance system, plant management should know the following:

- Evaluate which components, equipment and systems needs to be monitored
- Identify the main failures for these components, equipment and systems
- Find the causes, effects and consequences of each failure
- Select the cost-effective software and hardware system for the plant needs and choose the best condition monitoring approach
- Evaluate how often the monitoring data is required to identify the best maintenance repair intervals

- Identify the features which automation systems should have in order to support the condition monitoring program (for example, trend logging, accuracy, reliability, alarm handling, user-friendly HMI interface)
- Cost should be taken into the account while deciding the final solution for conditional monitoring (Moreno-Trejo, et al., 2012, p.458).

Subsea environment limits the selection of condition monitoring techniques. In addition to the usual maintenance principles used for onshore and offshore facilities subsea maintenance implies the following:

- "*All active or pressure containing elements of the systems should be maintainable*" (Koch and Charters, 1990, p.36).
- All maintenance activities should be <u>unmanned</u> meaning that monitoring sensors which transfer data to the automated management system and ROVs (Remotely Operated Vehicles) should be preferably used to monitor equipment conditions.

The use of visual inspection together with subsea is very limited: it can be utilized before equipment installation to identify loose mountings and structural cracks or when equipment is already in use with the help of ROVs.

In the next chapter we would have a closer look which condition monitoring methods are used in subsea industry.

2.2 Condition monitoring methods for subsea industry

Subsea equipment systems should be treated as critical as they are located at the seabed and require very expensive underwater operations. That is why any unexpected equipment failures need to be avoided. The cost of the preventive measures often is much cheaper than production loss together with unscheduled subsea intervention activities. Therefore condition monitoring approach has been used to monitor condition of the subsea equipment and system in general to plan maintenance properly and eliminate unwanted downtime.

As it was mentioned in the previous chapters the most popular conditional monitoring methods for subsea industry are whose which provides remote monitoring as it is not so easy to reach subsea equipment and check what is wrong with it; for this purpose the special services need to be ordered, like ROV inspection. Particularly the sensor which is installed at some equipment at the sea bottom makes measurements and sends them to the operator and maintenance station located at offshore facility or onshore. Sensors in this case become eyes, ears, nose and mouth of the equipment, which tell the operators and maintenance engineers whether equipment is healthy or needs some repair.

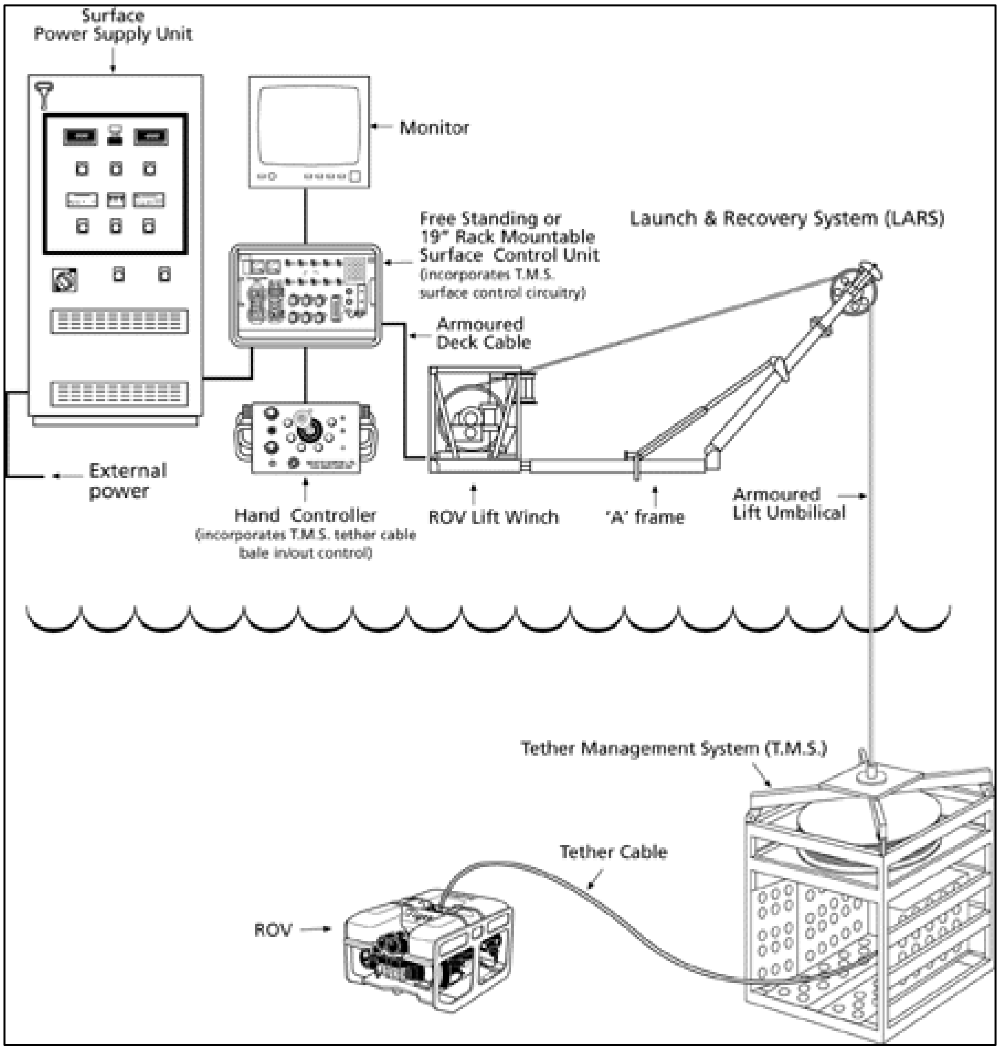


Figure 2.3 ROV (Odland, 2011)

Visual inspection can be also used in subsea with the help of Remotely Controlled Vehicles or ROVs (Figure 2.3). ROV is an unmanned underwater robot, which is very maneuverable and can be controlled by the person from the board of a vessel. It is linked to the vessel by a tether which is a type of umbilical cable that sends electrical power, data signals and video stream back and forth between the operator and ROV. The ROV is equipped with at least one camera and lights which give the operator possibility to see the underwater equipment: robot lightens the dark areas on the seabed and camera records and transfers the pictures up to the operator through the umbilical. That is how visual inspection of the subsea processing plant can be performed.

Another type of conditional monitoring method which can be used in subsea is Non-Destructive Testing (NDT). NDT of subsea equipment is useful in case there is a suspicion that there is equipment failure or for regular monitoring as for example pipeline scan to identify possible cracks. This can be also performed with the help of ROV (Figure 2.11).

In the following chapters we are going to review the following condition monitoring techniques for subsea:

- Vibration monitoring
- Subsea specific monitoring techniques (sand, corrosion and leakage detection, etc.)
- Process parameter monitoring.

2.2.1 Vibration monitoring

Theory behind the method

Vibration stands for "*the oscillation or repetitive motion of the object around the equilibrium position. The equilibrium position is the position the object will attain when the force acting on it is zero*" (White, 1997, p.9). Different components of the mechanical equipment can produce vibrations which all together forms vibration signal. Over the time vibration signal is recorded and time domain graph is formed which is later transformed into the frequency domain by the means of spectrum analysis (Figure 2.4). Vibration spectra shows different frequencies which corresponds to the different types of faults (Figure 2.5).

Vibration monitoring helps to identify the wide range of problems, such as imbalance or misalignment of equipment, fatigue detection in equipment or structures, influence of external force (e.g. electric or hydraulic), component looseness, resonance, etc.

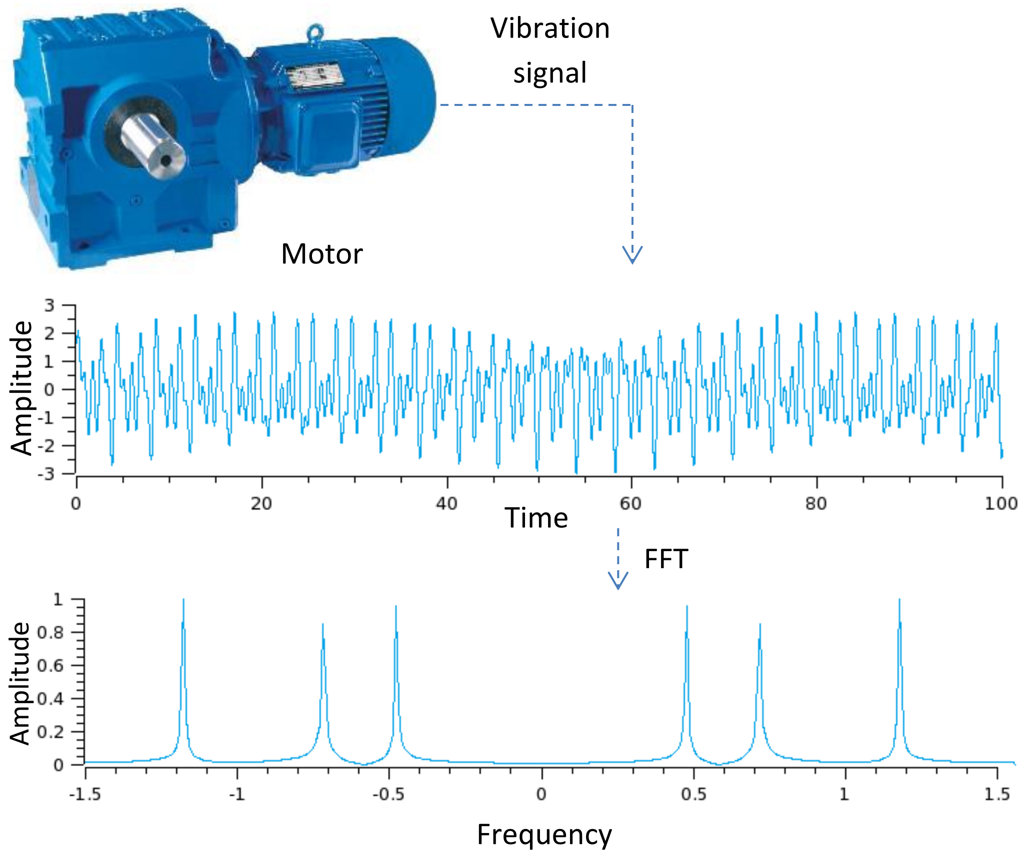


Figure 2.4 Example of spectrum analysis

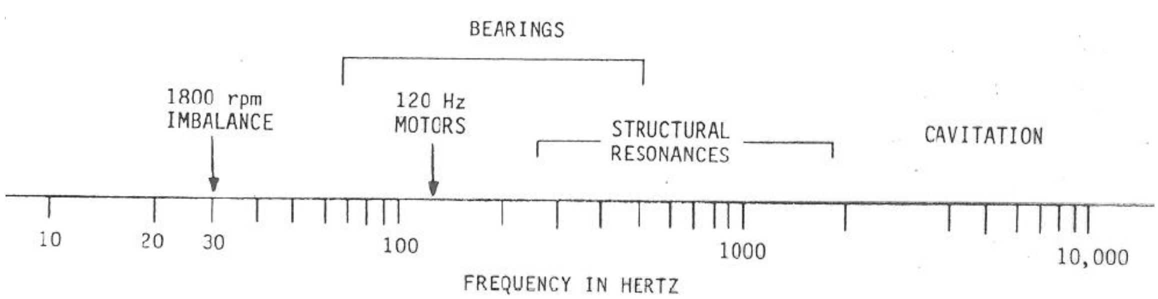


Figure 2.5 Interdependence between the frequency and equipment components (Markeset, 2012)

Application in subsea

There is large scale of application of vibration monitoring method at subsea plant. Eriksson and Staver (2010, pp.5-7) have briefly described the concept of condition monitoring of Ormen Lange subsea gas compression pilot. They mentioned the following subsea equipment where vibration monitoring sensors were installed:

- All mechanical machinery as, for example, pumps, compressors, etc.
- Steel structures for every subsea module to monitor structural vibrations
- Variable speed drives (VSD)
- High Voltage Circuit Breaker (HVCB)
- Uninterruptible Power Supply (UPS).

Sensors that are used with subsea equipment are generally less sensitive than topside ones as they are encapsulated to withstand the high pressure.

In addition vibration monitoring sensors are used at flowlines and pipelines to monitor flow induced vibrations. That is why some vibration sensors help to detect leaks (Chapter 2.2.2).

It is a good practice to combine vibration monitoring of equipment together with some process measurements, as sometimes vibration represents the effect caused by some process related issue. For example, compressor low suction pressure causes the high vibration of magnetic bearing that is why it is good to monitor compressor bearing's vibration together with the suction pressure.

Technology suppliers

ClampOn produces ultrasonic non-invasive vibration sensors for subsea industry. Sensors can be used at flow lines, jumpers, rotary machinery and subsea structures. Each vibration sensor integrates two measurement principles (clampon.com):

- Ultrasonic element captures shear waves caused by the metal friction (frequency range 1024 – 262 144 Hz)
- Accelerometer measures 3D vibrations (frequency range 0.125 – 1 000 Hz).

As vibration sensor from ClampOn is able to detect so wide range of frequencies, many faults can be observed at the early development stage.

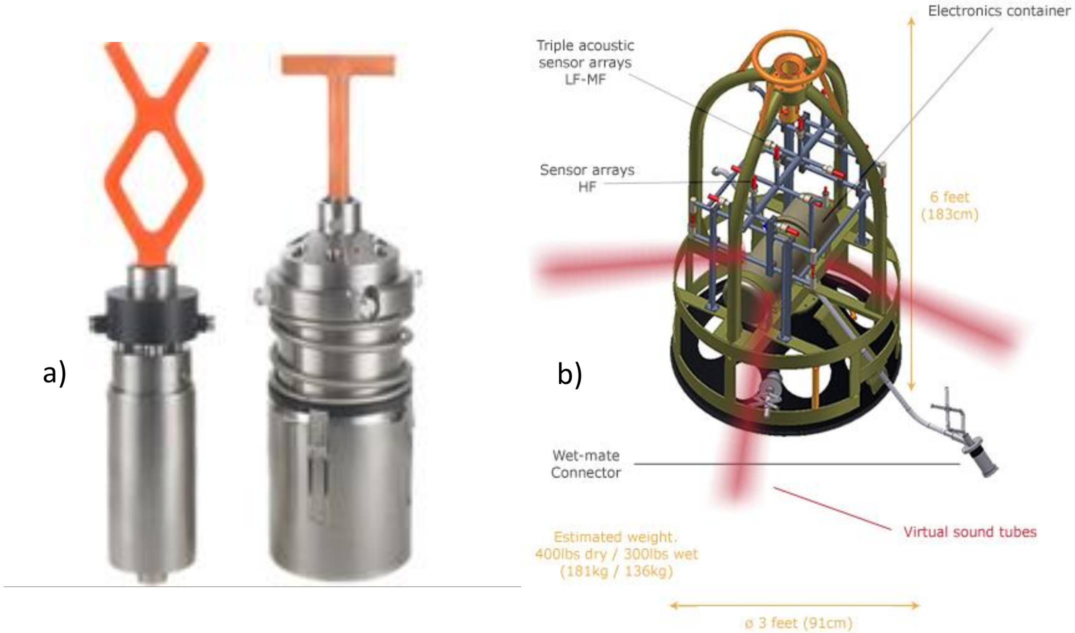


Figure 2.6 a) Subsea vibration sensor from Clampon (clampon.com) b) Naxys Acoustic Monitoring Module with inbuilt vibration sensors (asel-tech.com)

Naxys is a supplier of multi-concept domain (acoustic, electric and magnetic) condition monitoring module with built in vibration and leak detection sensors (naxys.no). This module was installed at Troll Pilot (2001) and Ormen Lange (2005) fields on the Norwegian Continental Shelf.

2.2.2 Leakage detection

Leakage detection for subsea is very important as any hydrocarbon leak directly into the sea will lead to significant environmental consequences and financial expenditures. There are two main approaches how to monitor the leakage of subsea assets. First method is inspection and survey with the help of ROV or "*periodic pig runs with an acoustic sensing tool*" (Eisler and Lanan, 2012, p.2). ROV survey is used at the commissioning stage of subsea facility or to verify and/or localize the suspected leaks. The second method is continuous monitoring with the help of sensors which are directly installed at the subsea pipelines, structures and equipment. This by-turn can be divided at external and internal-type leak detection system. External-type is based on the measurements which takes place outside the pipeline. Dwell on the details on this type of leakage detection system. Vrålstad et.al. (2011, p.103) presented the results of the test of five leakage detection technologies: capacitance sensor, methane sniffer, optical camera, active and passive acoustic sensors. Applicability and limitations of each method were identified. The summary of the test results is presented in Table 2.1.

Table 2.1 Summary of test results of external leakage detection methods (Vrålstad et.al., 2011, p.103)

	Capacitance	Methane sniffer	Optical camera	Active acoustic	Passive acoustic
Gas detection	Very good	Excellent	Very good	Excellent	Very good
Crude oil detection	Good: coalescence problems	n/a	Very good: dependent on background	Limited (lower density difference b/n water and cr.oil)	Good
Area coverage	Dependent on collector	no	3-4m range	yes	Yes
Limitations	Functionality dependent on size and shape of collector	Point sensor: depends on water currents to detect leak	Visibility and turbidity of water is important	Redundant noise (fish, production) affect measurements	Production noise affects measurements. Detection depends on pressure difference.

At this report we need to look closely at passive acoustic technique, as it is can identify both crude oil and gas leaks at the wide area. Passive acoustic leakage detection method is based on the hydrophone sensor, which passively "listens" sounds in water and converts them into electrical signals. As production process also is a source of noise, hydrophones need to filter only specific sound which only typical for a leakage. "*If three or more hydrophones are connected together, the leakage may be localized by triangulation*" (Vrålstad et.al., 2012, p.98).

One of the suppliers of passive acoustic leak detection systems is Naxys (Figure 2.7). Company offers Acoustic Leak Detection (ALD) module which provides wide area leak detection (i.e. within the radius up to 500 m). Module is mainly dedicated for use at templates and flowlines. Besides Naxys supplies hot-spot acoustic sensors which can be installed at x-trees and other critical points of subsea facility. Hot-spot is the area of equipment where leakage is most likely to occur. In addition Naxys' leak detection sensors together with vibration sensors belong to multi-concept domain condition monitoring module which was mentioned earlier in Chapter 2.2.1. Monitoring system lifetime is 25 year with no-maintenance required.

Figure 2.7 Acoustic leak detection from Naxys, left: ALD module (naxys.no), right: hot-spot acoustic sensor (naxys.no)

Another supplier of passive acoustic sensors for subsea is ClampOn. Its product is called the ClampOn DSP Leak Monitor (DSP stands for Digital Signal Processing). It can be used at such critical points on the pipes as valves, flanges, joints, etc. Together with passive acoustic sensor ClampOn supplies a database containing information which helps to identify the leak volume.

Figure 2.8 Acoustic leak sensor from ClampOn (clampon.no).

Moreover in order to detect the leaks at subsea equipment it is often used so called internal leaks detection systems based on the internal monitoring of flow, pressure, temperature and sometimes density. For example, if we know the flow entering the system and compare this value with the flow which is leaving the systems with adjustments of the pressure and temperature measurements then we can estimate whether there is a possible leak in the system. Such process measurements are often used to reduce amount of leak sensors (Chapter 2.2.6).

2.2.3 Sand monitoring

In this chapter we are going to review sand monitoring methods in wellhead equipment and subsea separators.

Sand monitoring in the wellhead

Sand production is one of the main problems during the oil and gas extraction, as it causes erosion damage of the equipment, degradation and even collapse of the reservoir. It is very usual that operator closes choke valve from 20% to 75% (choke valve is a control valve which is used to control the flow of well fluids) and therefore significantly reduces oil and gas production and as the result reduces the revenue since he tries to limit as much as possible sand production and protect the equipment from erosion damage (Aldal, et al., 2003, p.4). Rapid and accurate sand monitoring helps operator to adjust the choke valve setting and increase the production without producing too much sand.

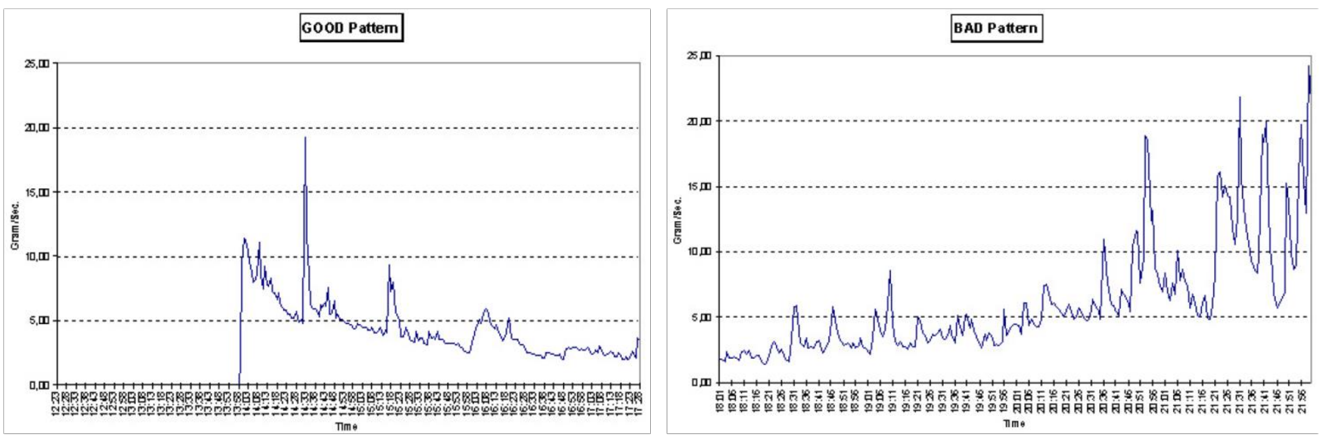


Figure 2.9 Sand monitoring of a production well. GOOD pattern – sand production decreasing, BAD – increasing (Aldal, et al., 2003, p.4)

On Figure 2.9 we can see two situations. The picture shows a "*GOOD pattern*" where sand production is reduced because of consolidation of the reservoir. After a while when the sand production stabilizes operator can again adjust the choke valve and increase the production, that is why we see this sudden growth of sand and then reduction and stabilization. On the other picture we can see exact opposite scenario or a "*BAD pattern*", when sand production continuously increasing. This informs the operator that he needs to limit the production and return to the previous sand-free level. Sand monitoring allows operator to identify the best choke valve settings to produce maximum amount of oil and gas at the sand-free rate.

For sand detection intrusive and non-intrusive techniques are available. Intrusive sand detectors have proven their effectiveness and are preferable for subsea systems, but it is more difficult to install them on the “live” subsea equipment. Non-intrusive sensors provide less accurate measurements, but can be easily installed by ROV (Remotely Operated Vehicle).

The common practice for efficient data acquisition related to subsea sand monitoring is to install the sand sensor directly in wellhead. There are several technologies available for wellhead sand detection. The CorrOcean Sand Monitoring System (SMS) owned by company CorrOcean Srl (subsidiary of Roxar ASA) is one of them. It was installed at Tordis in 1993 and Vigdis in 1996 subsea fields. Technology is based on “*the well-known ER (Electrical Resistance) technique for measuring erosion on thin corrosion resistant sensing elements*” (Skavang and Braaten, 1994, p.11). This technology does not require any on site calibration and provides live monitoring of sand production from the subsea wells. On Tordis sand monitoring is utilized to trace erosion and damages in process systems, piping, valves and fittings (Braaten, et al., 1995). After installation of these sensors the operability was significantly improved, and the operating cost and cost of sand prevention methods were reduced (Skavang and Braaten, 1994).

Second technology for sand monitoring is non-intrusive ultrasonic sensors from producer ClampOn (Aldal, et al., 2003). Sensor registers ultrasonic pulses created by sand or chalk particles when they hit the pipe wall. For these sensors calibration is required as ultrasonic sensor is based on “*listening*” principle and other sound sources influence the measurements. Roxar also supplies the non-intrusive acoustic Sand Erosion Monitoring (SAM) system.

Another technology for sand detection is Distributed Acoustic Sensing (DAS). It is based on a newly developed fiber optic sensing technology which can “*detect acoustic signal anywhere along the length of the fiber with the high frequency response and a tight spatial resolution*” (Cannon and Aminzadeh, 2013, p.1). Spatial resolution tells us how small objects system can detect. DAS pulses laser down to the fiber and records the intensity of back-scattered light. As sand particles together with oil, gas and water travel at the very high speed during oil and gas production, they hit the back of casing creating acoustic energy which can be detected by the DAS. By monitoring this data operator can adjust the choke settings and reduce the wear of the well sand screens. DAS can be used as well for hydraulic fractures and well integrity monitoring, gas-lift optimization, etc. (Cannon and Aminzadeh, 2013, p.3).

Sand monitoring in the subsea separator

The monitoring of sand deposits in subsea separator becomes very important. "*If separator is e.g. filled to 50% with sand, then the effective volume available for fluid separation has decreased to 50%...*" and therefore significantly reduced the production of oil and gas (Eriksson and Kirkedam, 2004, p.1). Besides if there is too much sand which has accumulated in the vessel, flushing system will not work and heavy lift intervention operations would be necessary to empty vessel from sand.

Usually the separator is flushed to remove the sand at the regular intervals. The sand deposit monitoring helps to make the flushing process of the separator more effective. If there is too much sand in the vessel and previous flushing did not remove all of it then flushing power needs to be increased for the next flushing round. At the same time there is a cost associated with every flushing and it is beneficial to flush as seldom and as safe as possible.

It is very difficult to define exactly the area where the sand will accumulate in the separator. Some particles are large and would drop at the inlet. Other particles are lighter and flow would bear them further. Therefore wide area sensing system is necessary to monitor sand deposits in the separator. Based on the data from sand detectors the sand accumulation areas could be identified and the flushing rounds can be planned more effectively. In addition flushing systems can be split into sections to perform flushing of the area with most sand accumulations.

Subsea Processing Collaboration (SPC) project which represents collaboration between BP, ChevronTexaco, ABB and Aker-Kværner carried out a research of the available techniques which detect sand accumulation inside the separators and selected two technologies based on the thermal methods. They are *external temperature sensing* and *internal thermal sensing "HotRod"*. The idea behind external thermal measurement is that "*for a 100° C temperature differential between crude oil and sea water, a 25 mm sand layer will cause a temperature drop of the outside steel temperature (inside the insulation) of appr. 1° C*" (Eriksson and Kirkedam, 2004, p.5). The method requires large amount of subsea sensors (25 sensors per 1 m^2) and it does not work when inside and outside temperatures are equal (e.g. during the shutdown). "Hotrod" method measures the temperature of the resistor which is heated up with the constant power. If resistor is surrounded by water then its temperature would be approximately 5° C, if it is surrounded by wet sand then temperature might reach 50° C. "*There is a very large difference in cooling between convective cooling (where the cooling medium can* *circulate freely) and conductive cooling (where the heat needs to penetrate an insulating sand layer)*" (Eriksson and Kirkedam, 2004, p.6).

2.2.4 Corrosion and erosion monitoring

Corrosion and erosion are one of the main reasons of pipeline fracture. At the seabed corrosion is more rapid as it is stimulated by the properties of salty sea water. In addition many other factors influence the speed of corrosion process, like temperature, pH, water composition, flow velocity, pollution (Ogu, 2012, p.2). All these parameters change with the depth and that is the reason why corrosion development velocity also differs with the depth. Erosion is usually caused by the sand production and its monitoring is partly covered in the Chapter 2.2.3. At the same time corrosion and erosion monitoring can be done simultaneously as both lead to the **fractures and cracks** in subsea assets.

Technologies available for subsea corrosion monitoring

Baltzersen, et al. (2005, p.3) stated that since corrosion is a very slow process, there is not necessary for its steady monitoring, as it is very expensive to create a constant connection to the electric power and communication at the seabed to corrosion sensors. However the monitoring of corrosion is still possible by means of ROV (Remotely Operated Vehicle). In fact corrosion sensors are installed throughout the pipeline, just there is no electric power connected. At a certain intervals ROV temporary connects to the instrumentation, provides electricity and reads ultrasonic measurements. For example, ultrasonic system from Sensorlink AS is able to monitor the wall thickness of the pipes. The system consists of the pipeline clamp and inductive coupler. Pipeline clamp is filled with sensors and other electronics and usually located directly at the field joints or near the weld. Inductive coupler is capable to connect to the clamp and supply the electric power. It is much smaller than usual subsea electricity connectors (Baltzersen, et al., 2005). The article does not tell whether the pipeline clamp is intrusive or not. At the same time this article was presented at 2005 and many things has changed during 8-year period, therefore today Sensorlink presents another technology which provides real-time non-intrusive ultrasound corrosion monitoring named UltraMonit®(sensorlink.no).

Another technology for corrosion/erosion monitoring is a Corrosion-Erosion Monitoring (CEM) system from ClampOn which monitors the wall thickness and consists of set of ultrasonic transducers (Figure 2.10). Transducer is a device which measures sound waves and changes them into electric signals. "*Transducer pairs operate in a pitch-catch mode and use the ultrasonic waves to give the average wall thickness between the transducer pairs*" (clampon.com). This technology has proven reliability for topside and can be used for subsea because it is non-invasive, highly reliable, provides real-time measurements, can cover a wide area (up to two meters) and does not require any recalibration. The sensor does not need a direct contact with the metallic surface to make a measurement. Kristiansen and Instanes (2012, p.1) indicate that all these advantages make CEM more attractive for subsea installation than pre-installed sensors and ROV-based solutions. The reason for it this is that it is difficult to identify the real "hot-spots" of the asset before starting the production. Hot-spot is the area of the pipe which is most likely to be affected by corrosion and erosion. ROV based solutions are using preinstalled invasive sensors therefore the data provided by ROV is usually unreliable. Hence CEM is more effective technology for corrosion/erosion monitoring of the subsea pipelines, manifolds and jumpers.

It is not only wall thickness of pipes can be monitored with this technology, but also wall thickness of tanks and separators, which proves that this is very flexible solution for subsea assets. On the other hand, as CEM provides real time data then this solution requires constant electric power supply.

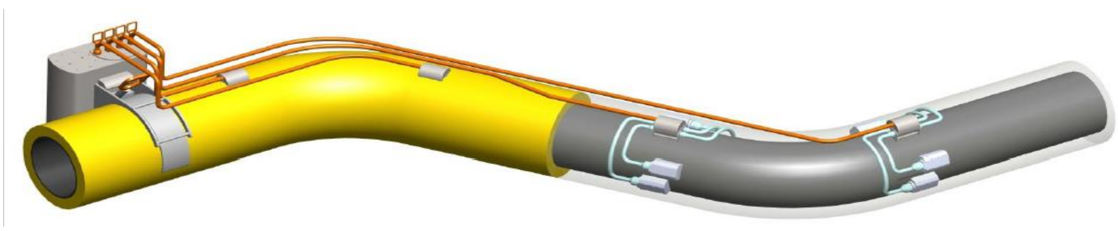


Figure 2.10 Preinstalled solution with transducers mounted underneath the coating (Kristiansen and Instanes, 2012, p.6)

The last technology for corrosion/erosion monitoring that is going to be reviewed is NDT (Non-Destructive Testing) corrosion monitoring method for pipes from Impresub. This method is called PEC or Pulsed Eddy Current and it is "*based on the eddy currents created by a magnetic field induced in a metal structure*" (Slomp, et al., 2012, p.1). PEC sensor encloses one transmitter and one receiver coils. Voltage pulses at transmitter coil generate magnetic field inside the steel, which create electrical eddy currents. These currents produce the secondary magnetic field which is caught by the receiver coil as an induced voltage. This signal tells system about the wall thickness. PEC inspection is made by pipe scanner which is mounted on the WROV (Work class ROV, Figure 2.11). Advantages and disadvantages of the PEC are represented in Table 2.2.

Table 2.2 Advantages and disadvantages of the PEC

Advantages	Disadvantages
– 360° scanning of the pipes – Can be used at any depth – Direct contact with the metallic surface is not required – Corrosion inspection is carried out without production shutdown – Can be used for any pipe diameter – Possible to identify “hot-spots” – 3D graphical report about corrosion status	– Calibration is required – Marine flora needs to be trimmed around inspected pipe – Real time measurements are not possible due the method specifications – 20-30 cm around the pipe should be free from any equipment/structures to provide free spam for scanner

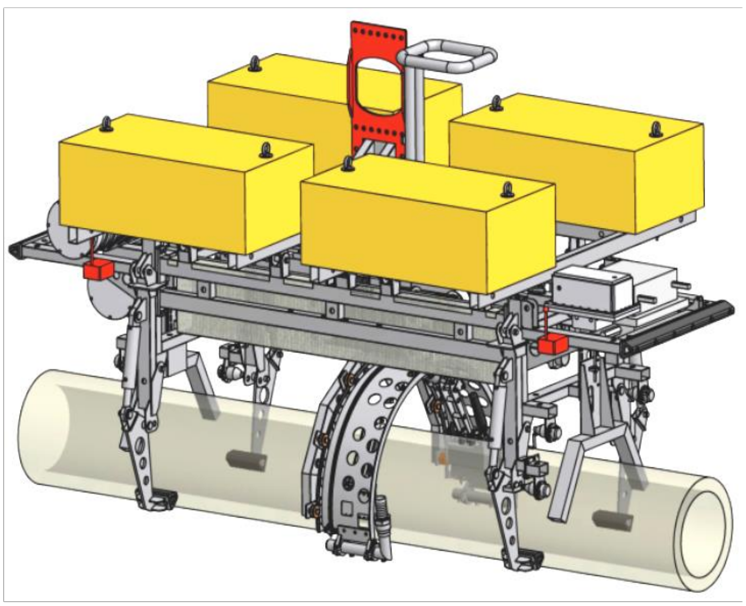


Figure 2.11 Subsea PEC system for pipeline corrosion/erosion monitoring (Slomp, et al., 2012, p.11)

2.2.5 Monitoring of water quality

Monitoring of water quality is closely related to the development of subsea separation technology. The reason why subsea separation is moving at the seabed is that it brings many benefits to the oil and gas processing. Firstly subsea separation occurs easier as the temperature of the fluids is higher; under subsea temperature and pressure conditions shearing and mixing of the fluids is reduced. Secondly, technology reduces the use of production chemicals, less production water is discharged into the environment and, in addition, subsea separation helps to save the energy as water remains at the bottom, there is no need to pump it up to the surface (Yang, 2012, p.2).

After separation water is re-injected back into the reservoir or discharged. Such water reinjection concept was utilized by Statoil at Tordis and Troll C projects. However no effective instruments are available today to monitor the quality of the re-injected water.

The quality of re-injected water needs to be monitored because "*solid particles and oil droplets cab cause plugging and formation of surface cakes, thereby impairing the reinjection process*" (Yang, 2012, p.2). In order to evaluate the quality of the water the following parameters should be measured:

- Amount of oils and amount of solids in the water
- Content of H_2S, heavy metals and radioactive materials
- Particle size and particle distribution.

Technological concepts available for water quality monitoring

There are several technological concepts that are available on the market:

- Laser Induced Fluorescence (LIF) measurement principle monitors oil in water content. Technology is mainly used for topside, no examples of using it in subsea. On the market ProAnalysis company develops a project Argus® Subsea in order to satisfy the subsea need in oil in water monitoring.
- Photoacoustic sensor and ultrasonic based systems are other methods of measuring oil in water content.
- Sand measurements can be performed by erosion and acoustic based technologies (Chapter 2.2.3).

All these methods are very new and have not been applied in subsea industry. At the same time there is no integrated solution available to monitor water quality remotely. Listed technologies are directed either to monitor oil in water content, or sand. No technologies were found which monitor chemical content (H_2S, heavy or radioactive metals) or which could monitor size and distribution of particles.

A lot of requirements are imposed to the new technological innovations that are going to be used in subsea. They ought to be well tested to proof the reliability and eliminate the risk for subsea plant integrity. As there is no currently technology available which would monitor in the real time the water quality, the future for this type of monitoring would probably involve the usage of the complicated technology. One of the keys here is to gather together experts from the different areas in order to create a new reliable technology for real-time integrated monitoring of the water quality.

Technologies available for subsea water quality monitoring

As there is no good solution available for water quality monitoring oil and gas operators do the following:

1. Sampling lines are made to connect subsea separator and topside facility and provide the water for water quality check. This solution has several limitations: no real-time measurements and subsea plant needs connection to the topside facility where water probes needs to be tested.
2. ROV are used to bring the samples to the surface. Such monitoring method is expensive, provides delayed measurements and ineffective.

2.2.6 Process parameter monitoring

Process parameter monitoring includes monitoring of pressure, temperature, flow and sometimes level and density. This monitoring provides information about subsea processing (e.g. whether the flow, temperature and level are sufficient in the separator so that shutdown of equipment would not occur) and about the condition of the subsea asset. As there are so many situations when process measurements help to identify the equipment issues, it would not be possible to cover all of them in this paper. That is why only few points will be mentioned.

Firstly, vibration monitoring requires some data from process parameter monitoring to clearly identify the problem with rotational machinery. For example, compressor’s low suction pressure leads to high vibration from magnetic bearing. Therefore vibration level of magnetic bearing should be monitored together with the suction pressure.

Secondly, internal and external leakages can be detected with the help of process parameters. This method is used, for example, at Ekofisk Viktor A subsea injection wells. Operators carry on leakage testing every six months to check the valve leakage. During the testing they close the valve and monitor the pressure: if pressure increases then the valve leakage is possible. Some other leakage detection methods, which are based on process parameter monitoring, are listed in Table 2.3.

Table 2.3 Leak detection based on process parameter monitoring (Eisler and Lanan, 2012, pp.2-3)

Leak detection method	Principle	Limitations
Mass Balance with Line Pack Compensation (MBLPC).	This method computes flow which is leaving the systems based on the flow entering the system with adjustments of the pressure and temperature values.	1% deviation with single-phase flow. To achieve sufficient threshold with multi-phase method needs to be used with other methods
Pressure trend monitoring	Method monitors pressure in the pipeline and compares it with historical data. In case of mismatch alarms occur.	Worse threshold for single-phase than MBLPC.
Real Time Transient Monitoring	Method estimates the flow based on the information from process parameters. In case of deviation between the estimate and the flow measurements alarm occurs.	Depends on the instrument and leak detection accuracy threshold.
Pressure Safety Low (PSL)	A large leak causes the pressure drop below the normal operating value.	False alarms occur in case low limit value is not correctly set. Small leaks are difficult to detect.

Thirdly, each subsea asset has its limitations, e.g. normal operating pressure, temperature, upper and lower ranges of the level. These ranges should be monitored and in case abnormal situation the alarm should be triggered and protective actions should be takes (e.g. valve enters save status – close or open depending on the process, the motors shut down, etc.).

Instrumentation suppliers

The review of process instrumentation (mainly sensors) suppliers for subsea is presented in the Table 2.4.

Table 2.4 Review of subsea process instrumentation suppliers

Type of instrument	Supplier	Name
Pressure sensor	GE	PTX 300 Series (hydraulic pressure within the Subsea Control Module)
	ESI Technology	PR3920
Pressure/Temperature sensor	Roxar (Emerson)	- Roxar subsea SenCorr PT sensor (single pressure & temperature) - Roxar subsea SenCorr PTPT sensor (dual pressure & temperature)
	Siemens	WEPS-100 Series Subsea Pressure/Temperature Sensors
	GE	- Wellhead Pressure and Temperature Sensors - Downhole Gauge Sensor (pressure and temperature measurements)
dP (differential pressire) sensors	Siemens	Siemens SDP-5 dP Sensors
Multiphase Flowmeter	Slb	Subsea phase watcher multiphase flowmeter
	Roxar (Emerson)	Roxar multiphase meter
	MultiPhaseMeters (MPM)	Multiphase meter
Single phase flowmeter	FMC Technologies	Ocean-flo single phase flow meter
	Roxar (Emerson)	Roxar subsea single phase sensor
	Aker	Subsea venturi meter

2.3 Topside solutions for condition monitoring

Topside solution for subsea conditional monitoring is a system which allows remote monitoring of equipment condition, i.e. data from subsea sensor should be transferred to the operator and maintenance engineer for further processing and analysis. In this case we are talking about automation control system. According to Cohan (2010) the modern effective subsea control systems should have the following characteristic:

- System should be *reliable*, i.e. provide data which can be trusted
- System should be capable of working with *complex equipment* and process huge amount of data
- System *availability:* it should function at any time and under the different circumstances
- *Life cycle cost* of the system should be *low*
- System should be able to provide *outstanding performance*
- System should have *excellent serviceability* including:
    - *Secure* world wide *access* to provide expertise in decision making
    - *Decision support* rather than raw data on the screen
- System should be *flexible* for updates and troubleshooting.

The result of internet review of topside solutions for conditional monitoring from key subsea service companies, like FMC Technologies, Aker, GE, Slb, ABB, Siemens, Emerson, etc., showed that there is only one supplier of conditional monitoring system which meets the needs of modern subsea industry. Others use other ways how to investigate the equipment condition and plan the maintenance, like fetching information from offshore and executing data-analysis onshore.

Nevertheless, the first of its kind condition monitoring system is developed by FMC Technologies. It is called Condition and Performance Monitoring (CPM). System obtains information from instrumentation installed at the seabed, then analyzes it to see the status of different subsea assets and at some point it triggers an alarm when system detects some abnormal situation with equipment which may lead to the problems. The alarm is triggered early enough to plan maintenance activities including ordering of spare parts and necessary services from partner companies.

Alarm system is organized in a way that operator would get the most important information which would help to optimize the production. The rest of alarms, warnings, messages are forwarded straightly to FMC Technology's team which analyses, plans the maintenance activities. For example, small pressure measurement change may be not so important for the operator, but this is extremely important for the maintenance engineer as it may be a indicate equipment failure development (Stensvold, 2013, p.48).

Another benefit of this system is that it is located in FMC's office. Company's engineers do not need travel offshore to obtain necessary information. FMC has access to the real-time condition monitoring for every subsea plant where company has delivered this system.

Stensvold (2013, pp.48-49) points out that FMC is one of the leading suppliers of subsea equipment and they acquired the valuable knowledge about how its subsea equipment functions, how different measurements are connected with the equipment condition. This knowledge is very important for a development of subsea condition monitoring system such as FMC's CPM. Besides CPM can be adjusted in case customer has equipment from other suppliers that is installed at subsea facility.

FMC Technologies has already installed and successfully utilized CPM at Gjøa field in Norway (Stensvold, 2013, p.49).

2.4 Subsea equipment and possible failures

Subsea processing plant (Figure 2.12) includes the following subsystems and equipment (Odland, 2012; Belcomo, 2012):

- Wellhead system which consists of:
    - x-mas tree with choke valve
    - workover riser – a conduit between the topside and the subsea equipment
    - workover control system which is used to monitor and control the deployment and operation of subsea production equipment for subsea x-max trees
- Subsea structures (templates, satellites, manifolds, protection structures)
- Subsea piping, flowlines and risers
- Umbilicals (electric, hydraulic and chemical supply lines)
- Subsea processing (pumping, separation, compression, metering, water injection)
- Subsea electrical and control system (subsea power grid, subsea control module, subsea instrumentation including valves and sensors)

The subsea plant represents a set of small modules for intervention possibilities (Eriksson and Staver, 2010, p.5). Each module consists of the main piece of equipment (for example, a compressor or a separator) and auxiliary assets, like pipes, controllers, sensors and valves. An example of modularized subsea plant is shown on the Figure 2.13. This plant consists of separator, compressor, pump, VSD (Variable Speed Drive), UPS (Uninterruptible Power Supply), HVCB (High Voltage Circuit Breaker) modules.

Nevertheless, there is a technology lag of approximately 20 years between onshore and offshore factories and subsea plants. As people do not have enough knowledge about subsea, many uncertainties and risks are related to it. Subsea equipment suppliers still try to understand subsea environment and identify possible challenges which are related to the nature and complexity of subsea projects. They are going to be identified as more experience companies will gain and more subsea installations will be available.

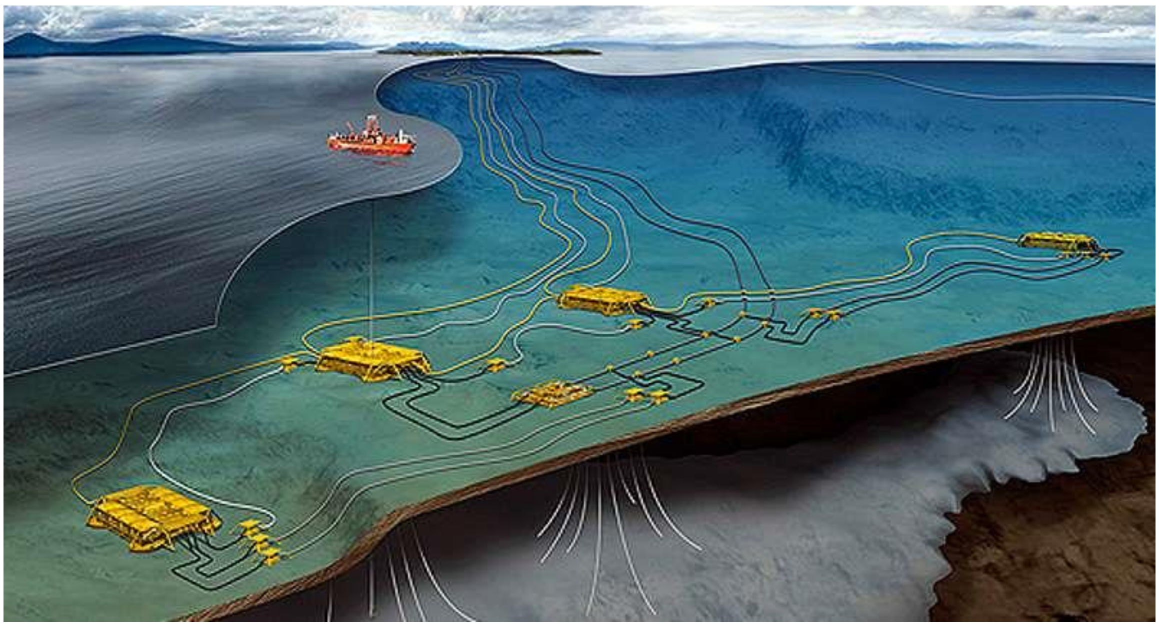


Figure 2.12 Ormen Lange subsea plant (Byggeindustrien, 2011)

Nowadays design of the subsea processing plant becomes more and more complex as more equipment which is filled with monitoring sensors and electrical signals needs to be put on the seabed. This design really contradicts with the original idea behind the subsea equipment design which was simplicity to be able to increase equipment's reliability and avoid unwanted failures, shutdowns and reduce expenditures related to maintenance. Therefore we need to analyze thoroughly already available information about subsea installations, equipment and which challenges companies encountered while working with it. Condition monitoring system which is made for subsea plant aims to help dealing with them and to plan the maintenance actions in advance.

The selection of relevant condition monitoring techniques for subsea equipment is based on the thorough systematic assessment of the system components and identification of their failure modes. According to NORSOK Standard Z-016 (1998) failure mode defines as "*the effect by which a failure is observed on the failed item*". Ang, et al. (2012) presented a tables which summarize the failure modes of subsea electrical (Table 2.5) and subsea processing equipment (

Table 2.6) based on the experience from Åsgard gas field located on the Norwegian Continental Shelf.

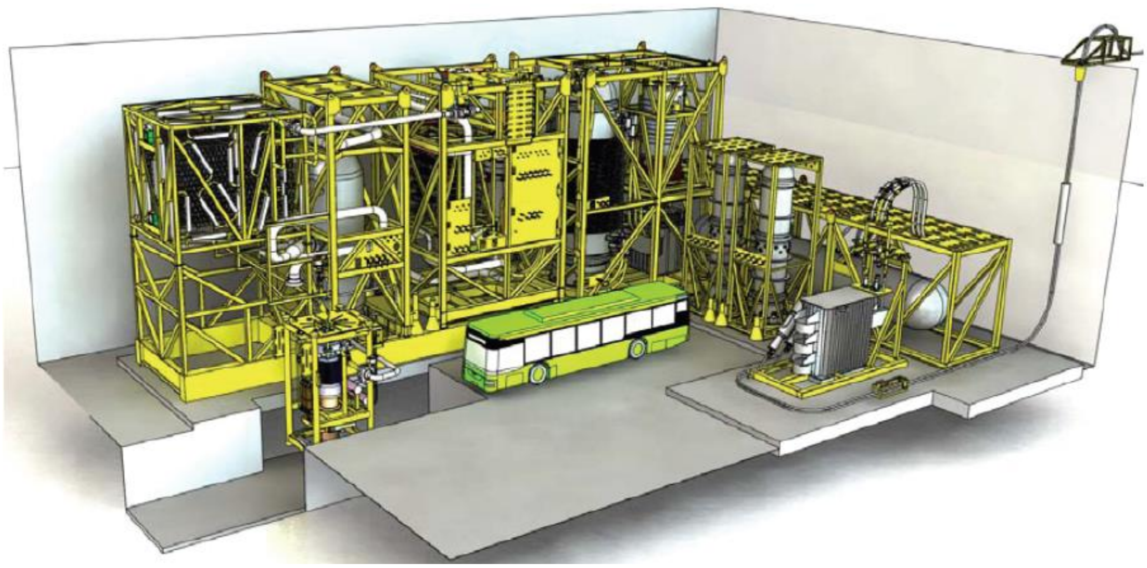


Figure 2.13 Ormen Lange pilot plan of modularized subsea plant (Eriksson and Staver, 2010, p.6)

Table 2.5 Subsea electrical equipment: failure modes and monitoring techniques (Ang, et al., 2012, pp.91-92)

Equipment	Failure Identification		Condition Monitoring Technique
	Possible failure modes	Symptoms of failure	Field sensing devices
Subsea step down transformer	Tap changer wear	Overnumbering of contact operation	ABB TEC intelligent monitoring system
	Excessive moisture content in oil	Increasing trend in moisture reading	Moisture in oil sensor

Equipment	Failure Identification		Condition Monitoring Technique
	Possible failure modes	Symptoms of failure	Field sensing devices
	Excessive hydrogen content in oil	Increasing trend in hydrogen reading	HYDRAN for hydrogen gas in oil sensor
	Earth fault	Significant increase in earth current	Earth fault current monitor
	Overheating	Increase in oil temperature, winding temperature, current	Oil temperature sensor, current transducer, ABB TEC intelligent monitoring system
	Insulation damage	Excessive hydrogen and moisture content	Moisture in oil sensor, HYDRAN (hydrogen gas in oil sensor), ABB TEC intelligent monitoring system
	Winding fault	Increase in leakage factors, winding temperature, winding current	ABB TEC intelligent monitoring system, current transducer
Subsea electrical motor	Stator faults	Stator Magneto Motive Force (MMF)	Current and voltage sensors
	Rotor faults	Unequal rotor bar currents	Rogowski coil measurement
	Insulation breakdown	Decreasing electrical resistance, moisture content in windings	Megaohm resistor, moisture sensor
	Overheating	Increasing stator and rotor temperature	Stator winding temperature detector (RTD or Resistance Temperature Detector) and lumped-parameter thermal method (used for calculation of the temperature rises in electric machines)

Equipment	Failure Identification		Condition Monitoring Technique
	Possible failure modes	Symptoms of failure	Field sensing devices
	Eccentricity faults, consisting of: mechanical imbalance, misalignment, bent shaft	Increasing machine vibration	Current, voltage sensors and ABB MACHsense (vibration and temperature monitoring sensors)
Electrical penetrator and wet mateable connector	Water intrusion	Dropping dielectric breakdown voltage	Withstand voltage meter
	Earth fault	Significant increase in earth current	Earth fault current monitor
	Insulation fault	Decreasing dielectric breakdown voltage	Withstand voltage meter
	Fault in electrical strength	Dropping dielectric breakdown voltage	Withstand voltage meter
	Interfacial breakdown between dielectric surfaces	Dropping dielectric breakdown voltage	Withstand voltage meter
Subsea power cable	Stretched and bent due to cable stress	Increasing temperature in the cable	DTS (Distributed thermal sensing)
	Wear and tear due to dynamic in the cable	Increasing temperature in the cable	DTS (Distributed thermal sensing)
Subsea switchgear	Dielectric breakdown	Decreasing gas pressure and density, increase in humidity and temperature	ABB MSM internal algorithm (Modular Switchgear Monitoring - SF6 gas density sensor), moisture and temperature sensors
	Mechanical faults	Increasing vibration, contamination and moisture content in moving parts	Moisture sensor, vibration sensor

Equipment	Failure Identification		Condition Monitoring Technique
	Possible failure modes	Symptoms of failure	Field sensing devices
	Excessive temperature	Increasing temperature in switchgear conductors and gas insulation	ABB SensyCal FC400 IR (temperature monitoring sensor), ABB MSM internal algorithm (see above)
	Arc faults	Oxidizing contact surface, rapid increase in temperature in contactor	ABB MSM internal algorithm (see above)
	Partial discharge	Excessive humidity and moisture content	Moisture sensor, withstand voltage meter

Table 2.6 Subsea processing equipment: failure modes and monitoring techniques (Ang, et al., 2012, p.92)

Equipment	Failure Identification		Condition Monitoring Technique
	Possible failure modes	Symptoms of failure	Field sensing devices
Subsea gas compressor	Bearing failure	Increasing in compressor vibration, bearing temperature	Temperature sensors, ABB MCM800 (Machinery Condition Monitoring – vibration sensor)
	Shaft failure	Increasing compressor vibration, friction and wear	ABB MCM800 (see above)
	Overheating	Increasing temperature in rotating parts, high compression ratio, high return gas temperature	Temperature and pressure sensors in compressor inlet and outlet
	Internal corrosion	Increasing vibration in compressor	ABB MCM800 (see above)
	Clogged suction strainer	Increasing pressure differential in filter	Pressure differential sensor

Equipment	Failure Identification		Condition Monitoring Technique
	Possible failure modes	**Symptoms of failure**	**Field sensing devices**
	Loss of gas output	Dropping in discharge temperature, compressor efficiency	Temperature, pressure and flow sensors in compressor inlet and outlet
	Surge and cavitation	Low flow rate at compressor inlet, increasing compressor vibration	Pressure and flow sensors in compressor inlet and outlet
Subsea liquid pump	Drop in produced head	Decreasing reading of pump pressure sensor, increasing pump vibration	Pressure sensors, ABB MCM800 (see above)
	Shalt failure	Increasing pump vibration	ABB MCM800 (see above)
	Pump wear	Dropping in pump produced head and pump performance, increasing leakage path internal to the pump and friction	Pressure sensors, flowmeter, operating head
	Pump overheating	Increasing temperature in rotating parts	Temperature sensors
	Corrosion	Increasing pump vibration	ABB MCM800 (Machinery Condition Monitoring – vibration sensor)
	Loss of liquid output	Dropping in pump produced head, decreasing pump performance	Pressure sensor, flowrate, operating head
Control valve and electric valve actuator	Erosion in body and trim	Increasing noise and vibration in the valve	Vibration sensors
	Overheating	Increasing temperature of internal gear and motor	Embedded temperature sensors
	Cavitation	Increasing noise and vibration in the valve, high flow rate and low pressure	Vibration sensors, flowmeter, pressure sensor

Equipment	Failure Identification		Condition Monitoring Technique
	Possible failure modes	Symptoms of failure	Field sensing devices
	Drive signal failure	Decreasing reading in actuator input voltage and current	Voltage and current sensors
	Valve trim travel deviation	Insufficient torque, actuator position feedback deviation	Torque monitor, resolver feedback positioner
	Slow response time	Increasing time delay between control signal and valve position feedback	Internal valve self-diagnostic timer
	Loss of communication	Insufficient feedback signal from valve actuator	Resolver feedback positioner

3. Methodology

In this chapter we are going to have a brief look into the problem review, mainly how we a going to use the literature to design condition monitoring system for subsea plant; then we are going to review the techniques and tools, mainly available international and Norwegian standards, human ,technology and organization issues and HSE (Human, Safety, Environment).

3.1 Problem review

The main purpose of the thesis is to design a reliable condition monitoring system suitable for subsea plant.

In first part of Chapter 2 a research was made which shows which condition monitoring methods are used together with subsea equipment and what they are able to monitor. At the same time it was briefly described which equipment these methods can be used with. Then the overview of available suppliers was made.

In the second part of Chapter 2 the brief overview of the subsea plant assets was made and moreover failure modes and monitoring techniques were listed for the subsea power supply and processing equipment.

Therefore at this moment we have condition monitoring methods for subsea, sensors and ROV based inspection information and subsea equipment which needs monitoring. The purpose of the following Chapter 4 is to investigate how to integrate the use of subsea condition monitoring practices together with the topside and maintenance planning and design reliable condition monitoring.

3.2 Techniques and tools

The main technique for this master's thesis is research. There are four types of research which is used in this paper: literature research, interview research, discussions with university supervisor and review of internal Siemens documents.

Literature research was selected as it allows familiarizing and understanding conditional monitoring methods used by other researchers, gives opportunity to learn advantages which can be incorporated into the design and disadvantages which need to be avoided, opens other areas which might be forgotten, provides ideas for the thesis and makes it more multilateral, increases the credibility of the thesis.

At the same time interview method was used. Engineers from oil and gas industry (operators working with remote monitoring of subsea wells, experts from subsea and automation service companies) were questioned to investigate more details about the subsea field equipment, to confirm the findings from literature research and to get familiarized with the better industry practices (if available).

Discussions with university supervisor improved the work process, provided ideas which direction the author should follow. Relevant and useful literature was suggested. Feedback and advices helped to make work process more effective.

Siemens internal documentation is another source of information.

Design of condition monitoring system was created with regards to the applicable standards, human technology and organizational factors and HSE (Health, Safety, Environment).

3.2.1 Available standards

The following standards are applicable for the design of the condition monitoring system for subsea plant:

ISO 13628 -1	Petroleum and natural gas industries – Design and operation of subsea production systems. Part 1: General requirements and recommendations
Standard includes general instructions and requirements related to the subsea system design. Standard contains many relevant chapters for this thesis: - Chapter 5.2.4. Process and operational data (e.g. main process parameters for assets, inspection requirements, etc.) - Chapter 5.2.5. Host facilities data (e.g. distance, electric service facility, etc.) Information about host needs to be known prior design start. - Chapter 5.2.6 Safety and hazards (e.g. iceberg activity, seabed characteristics, underwater environment). This information also should be available prior the design and system design needs to consider it.	

<table>
<tr><td>ISO 13628-5</td><td>Petroleum and natural gas industries – Design and operation of subsea production systems. Part 5: Subsea umbilicals</td></tr>
<tr><td colspan="2">Standard provides information about design of umbilicals which are the main source of electricity and communication for subsea equipment. It is important to know about the electric cables and operating voltages (chapter 7.2, p.28) for design of conditional monitoring system.</td></tr>
<tr><td>ISO 13628-6</td><td>Petroleum and natural gas industries – Design and operation of subsea production systems. Part 6: Subsea production control</td></tr>
<tr><td colspan="2">Standard provides design requirements for:
- subsea electrical system (chapter 7.4.3, p.47; annex A.4, p.76)
- Subsea Control Module (chapter 7.4.4, p.49)
- Subsea Electronic Module (chapter 7.4.5, p.50)
- subsea software and configuration (chapter 7.4.6, p.51)
- communication (chapter 7.4.7, p.51; annex F, p. 112; annex H, p.129)
- subsea instrumentation (chapter 7.4.8, p.52)
- interface for control system for topside (chapter 8, p.55)
- material selection with regards to underwater environment and corrosion (chapter 9.2, p.55)</td></tr>
<tr><td>NORSOK U-001</td><td>Subsea production systems</td></tr>
<tr><td colspan="2">Standard is based on ISO 13628 and at the same time contains additional requirements which are applicable on Norwegian Continental Shelf. The main consideration is addressed to chapter 5.17.1 – Subsea system design (p.9).</td></tr>
<tr><td>NORSOK U-009</td><td>Life extension for subsea systems</td></tr>
<tr><td colspan="2">Standard contains the requirements for integrity assessment (chapter 6, p.18), reassessment basis for subsea installation life extension (chapter 7, p. 21) and condition based assessment (annex K, p. 102).

The condition monitoring system should meet the following requirements:
- sufficient quality of collected data, quality of inspection and quality of maintenance</td></tr>
</table>

program should be met for the right decision making about the equipment status - the proper limits should be set for the measurements - current condition mapping should be made to be able to follow the equipment degradation In addition annex A-J describes what exactly to consider during the condition based assessment of service life extension of subsea system in general and subsea equipment (e.g. subsea X-max tree, structures, valves, control system). This assessment includes internal and external leakage checks of different parts of equipment, corrosion erosion degradation, wear, cavitation, etc.	
NORSOK U-CR-005	Subsea Production Control Systems. Common Requirements.
"This standard covers the minimum requirement to the subsea control equipment, power supply and signal communication". It is important to mention that this standard was used the most in the design of condition monitoring system.	
NORSOK U-CR-006	Subsea Production Control Umbilical. Common Requirements.
"This standard covers the minimum requirements for subsea control and service umbilicals".	
NORSOK I-002	Safety and Automation system (SAS).
"This standard covers functional and technical requirements and establishes a basis for engineering related to Safety and Automation System Design".	

3.2.2 Human, technology and organizational issues

It is important to consider conditional monitoring system as whole rather than regard different components separately. That is why it is necessary to think not only about the design of the system functionality but also about how human, technology and organization would work together with the subsea condition monitoring system.

Human.

System should be designed to fit to human capabilities in order to eliminate the human errors. The graphical user interface for operators should be made user-friendly, complying with ergonomic rules, i.e. taking into account limitation of physical and mental abilities of the person to process the information and that the system may demand more from the person than he/she can perform.

Organization.

Subsea industry is related to, so called, *high reliability organizations*. Such organizations cannot allow any error to happen since the result of any error is a devastating disaster which leads to facility damage and contamination of the environment and ecosystem.

Technology.

Conditional monitoring system for subsea needs to be reliable to fulfill organizational requirements and to be simple enough so that people can safely use it.

3.2.3 HSE

The design of the system should comply with HSE rules, meaning that the system would not cause any harm to human's health, safety and environment. Since conditional monitoring system entails the use of electricity at the seabed and topside, system design should ensure that all connections to power units would be made safely and reliable.

Underwater environment should be exposed to the least possible impact from any subsea system, as it has living creatures and plants. This should not be forgotten while technology and human enters into this area.

4. Case study: Design for conditional monitoring system for subsea plant

In this chapter we are going to look at an example of condition monitoring system design for subsea processing plant, including subsea and topside control and electrical equipment, Safety Automation System (SAS). Then we are going to look at reliability of the design concept, how to use condition monitoring to carry on the maintenance planning. At the end a brief look is given at today's challenges related to subsea conditional monitoring.

4.1 Design concept

Condition monitoring system is an automation system which is used for an effective maintenance planning. It has the following concept: there are sensors located at subsea equipment, which send the data to the topside at offshore facility or onshore station, where these data are analyzed by operators and maintenance engineers to plan the maintenance so that repair and downtime is eliminated.

Design of conditional monitoring systems for subsea plants should be done with regards to reliability and safety of the system and effectiveness of the maintenance planning.

Reliability and safety are placed at the top priority if it is related to the oil and gas industry, especially subsea. Reliable system is a system which can be trusted that it delivers data that are expected: whatever happens the system should be in operation, i.e. in case if one part of it fails then there are other ways how these data can be delivered. This ensures that the system serves its main purpose. Besides, subsea implies that conditional monitoring system is going to function at the harsh underwater environment. This imposes even higher demand on reliability which needs to be maximized and failure rate which needs to be eliminated.

Safety system eliminates situations which would lead to any personal injury, environmental or equipment damage. Condition monitoring system utilizes measurements from different type of sensors; temperature, pressure and level sensors are among of them. These sensors are setup to provide alarms in case of abnormal scenario in the process system that may breach the safety measures. For example, the separator tank is too full and cannot take more fluid in. In this case inlet system needs shutdown. Another example, the temperature in lube oil tank is too high so that the tank integrity is in danger; therefore the heater which heats up the oil needs to be stopped immediately. These and many other examples may occur underwater and shoud be considered during the design of condition monitoring system.

At the same time the system needs to be designed to serve the main purpose which is effective planning of the subsea equipment maintenance. Reliable conditional monitoring system should to be designed with the respect to *human*, *organization* and *technology* which mean:

- *Human*: conditional monitoring system needs to be designed with the respect to human factor, i.e. it should be fit to human use eliminating misunderstanding and human errors.
- *Organization*: conditional monitoring system needs to serve the main organizational purposes, like reduction of maintenance cost, repair time, equipment downtime, personnel risks and, as a result of it, bringing higher profit to the organization.
- *Technology* has to serve organizational purposes with the respect to human nature.

The design of conditional monitoring system needs to consider system as whole rather than just components. All human, organizational, technological factors and the interconnections between them should be identified and included into the design basis for conditional monitoring system for subsea plant. In real life this approach requires more time and money used for analysis and planning at the beginning, but the end result, which is conditional monitoring system, would surely meet all expectations.

At the end the design of the conditional monitoring system should include the concept of its utilization. Some set of questions needs to be raised in the beginning of the design process such as: which data should be monitored and how it should be interpreted to see the equipment performance, how other data would help to understand it in the better way, at what point engineers should plan the maintenance actions taking into the account degradation speed of equipment, spare part ordering and delivery time. The answers to these and many other question, plus team work and knowledge of maintenance engineers are required for effective maintenance planning of subsea installation.

In this chapter it is going to be described the design of the subsea condition monitoring system covering the subsea equipment, electrical and signal connection between the subsea and topside and the topside design of the system where people and the system are going to interact with each other. As conditional monitoring system is a tailor made which means that it should be done specifically for each and every subsea plant, the design is going to be skin-deep: the main part would be described, but without details related to specific subsea equipment instrumentation. The insight of this was described in Chapter 2.

4.2 Conditional monitoring system topology

Technopedia.com describes the term "*topology*" as "*interconnected pattern of network elements*". As conditional monitoring systems is a type of automation system, its elements are interconnected and they form a network. The topology of conditional monitoring systems for subsea plant is shown on the Figure 4.1. This is the general overview of the system design. As we see it is divided on the subsea and topside parts.

4.2.1 Subsea equipment

Subsea instrumentation

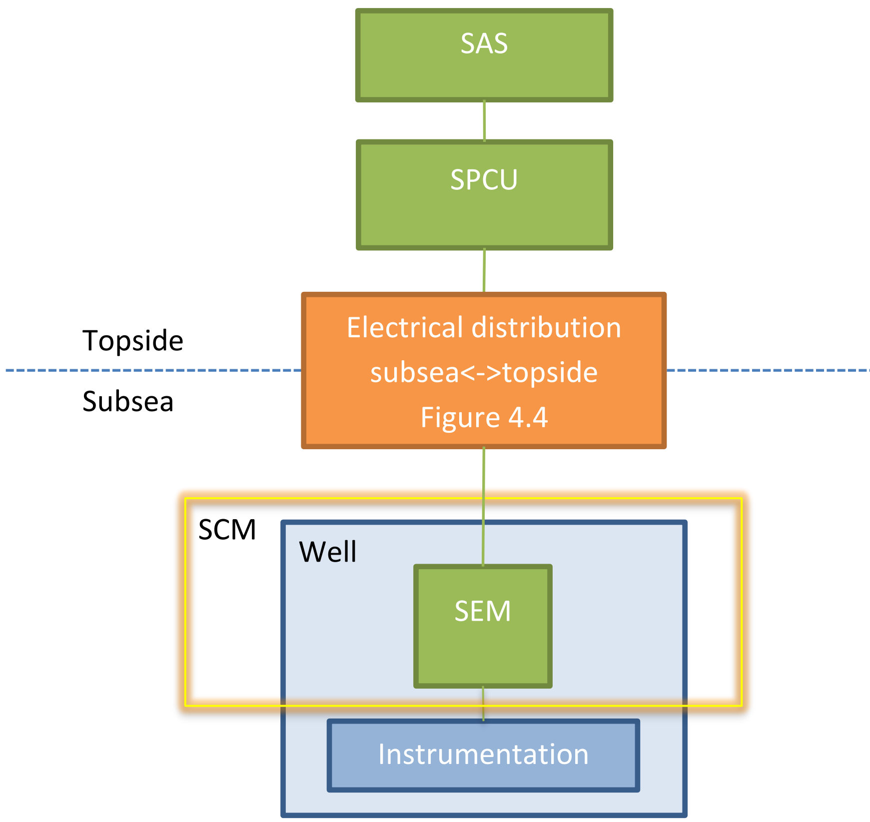
Subsea instrumentation includes the following equipment:

- subsea and downhole sensors for pressure, temperature, multiphase flow, sand production, valve position and process equipment status measurements
- control system and housekeeping sensors inside subsea and topside modules (Table 4.5); these sensors are located inside cabinets to monitor temperature and pressure, earth faults, voltages, etc.
- sensors for vibration, corrosion and erosion detection, sand and water quality monitoring.

According to NORSOK U-CR-005 (1995) all sensors which are located outside the SCU (Subsea Control Module) should transfer signal of frequency or serial type.

There are different protocols available which assures communication between subsea instrumentation and subsea control system. For example, subsea sensors communicate via SIIS protocol (Subsea Instrumentation Interface Standardization, based on CANbus or TCP/IP protocol); downhole intelligent well equipment communicates with Subsea Electronic Module or SEM via IWIS (Intelligent Well Interface Standardization) protocol. Information about these protocols is described in Table 4.1. Historically, every equipment supplier was free to choose any available communication protocol or to develop a new one for the sensors he produces.

This has created a challenge for subsea control system as it had to be equipped with the different modems, which increases system complexity and decreases its reliability. Therefore subsea control system would significantly benefit from the common interface protocol which standardizes communication with subsea instrumentation.



Abbreviations:
SAS – Safety Automation System
SCU – Subsea Control Unit
SPCU – Subsea Power and Communication Unit
SCM – Subsea Control Module
SEM – Subsea Electronic Module

Figure 4.1 Simplified conditional monitoring system topology

Table 4.1 Communication protocols used together with subsea instrumentation

Protocol	Description
SIIS (Subsea Instrumentation Interface Standardization)	Standardized protocol for communication interface between subsea instrumentation, mainly sensors and SCM. There are three main protocol levels: - SIIS 1: 4-20 mA instrument loops - SIIS 2 which is based on the CANbus (serial bus protocol which is used in car control systems) - SIIS 3: based on TCP/IP (IP in this case stands for Industrial Protocol and protocol uses Ethernet physical connection). SIIS 2 and SIIS 3 are used for subsea sensors.
IWIS (Intelligent Well Interface Standardization)	Protocol was developed in collaboration with oil and gas operators, subsea control system and intelligent well suppliers in order to standardize the communication interface between the subsea intelligent wells and subsea control system. One of the reasons why intelligent wells need a separate communication protocol is that these are bigger scale devices which require higher power consumption (Baird, 2002, p.93).

Subsea Electronic Module

SEM (Subsea Electronic Module) controls subsea instrumentation. According to Norsok U-CR-005 (1995, p.7) it consists of subsea control electronics, data storage, subsea modem, electrical connectors, cables and power supply. SEM is a brain of the subsea control system – a subsea computer which is located inside SCM (Subsea Control Module). It is connected to the power and communicated with the topside control equipment. Mainly module is used to monitor the subsea sensors and it should be capable to temporary store all necessary data from subsea production system. Processor which is kept inside SEM has a software program, which can be accessed and reprogrammed from topside.

In order to communicate with different topside and subsea equipment SEM has in-build modems. As different subsea instrumentation uses different communication protocols which require separate devices, technology suppliers provide numerous types of communication options (Table 4.2).

Table 4.2 Flexible communication solutions of SEM in-build modem (ge-energy.com)

Type of modem	Bit rate	Distance range	Comment
Fiber-optic	up to 1 Gbit/sec	up to 300 km	High speed communication for long distance. Method is based on the sending pulsed-light signal through an optical fiber.
DSL (Digital Subscriber Line)	up to 5 Mbit/sec	up to 40 km	Point-to-point
RS-422	up to 10 Mbit/sec	up to 800 m	High speed communication for short distance. Useful for communication within subsea area.
VSCM (Variable-Speed Copper Modem)	9.6 - 115.2 Kbit/sec	NA	
LSCM (Low- Speed Copper Modem)	1.2 Kbit/sec	NA	Used for legacy SEM support

Subsea/Manifold Control Module

SCM (Subsea Control Module) is a retrievable subsea module located on each X-mass tree and dedicated to control instrumentation for each well. It has a pair of redundant SEM (Subsea Electrical Module). In case of SCM each SEM controls and monitors actuators and sensors located downhole, in well tubing, X-mas tree, risers, flowlines and subsea manifold. SCM has an access to electric signal and hydraulic fluid, so that when the operator from the topside wants to open a valve, SEM inside the SCM gets electrical signal and then SCM directs the hydraulic fluid to the right subsea valve and valve opens, for example. This function is achieved through electro-hydraulic directional control valves which use electrically operated control valve to control hydraulic control valve and change the hydraulic oil direction (hoyea.com). Hydraulic and electric supply to SCM should be redundant. According to Norsok standard U-CR-005 (1995, p.6) SCM contains the following equipment:

- SEM in a one atmosphere pressure vessel
- Electro-hydraulic directional control valves and other valves
- Feed through connectors
- Control module base
- Control module housing

- Couplers for electrical cables and hydraulic lines
- Valves contained in an oil filled pressure compensated housing.

MCM (Manifold Control Module) is very similar to the SCM. The only difference is that instead of X-mass tree, it is placed on the manifold.

4.2.2 Subsea plant electrical supply

Electrical and hydraulic supply to subsea plant and particularly to subsea control system is delivered from topside through the umbilical cable. This is the essential part of the design of conditional monitoring system. Firstly, subsea part is going to be described; description of topside equipment comes afterwards.

Subsea part

Umbilical (Figure 4.2, Figure 4.3) provides electric supply and signal communication from topside to subsea equipment. It is a key component of subsea plant. In general subsea umbilical contains hydraulic and chemical fluid conduits, electrical power and fiber optic lines. "*The hydraulic power and control lines are individual hoses or tubes manufactured from steel or thermoplastic materials (most common) and encased in the umbilical. The electrical control cables supplying power and control signals can either be bundled with hydraulic lines or laid separately*" (Odland, 2011). Dependent on the type of umbilical and utilization purposes different components are included inside umbilical structure. For example, direct hydraulic umbilical mainly consists of hydraulic lines; however it may have a few electrical connections as well.

Subsea plant comprises many umbilical cables. Main umbilical cables (usually there is a pair of them to ensure redundancy) connect topside and subsea hydraulic, electric and chemical distribution systems. Other umbilicals (production, injection, power, control, etc.) connect Umbilical Termination Assembly (UTA) with Subsea Distribution Unit (SDU), subsea equipment and instrumentation (Figure 4.4).

UTA is a "subsea junction box" which receives electrical signal, hydraulic and chemical fluid from topside. This is the first termination station at subsea facility which supplies necessary communication, electricity and hydraulic fluid to the whole subsea processing plant, including subsea control system.

Figure 4.2 Power umbilical cross section (akersolutions.com)

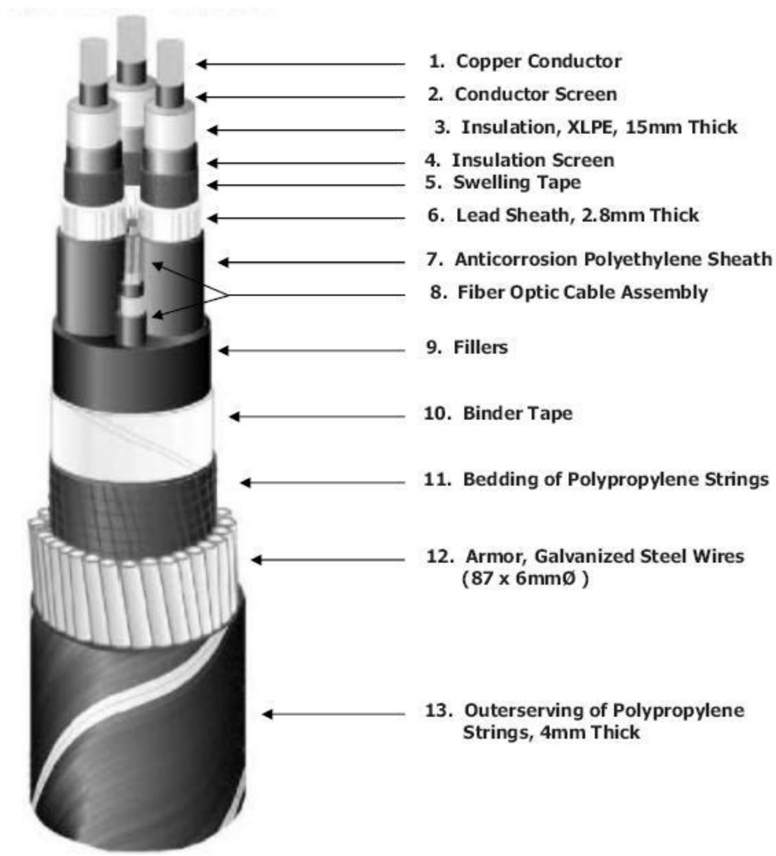


Figure 4.3 Example of subsea umbilical component structure (openelectrical.org)

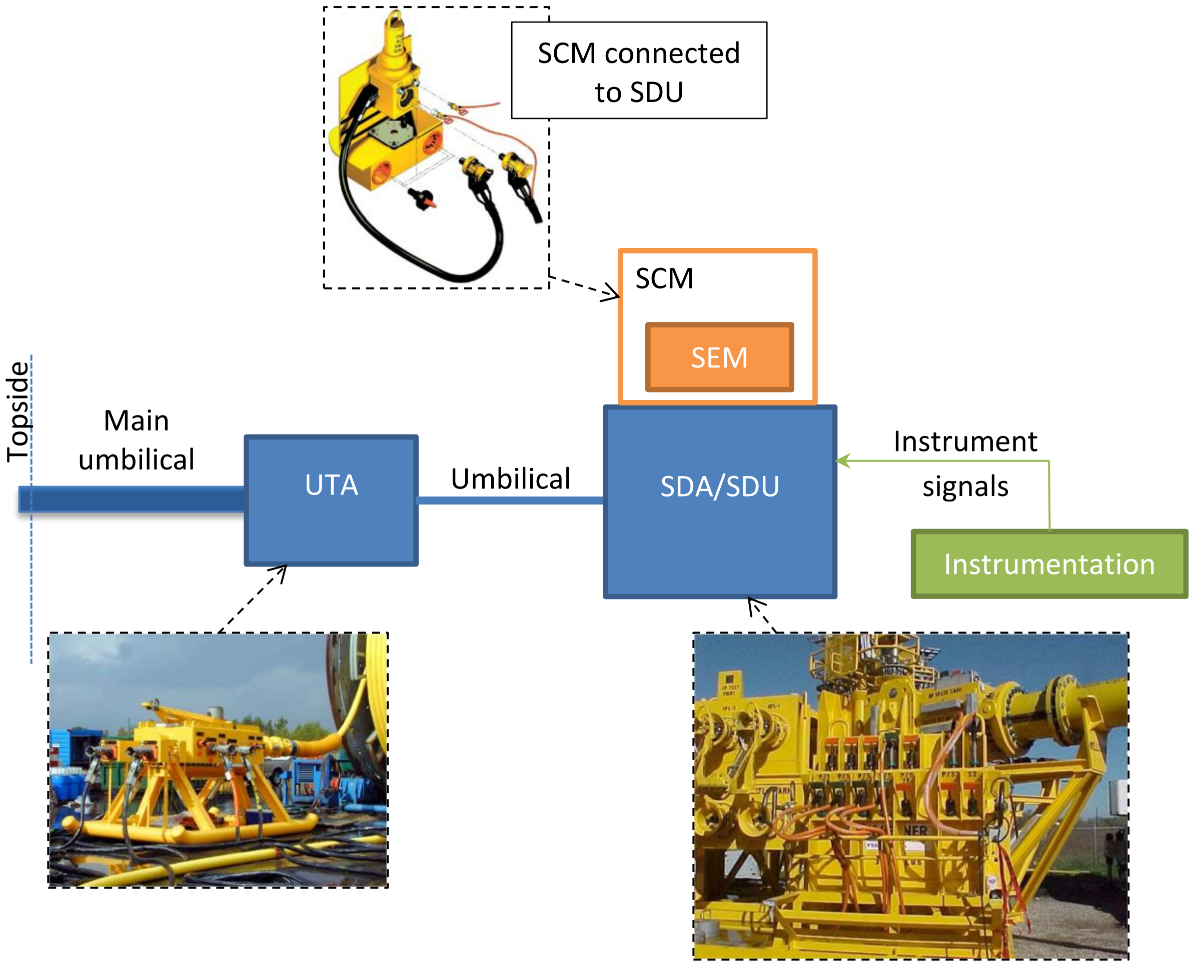


Figure 4.4 Schematic subsea electrical connection

From UTA there goes another umbilical which delivers electricity and hydraulics further to subsea wells and manifolds; it is terminated at SDU (Subsea Distribution Unit, or another words for it is SDA – Subsea Distribution Assembly). SDU is another subsea junction box which distributes electric power and hydraulic fluid to subsea equipment and instrumentation. Finally, subsea control system gets necessary supplies for operation.

Topside part

Subsea UTA receives power supply, hydraulic and chemical fluids from TUTU (Topside Umbilical Termination Unit, Figure 4.5). TUTU is a topside collection point which is connected to the topside power distribution unit, hydraulic power unit and chemical distribution module.

TUTU represents an enclosed unit which includes double block and bleed isolation valves and pressure gauges which may block the flow of hydraulic or chemical fluid inside the unit. At the same time TUTU includes electrical junction boxes and communication equipment.

Figure 4.5 Bennex TUTU (Husby and Morgan, 2011)

Power and SAS signals TUTU receives from other equipment which is described in the next chapter.

4.2.3 Topside equipment

In this chapter we are going to describe the topside equipment for conditional monitoring system. The main characteristics for topside system were discussed in Chapter 2.3.

Subsea Power and Communication Unit

Topside part consists of SPCU (Subsea Power and Communication Unit) and SAS (Safety Automation System) cabinets. SAS is going to be described in detail in Chapter 4.2.4.

The next stop point after TUTU is SPCU (or other name EPCU – Electric Power and Communication Unit). SPCU supplies power and communication interface towards the SAS. Unit encases subsea communication interfaces (modems and filters) to convert subsea signals to the format which can be understood by the topside SAS. SPCU and SAS communicate via direct Ethernet physical connections.

As we already know, umbilical as the main source communication between topside and subsea sends and receives large amount of data. Dependent on the design umbilical may include power cables to transfer the power signals and fiber-optic cables to transfer the control signals. However in order to save the space in the umbilical, it is possible to use only one cable to transfer both power and control signals. Different frequencies are used so that it would be possible to differentiate them. In any case the signals need to be interpreted in the correct way and transmitted to the SAS system. This is done by the subsea communication interfaces (modems and filters) located inside the SPCU. Afterwards signals are sent to SAS through the serial data links via MODBUS protocol, for example. MODBUS is serial (means that a bit of a data is sent at a time) communication protocol, which is used "*to monitor and program devices; to communicate between intelligent devices and sensors and instruments; to monitor field devices*" (modbus.com). MODBUS is widely used in different industries (energy, building, infrastructure, transportation).

4.2.4 Safety Automation System

Conditional monitoring system is a specially designed SAS (Safety Automation System) which provides opportunity to monitor operating conditions for subsea equipment. End users of this system are operator and maintenance engineers. Their job is to look at the screen, monitor the parameters and plan the maintenance actions. All what they see at the end is the computer screen with objects and trends. Therefore conditional monitoring system is a sort of automation system which collects and analyses information from the sensors and data from ROV-surveys (Remotely Operated Vehicle). System provides alarms and warnings to operator and maintenance engineer about possible equipment malfunctions, faults and damages of the subsea equipment.

As condition monitoring systems for topside is an automation system, therefore it can be delivered by any automation supplies as Siemens, ABB, Honeywell, etc. However these companies need to receive a good design basis from the customer. In order to produce a really good solution for condition monitoring for topside customer company should provide a correct limit values for different measurements, i.e. at what time alarm needs to be triggered. The same concept is used by FMC technologies. Company is a world's leader in production and installation of subsea equipment. As they are following their equipment throughout its life time, FMC has unique knowledge about equipment failure modes, their symptoms, the ways how to monitor them, plan and provide necessary maintenance (Chapter 2.2).

SAS which is going to be used on the Norwegian Continental Shelf needs be designed according to the NORSOK Standard I-002 (2001). Standard defines SAS as system which "*performs monitoring, logic control and safeguarding of an installation*".

Typical SAS comprises SAS cabinet (another name Subsea Control Unit - SCU) with redundant CPU (Central Processing Unit) and CP (Communication Processor) cards, redundant Control (CN) and Server (SN) Networks, ES (Engineering Station), OS (Operator Station) server, OS client and IMS (Information Management System). Typical topology of SAS is shown on the Figure 4.6.

Table 4.3 SAS component details

SCU (Subsea Control Unit)	-	SAS cabinet which includes CPU, CP cards, power supply unit. CPU receives data via serial link from SPCU communication interface.
ES (Engineering Station)	-	Engineering computer which has all programming tools and established connections to access and modify the CPU logic.
OS (Operator Station) server	-	Server computer which holds the data, alarms, screen pictures. It communicates with the CPU and reflects information at OS client.
OS client	-	Computer which shows operators and maintenance engineers the data measurements, alarms on the screen about subsea process plant.
IMS (Information Management System)	-	Long term storage system for alarms, data trends, operator and logical actions. System incorporates report tools.

Subsea Control Unit

The typical inside view of SCU (Subsea Control Unit) cabinet is displayed on the Figure 4.7. Equipment shown on the figure is from Siemens. As we can see cabinet contains redundant CPU together with power supply and CP cards. SCU is connected to redundant SAS control network and it transfers signals coming from the serial bus to the OS server. OS server in-turn communicates signals to the OS client. OS client is the end point of the subsea condition monitoring system where operators can monitor and control subsea equipment. More detailed information about SCU equipment can be found in Table 4.4.

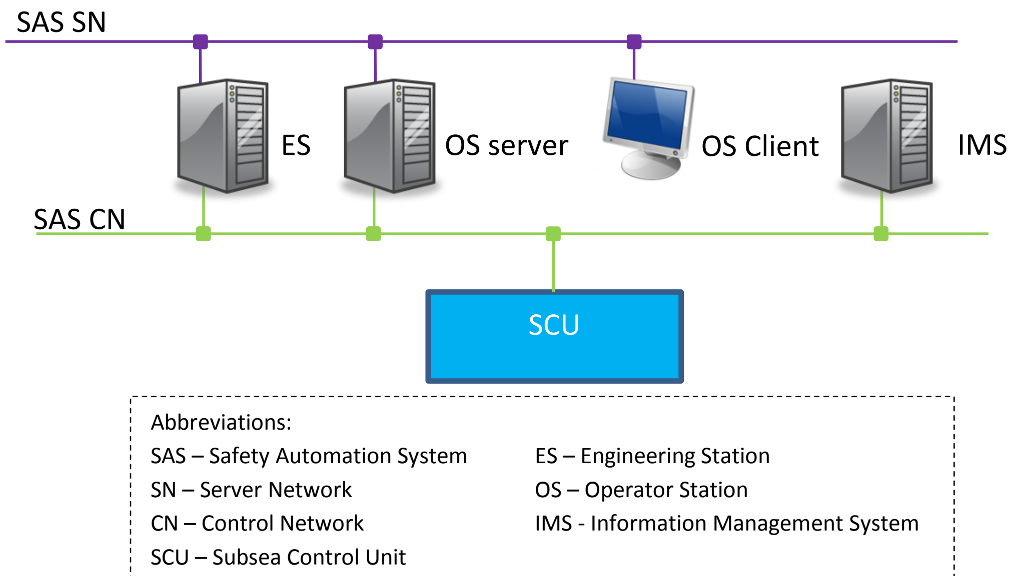


Figure 4.6 SAS topology

Table 4.4 Details about SCU equipment

CPU (Central Processing Unit)	This is a brain of automation system. Device represents a controller which has a program code inside to perform required monitoring, operator commands and internal logic. Program code to the CPU can only downloaded from a special computer, called ES (Engineering station). This computer has all necessary software and CPU connection to perform the program download.
CP (Communication Processor)	Device takes care of all communication processes releasing this work from CPU, like communication with server, serial signals and other controllers. The number of CP cards can be used if many different communications services are in use.
Power Supply	Module supplies power to CPU and CP cards.

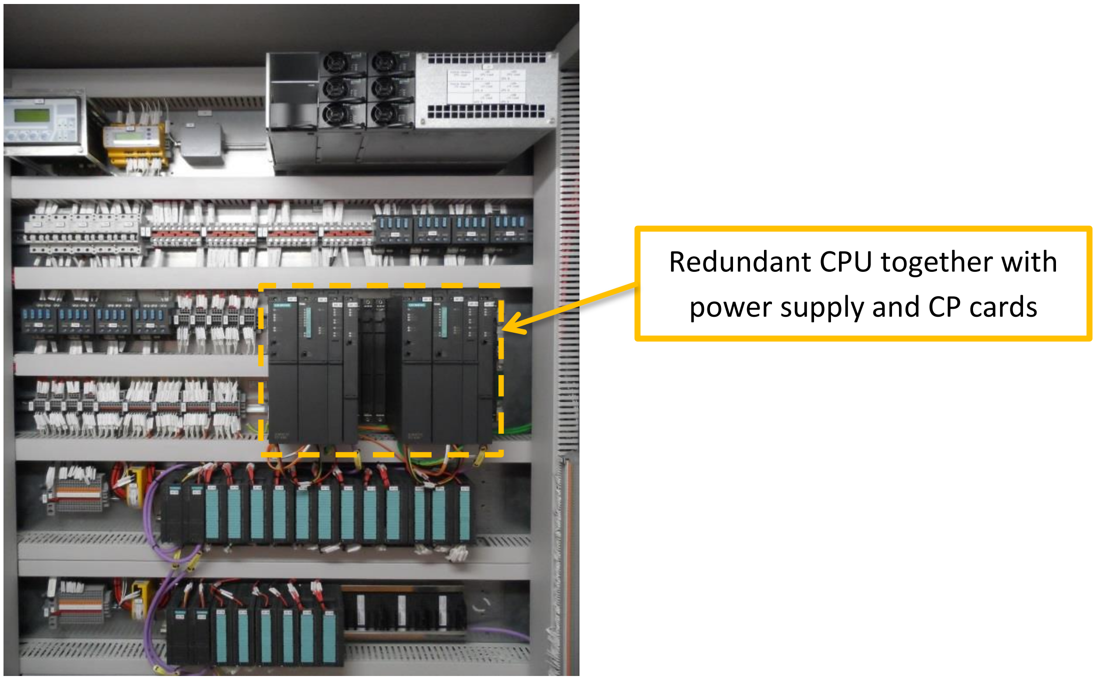


Figure 4.7 Inside view of SCU cabinet

Monitoring of housekeeping parameters of subsea modules

Macmillandictionary.com defines word "*housekeeping*" related to the engineering and computer systems as "*things that have to be done regularly on a computer system to make sure that it will run well*". In our case instead of computer system we need to monitor the operating conditions of subsea cabinets (e.g. SEM, SPCU, SCU). This equipment is also a part of subsea plant asset and we need to know, for example, whether temperature inside of these cabinets is within the normal limits so that it is not too hot inside and there is no danger of damaging the equipment. It is very important to monitor the housekeeping parameters of all the modules which are a part of conditional monitoring system to avoid any problems with the signal transfer between subsea and topside. Common housekeeping parameters which are usually monitored are listed in the Table 4.5.

Table 4.5 Condition monitoring of subsea modules and units

Module of conditional monitoring system	Monitoring parameter
SEM (Subsea Electronic Module)	– SEM temperature – SEM pressure – Humidity – Fluid ingress level – Supply voltage – Supply current
SPCU (Subsea Power and Communication Unit)	– Input voltage – System current – Umbilical voltages – System failure
SCU (Subsea Control Unit)	– Power fault for every power supply – Earth fault – MCB (Mini Circuit Breaker) fault – Cabinet temperature – Electronic fuse fault

Signal diagnostic

SAS (Safety Automation System) should be able to provide fault diagnostics which tells operator about the quality of the signal. The aim of fault diagnostics is to detect type, size, location and time of the fault. Every input from sensor needs to be monitored with regards to signal quality.

SAS for conditional monitoring system is receiving data via serial data communication protocol, as e.g. MODBUS. Design of the protocol already defines how signal diagnostic is performed: this is defined in protocol specification documentation (for MODBUS documentation refer modbus.org). MODBUS has special counters, which count data at sender and receiver. If data at sender doesn't match with the data at receiver then the signal is faulty. SAS needs only to monitor this information and provide an alarm to the operator.

Alarm handling

SAS (Safety Automation System) with proper design of alarm handling would increase the system usability and simplify the work of the operator and maintenance engineers. The reason of alarm handling importance is that system should have least possible alarm messages and at the same time keep the operator and maintenance engineer informed what is happening at subsea plant. Person that works with the condition monitoring system should be able to react fast to the messages that appear on the screen.

NORSOK Standard I-002 (2001, p.12) defines the color for different alarm categories. For example, alarm of category "warning" should be displayed with the yellow color on the screen. In addition standard lists requirements for the alarm handling in SAS; among of them the most important requirements are (NORSOK i-002, 2001, p.13):

- "*The number of alarms during abnormal conditions shall be reduced by alarm processing/suppression techniques in order to have operator attention to the most critical alarms that require operator action.*"

  Too many alarms would disturb an operator. For example, if the heater has heated up the oil in the scrubber up to a very high temperature so that secure conditions of the whole system supplying lube oil to the fuel gas compressor are beached then operator needs to see only the high-high temperature alarms on the screen. Then it will be easy for him to understand the situation and carry on the necessary actions.
- "*The system shall ensure that alarms requiring immediate operator action are presented in a manner that supports rapid detection and understanding by the operator under all alarm loading conditions.*"

  This requirement is quite similar to the previous one. It supports the demand that the most important alarms should be immediately visible for operator so that he understands that his reaction is required.
- All the alarms need to be archived, for example, in IMS (Information Management System).

Listed requirement are important for the condition monitoring system as well. All alarms should be clear and visible for operators and maintenance engineers.

One more important requirement for the condition monitoring system is that different users need to access different alarms. Maintenance engineer needs to get more alarms and SAS messages than the operator. Maintenance engineer due to his competence related to the asset management knows how a small deviation in the pressure may signal that equipment or its spare part needs to be changed during the next maintenance schedule. However this alarm is not important for the operator, as it would not affect the main oil and gas processing. In order to setup different alarm user groups, different experts should participate and work together to set the right limits for different sensor values, define which alarms are required for which user and include this information into the SAS design.

IMS and data management

Information Management System or IMS is long term storage system for alarms, data trends, operator and logical actions. This should be a part of any conditional monitoring system. Historical data from IMS is required for analysis of equipment's conditions over the long time. This analysis is very useful to improve understanding of equipment performance and progress maintenance planning.

However data storage capacity is limited. Therefore it is not possible to store all the values obtained from sensors. Data have to be reduced with a time. "*Data reduction is conversion of data files from high frequency sampling to lower frequency files*" (Markeset, 2012).

Signal diagnostics helps to identify the faulty data which should be eliminated from the data storage process. Faulty data is useless.

Data reduction process of the thrust bearing temperature measurement is shown on the Figure 4.8. There are several types of values: second, minute, hours and day values. A certain predefined period of time is set for every value type which defines how long these values are going to be stored before they undergo conversion process. Conversion process is based on the averaging of the data. Data which are outside predefined period are continuously overwritten. Different value types are:

- Second values: the freshest data in the system
- Minute values: calculated by the averaging of 60 second values
- Oldest minute values are converted to the hour values; later on hour values are converted to day values.

Data reduction process requires a procedure which should define how conversion process should be executed, how to overwrite the oldest values. Procedure should also clearly define the length of the predefined period for every value type. The good practice is to store minimum and maximum values for every period together with the average values. Data reduction provides IMS the capability for long-term memory.

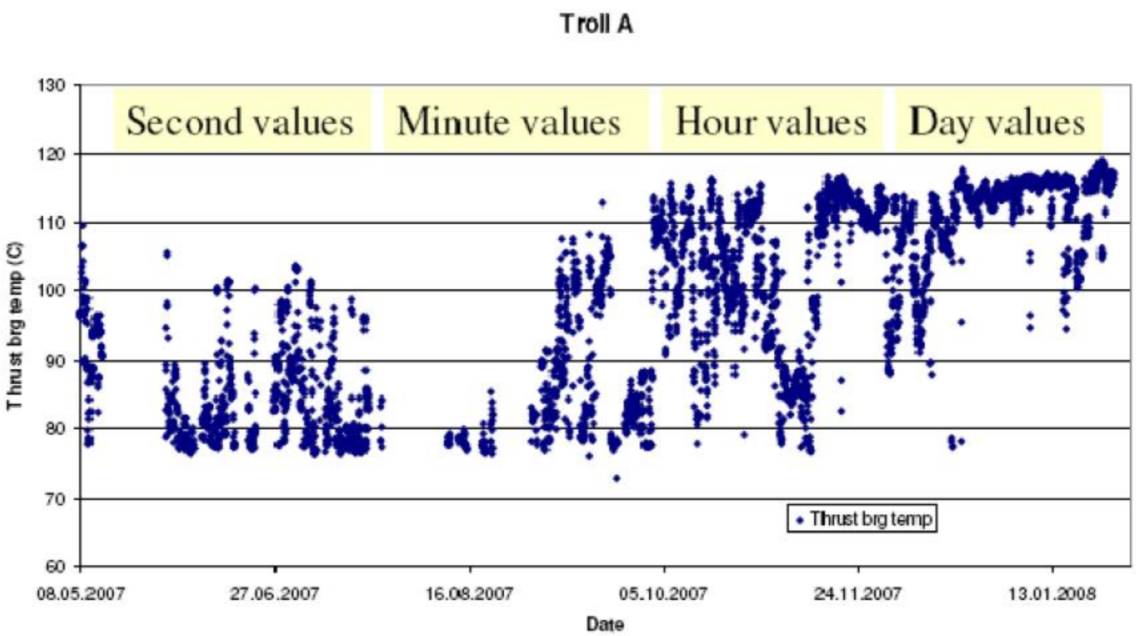


Figure 4.8 Data reduction of thrust bearing temperature measurement (Markeset, 2012)

In case of equipment breakdown, for example, the system should generate the permanent data file which stores the second values that cover 10-15 minutes interval before the event and a period after the event. This is important for the data analysis of equipment performance behavior before the breakdown and investigation of the reasons that lead to it. Exactly the same needs to be done during the planned shutdown of the equipment.

Condition monitoring system collects data from subsea sensors and stores them in IMS. However there is another data which comes from the ROV surveys (Remotely Operated Vehicle), which is not a part of automation system. In this case there should be made a guideline how to integrate the reports from ROV surveys into IMS. It is a good practice to store all the data required for conditional monitoring in one system.

4.3 Ensuring reliability

Information from instrumentation represents the main source of data for condition monitoring system which tells maintenance engineers about current subsea equipment status and equipment operational conditions. All the components of the conditional monitoring system should be reliable, meaning the data that they transfer can be trusted.

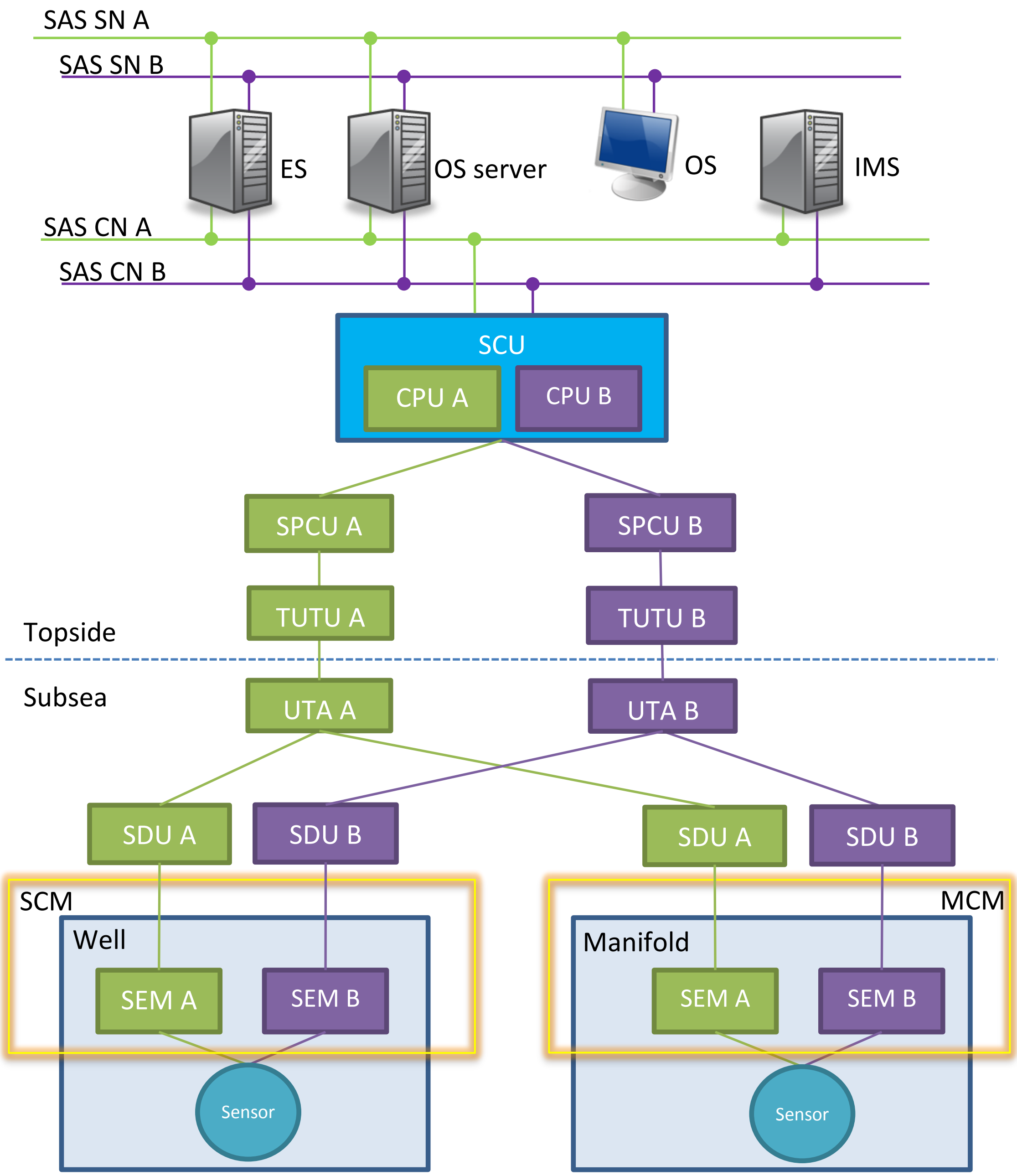
It is very common to use the redundancy concept together with instrument design. But how can redundancy assure the reliability of conditional monitoring system for subsea plant?

As it was mentioned before reliable systems deliver results that can be trusted and whatever occurs, the system should be in operation, i.e. in case if one part of it fails then there are other ways how the result can be delivered. In engineering world this is can be achieved by means of redundancy. According to collinsdictionary.com redundancy is "*duplication of components in electronic or mechanical equipment so that operations can continue following failure of a part*". How can we use it in case with our conditional monitoring system design?

In order to create the reliable condition monitoring system we need to modify system topology shown on Figure 4.1 so that there is a minimum two paths to reach every sensor. Reliable design of conditional monitoring system is shown on the Figure 4.9.

This principle is very common for the current subsea installations. Every subsea sensor has two channels A and B (on Figure 4.9 channels are shown with the different colors: A channel is green and B channel is purple). This is achieved by implementation of dual electronic measurement circuits which guaranties complete separate communication between instruments and redundant Subsea Electronic Module (Davalath, et al., 2002, p. 5). Operator selects whether channel A or channel B should be a master. For example, he may select channel A as a master and B as a slave. If communication with channel A is lost, the system switches to measurements from channel B and meanwhile equipment from path A could be fixed. The probability that communication with channel A and B would fail at the same time is very low.

If communication works well for both channels, sensor measurements from channel A and channel B are constantly checked by SAS (Safety Automation System). In case there is a difference between the channel readings which exceeds a preset limit, discrepancy alarms should be generated.



Abbreviations:

SAS - Safety Automation System
SN - Server Network
CN - Control Network
ES - Engineering Station
OS - Operator Station
IMS - Information Management System
SCU - Subsea Control Unit
CPU - Central Processing Unit
SDU - Subsea Distribution Unit
UTA - Umbilical Termination Assembly
TUTU - Topside Umbilical Termination Unit
SPCU - Subsea Power and Communication Unit
SCM - Subsea Control Module
MCM - Manifold Control Module
SEM - Subsea Electronic Module

Figure 4.9. Reliable conditional monitoring system topology

All the sensors installed at subsea plant are dual: two sensors of the same type are located close to each other. Operator looking at the screen and monitoring subsea equipment can compare measurements from two sensors and see whether there is a deviation. In case there is a deviation, reasons for it need to be investigated.

Dual sensor concept is the most common for current subsea plants. But why only two sensors are used? If there is a discrepancy between the sensors, then operator does not know which of them shows the correct measurement. In case there are three sensors of the same type then automation system can use voting principle, when at least two from three sensors show the same measurement (Figure 4.10). Operator sees only correct measurement on the screen. The disadvantage of this solution is that it would make the design of condition monitoring system too complicated. If system is more complex, then more components could fail. Therefore three sensors concept would decrease system reliable.

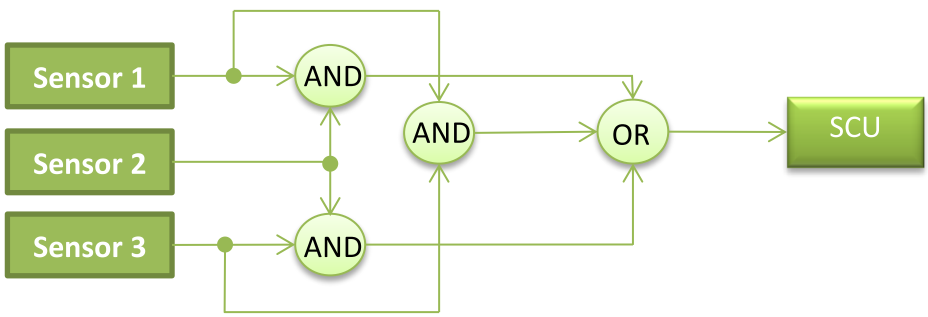


Figure 4.10 "Voting" concept with three sensors

And finally according to the NORSOK Standard U-CR-005 (1995): "*Reliability of the subsea control system should always be optimized to result in minimum lifecycle cost*", meaning that the level of reliability should be made with regards to the planned lifecycle cost of the system.

4.4 Maintenance planning

Let us imagine that designed reliable condition monitoring system is installed at the subsea facility and operators and maintenance engineers are ready for using it. Now it should be used for maintenance planning and prevention of the unexpected shutdowns at subsea plant.

Figure 4.11 shows an example of subsea equipment performance degradation trend. Performance degradation could be calculated based on the readings from several sensors. In the beginning of the trend we see the green line showing good performance within the acceptable limits. After a while we see that the trend changes its color from green to yellow. This is a right time for maintenance. The maintenance needs to be carried out before the trend will turn red which indicates the possibility of the equipment breakdown. In order to implement necessary repair it needs to be ordered required spare parts and services from the expert company. The delivery time for required spare parts needs to be investigated and known in advance before the line would enter the “yellow zone”. The same procedure is applicable to the maintenance company: they should have a people and equipment in place for subsea operations. Therefore, while making the limits for different condition monitoring measures, many things needs to be considered to make a proper upper and lower limits for “yellow zone” when maintenance needs to be carried out.

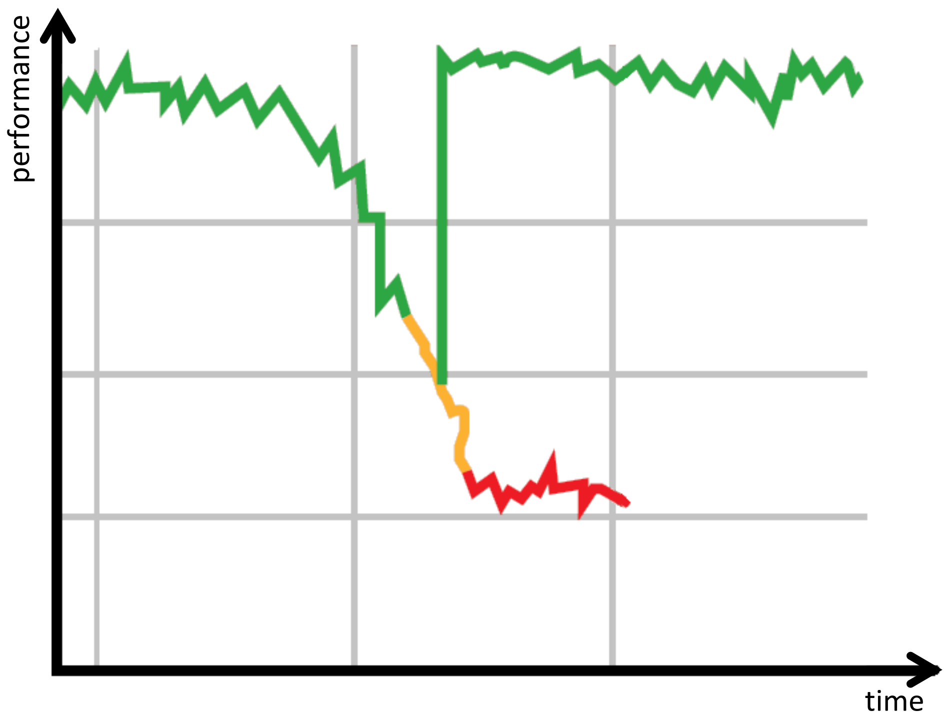


Figure 4.11 Trend showing subsea equipment performance degradation (fmctechnologies.com)

4.5 Towards integration of condition monitoring systems

While studying of different systems for subsea condition monitoring it has been observed that nowadays every equipment supplier uses its own automation solution to execute maintenance planning. Figure 4.12 shows exactly the way it is done now: FMC condition monitoring system works with FMC equipment, ClampOn is following measurements from their detectors, same applies to Naxys. The more equipment suppliers the oil and gas operator selects, the more monitoring systems company needs to order. Such disintegrated concept of condition monitoring system costs more money and resources for the company. People need to run around the facility to overview different equipment statuses on the different computers. System Human Machine Interface (HMI) from different suppliers differs as well. Therefore operator should be able to switch from one HMI type to another; he needs to react fast and be ready for making decisions.

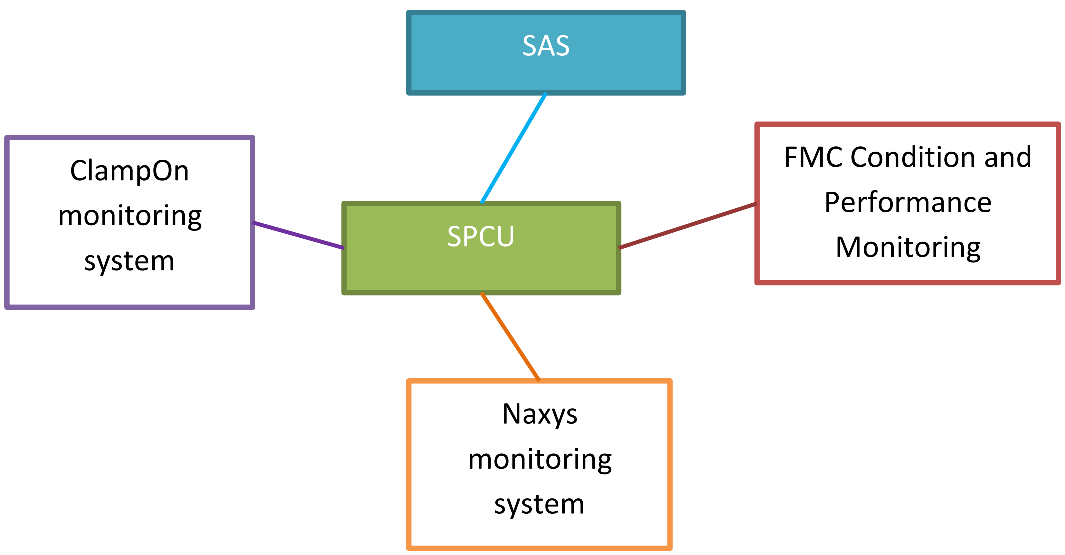


Figure 4.12 Current disintegrated subsea conditional monitoring system concept

The main reason for disintegrated condition monitoring systems is the absence of common topside protocol which allows communication with subsea devices produced by different companies. Different suppliers have their own protocol to read data from the sensors; therefore it is a challenge to create integrated control system.

Oil and gas companies understand this issue; therefore in collaboration with subsea engineering companies and subsea equipment suppliers they are developing a standard communication protocol for topside control system allowing it to monitor the data from subsea sensors from different suppliers. The name of this protocol is MDIS. MDIS stands for MCS-DCS Interface Standardization, where MCS is Master Control System and DCS – Distributed Control System. In proposed design of condition monitoring system, SPCU (Subsea Power and Communication Unit) is a type of extended MCS, as SPCU provides power supply, and SAS represents DCS system. Common communication protocol for topside control system is going to simplify implementation of data communication links and increase the data quality.

5. Concluding remarks and future work

The main purpose of this master's thesis was to propose reliable design of condition monitoring system for subsea processing plant.

Firstly paper described subsea environment and condition where subsea equipment needs to operate and why condition monitoring is so important for subsea installation.

Secondly report explained what kind of effective maintenance practices are available and how they can be used in subsea. The focus was made to the condition-based maintenance, mainly how condition monitoring can be used together with subsea equipment, types of subsea sensors that are available on the market, successful examples of condition monitoring from current subsea facilities. Moreover the common subsystems and equipment of subsea plants and failure modes of some electrical and process equipment were described.

Thirdly we looked at the methodology for writing this thesis. Special attention was given to the international and Norwegian standards which are relevant for subsea maintenance activities and condition monitoring system.

At last we looked at the design of the condition monitoring system for subsea plant. Special attention was given to the electrical parts of the system, how electricity reaches subsea, which equipment is used for it at subsea and topside. Then we discussed how to make design reliable and practical use of condition monitoring system in planning of the maintenance activities. At the end we made a brief look at current challenge related to completely isolated conditional monitoring systems from different manufacturers that is used in current subsea installations.

At the end of the master's thesis which is related to subsea and conditional monitoring systems the following conclusion remarks are made:

- Very little information available about subsea installations, mainly conference papers and information from internet about different subsea equipment suppliers formed a basis for this master's thesis. Unfortunately conference papers do not give too many details regarding the electrical equipment, for example, how electrical connections are made in subsea and how they are protected against the water ingress. It has been mentioned that as subsea and subsea equipment is a very fresh area, companies are very cautious in publishing any detailed information most likely because of the competitors. However openness can bring subsea companies many benefits, like publishing paper is a sort of marketing, oil and gas companies could find out more about subsea knowledge and experience of service companies. At the same time such companies can attract fresh bright minds which may help them to create more effective technologies. Besides subsea companies can work together on some issues.

- Condition monitoring is not just automation systems. It is not enough just to connect signal and make a process pictures for HMI (Human Machine Interface). Condition of the equipment could be a set of many different sensor measurements. Every condition should be assigned with the proper limits to know exactly when to start maintenance planning. This requires knowledge about equipment failure modes, symptoms and its development to make proper alarms for maintenance people.

- Details such as availability of spare parts, delivery time and availability of service companies should be known in advance in order to plan the effective maintenance.

- As subsea field development is a new area, much information is still hidden from the companies. Therefore every system component needs to be tested more thoroughly. This would make the system more robust and improve reliability.

- Oil and gas operators, engineering companies and subsea equipment suppliers should continue moving towards integration of the condition monitoring system. Common integrated condition monitoring systems which incorporates equipment and sensors from different suppliers would make maintenance planning easier, better and more effective. If all the subsea components located in one place, then work of operators and maintenance engineers would become easier, as they would not need to move from one screen to another, adapt to the different HMI, which may vary from supplier to suppler.

Recommendations for the future work

The design of the condition monitoring system is presented very generally, not so many details are included due to the time constraints and limited information available about the topic. The main focus was to show how the condition monitoring system could look like from the subsea to the topside, which equipment could be used.

While working on this master thesis many, interesting topics for future theses were found. Among of them are:

- Every condition monitoring method described in chapter 2 could be an independent master's thesis. Sand and corrosion monitoring, leakage detection for subsea installations could form perfect master's theses. The focus in these papers could be made not only to the subsea practices, but also to the methods used at topside facilities. It could be interesting to suggest how methods used onshore could be adapted to subsea installations.
- Main attention should be given to the water quality monitoring. Many findings and discoveries can be made here, as there is no effective method available which provides remote real-time integrated measurements of oil in water, solids in water, content of H_2S, heavy metals and radioactive materials, size of solid particles and their distribution in the fluids.
- It could be interesting to study and compare different communication protocols for topside systems which currently used for monitoring of subsea equipment. This work would be very important and useful for MDIS (MCS-DCS Interface Standardization) project.

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