Western Norway
University of
Applied Sciences

BACHELOR'S THESIS

Improving the efficiency of Deepsea Aberdeen's central cooling system

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28/05/2021

Document Control

Report title BO21-20 Improving the efficiency of Deepsea Aberdeen's central cooling system	*Date/Version* 31. May. 2021/1.3 *Report number:* B021E-20
Author(s): Even Sælen Uthaug Kjell Martin Dagsvik Patrick Desmond McCann Sindre Eide Steffensen	*Course:* ELE150 *Number of pages including appendixes* 58
Supervisor at Western Norway University of Applied Sciences Svein Haustveit	*Security classification:* Open
Comments: We, the authors, allow publishing of the report.	

Contracting entity: Name of company or institution	*Contracting entity's reference:* (Number or ID if any)
Contact(s) at contracting entity, including contact information: *Odfjell Drilling, Thomas Borsholm*	

Revision	**Date**	**Status**	**Performed by**
0.1	29/01/2021	Draft Issued to Odfjell Drilling	HVL Students
1.0	29/01/2021	Issued for Validation	HVL Students
1.1	20/05/2021	Issued rough draft	HVL Students
1.2	25/05/2021	Issued draft	HVL Students
1.3	28/05/2021	Issued paper	HVL Students

Preface

This bachelor thesis is written as a solution for Odfjell Drilling's cooling system, and as the final assignment for our bachelor's degree in Automation engineering at Western University of Applied Sciences (HVL).

We would like to thank everyone involved in this project at Odfjell Drilling, both from our visit to the platform back in December 2020 and from meetings and discussions throughout the year. We would especially like to thank Thomas Borsholm for the constant help and support he has provided while working on our thesis. We would also like to thank our internal supervisor at HVL, Svein Haustveit, for guiding us in the right directions. Lastly, we would like to thank Lars Manger Ekroll from HVL for providing us equipment that has proved to be invaluable for developing and testing our software.

Summary

In this project our job was to explore the possibility of optimizing the central cooling system on one of Odfjell Drilling's Semi-submersible drilling units. The project involved developing a solution to optimize the operation of the central cooling system and determining the saving potential of the solution. The scope of the project was initially to evaluate the freshwater part of the cooling system. We later expanded the scope to also include the seawater system as there was an even greater savings potential.

The recommended solution we will discuss in our thesis is to implement variable frequency drives (VFD) to the seawater and freshwater pump. The seawater cooling pumps will run at variable speed based on the demand for cooling in the freshwater system. The freshwater cooling pumps will be able to run at constant pressure meaning that the system will actively control itself to only deliver the needed flow. In addition to the VFD's on the freshwater cooling system, we will also recommend mounting pneumatic actuators on several consumers of the freshwater cooling system. This will reduce unnecessary use of cooling water and reduce the overall flow of the system.

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Abbreviations

FBD	Function block diagram
FW	Freshwater
FWD	Forward
IAS	Kongsberg’s Integrated automation system
MCC	Motor control Center
MODU	Mobile offshore drilling unit
PKW	Parameter values
PLC	Programmable Logic Controller
PT	Pressure transmitter
PZD	Process Data
STBD	Starboard
STO	Safe Torque Off
SW	Seawater
TT	Temperature Transmitter
TV	Temperature control valve
VFD	Variable frequency drive
VSP	Variable speed pump
WCFDI	Worst case failure design intent

1 Introduction

This project report will present a solution to the stated problem of our bachelor thesis at the Western Norway University of Applied Sciences. The purpose of the thesis is that we, as students, must acquire knowledge about performing and solving a project together in a group. The problem was given to us by Odfjell Drilling. They wanted us to look at the possibilities of reducing the energy needed to operate the central cooling system on Deepsea Aberdeen.

In later chapters, we will describe the steps we will take, how we acquire the necessary and relevant information to find a solution. In the main part of the report, we will describe the specifications and other details that are relevant to the task. Examples of this are the description of hardware, software, protocols, standards, test procedures and application designs.

1.1 Contracting entity

Odfjell Drilling is an offshore drilling contractor that specializes in the operation of deep-water, harsh environment, Mobile Offshore Drilling Units (MODU). The offshore industry is very competitive and everchanging. The last couple of years there has been an extreme drive to become more environmentally friendly. This means that for Odfjell Drilling to stay competitive in the market, it is essential to have the energy efficient rigs.

Odfjell Drilling currently has a fleet of five rigs. In our thesis we will be focusing on Deepsea Aberdeen. Deepsea Aberdeen is a sixth generation MODU designed for harsh environment areas. The rig was delivered from Daewoo shipyard in South Korea in 2014. Deepsea Aberdeen has for the last couple of years operated on the coast of Scotland. The vessel has recently finished its contract and is in the early stages of new contracts in Norway. As a result of the environmental drive, especially in Norway, the vessel will be undergoing several upgrades to make it more energy efficient.

Figure 1. Deepsea Aberdeen

1.2 Problem description

With the everchanging environmental standards, Odfjell Drilling has given us the opportunity to have a look at the rigs cooling systems, with the aim of saving energy. The rig is designed to operate at maximum load with a seawater temperature of 32 °C. Normally it is operating at a much lighter load and is currently operating in the North Sea, which has an average temperature span of 6-17 °C. Currently both the seawater and the freshwater pump operates at full speed even though there is no need for it. This leads to unnecessary usage of energy and accompanying emissions. The aim of our bachelor thesis is to design a dynamic control system that actively regulates the cooling system to reduce the energy consumption onboard.

As the systems stands today, it is quite clear that the cooling system runs inefficiently in terms of fuel usage. The low temperatures in the North Sea, combined with the amount of cooling needed across the consumers on the rig makes the current system over dimensioned. This means that the pump is not required to run at maximum speed to provide enough pressure to uphold the recommended flow throughout the pipes.

Due to the high pressure from the pump, several pipes were measured to receive higher flow than recommended, and as such lead to higher erosion of the pipes, which has historically been a problem on similar rigs. Additionally, higher flow will lead to higher noise levels. We also discovered that valves were being closed by crewmembers to combat this noise. The of closing valves will result in a pressure increase in the system. Additionally, it will cause the flow obstructed by the valves to move elsewhere, leading to increasing the flow through the other pipes/consumers instead. This effectively transfers the problem to a new location in the system.

1.3 Cooling System Description

Deepsea Aberdeen is divided into four quadrants, each with its own diesel-powered generators, power grid and cooling system. Due to the rig's quadrant-based design, we have decided to focus on one of the quadrants, The Port aft. quadrant, to gain a better fundamental understanding of the system. We will later in the project do a reduced analysis on the other three regarding the total savings potential.

The cooling systems in each quadrant is functionally almost identical. Each system consists of a freshwater and a seawater sub-system. The freshwater system is a closed loop pump circuit, while the seawater system is an open loop pump circuit. The seawater system is used to cool down the freshwater through a heat exchanger. The purpose of the freshwater circuit is to cool down consumers on the rig. Typical examples of consumers needing cooling includes Diesel engines, generator, transformers, and breaking resistors. To illustrate the core functionality of the system, we made a simplified model shown in figure 2. Figure 3 illustrates that the system consists of many duplicate components in parallel to each other. This is due to redundancy and maintenance reasons. It is important to note that the freshwater circuit has most of its consumers in parallel to each other. In addition, the freshwater is pumped from below sea level to upper deck level, approximately 40 meters in height.

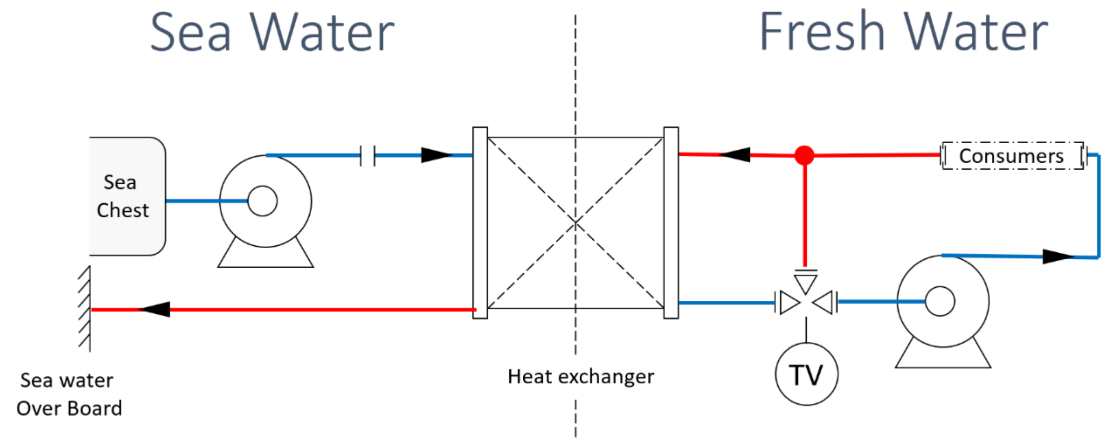


Figure 2. Simplified illustration of cooling system.

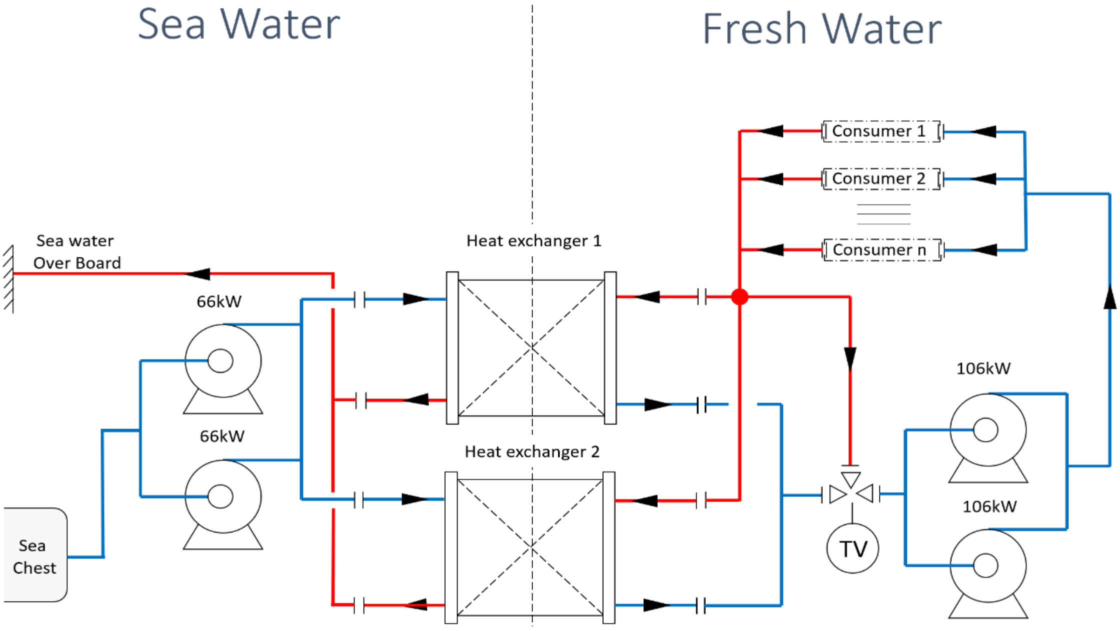


Figure 3. Illustration of cooling system, which is functionally almost identical for each quadrant.

The system regulates the temperature of the freshwater circuit through a three-way valve (TV) and a temperature transmitter. The temperature control system is located at the suction side of the pump, in front of the heat exchanger. If the temperature is above selected setpoint, which is currently set to 36 ^{o}C, the control system will let more water through the heat exchanger. If the temperature is below the setpoint, more water will bypass the heat exchanger. This temperature regulation must be taken into consideration when assessing the control strategy of both the freshwater and the seawater circuit.

1.4 Current energy usage

As the system stands today, it consumes 684 kW of electrical power, equivalent to 6 GWh each year. All this energy is currently being produced with diesel generators on board the rig, consuming about 1200 tonnes of diesel each year. This amounts to around 3800 tonnes of Co2 and 52 tonnes of NOx [1], and with the increasing focus on a sustainable industry, reducing this would be a competitive advantage for Odfjell. To put these numbers into perspective, this is equivalent to 375 household's energy consumption, or 2400 fossil cars greenhouse gas emissions [2]. The cost of running this system including diesel and environmental taxes [3] [4] is about 9 million NOK annually.

1.5 Specification of requirements

Project requirements

- Design an alternative system for freshwater cooling.
- Evaluate the financial viability of the implementation of VFD and automated valves on seawater cooling system.
- Design an alternative system for seawater cooling.
- Evaluate the financial viability of the implementation of VFD on seawater cooling system.
- Execute Failure mode effect analysis on design.
- Evaluate the effect on climate (CO2, NOx)
- Make materials list.
- Create necessary documentation for Kongsberg software implementation.
- Create ABB Drive software
- Create commissioning procedures.

Technical requirements

- Redundancy according to rig design philosophy
- Automated/remote operated flow control on consumers with high wastage

1.6 Redundancy philosophy

The design philosophy of Deepsea Aberdeen follows DNV-GL recommended guidelines for system design on dynamic position (DP) vessels [5]. By definition, a dynamic positioning vessel automatically maintains its position exclusively by means of controlled thrust. Deepsea Aberdeen is designed to a DP-3 standard, which is the highest tier of standard in its classification. The DP-3 classification requires that the vessel will not lose its position due to a single failure of any critical systems such as, generators, thrusters, or switchboards. The DP-3 classification also requires the loss of an entire subdivision/redundancy group due to a fire or a flooding should not hinder the vessels DP compatibilities. It is important to understand that the central cooling system delivers cooling to critical systems onboard, therefore it is important for us to take the DP-3 requirements into consideration when making changes to the system.

Deepsea Aberdeen is equipped with a K-Chief 700 control and monitoring system delivered by Kongsberg Marine. The system is a fully integrated automation system covering Power management, machinery, propulsion, and safety system. The systems are built on a distributed IO and control design, placing the IO’s closer to the process, making it flexible and redundant. The layout below shows a typical K-Chief 700 system. All the upgrades that we will be done to the central cooling system will have to be integrated into the K-Chief machinery control system.

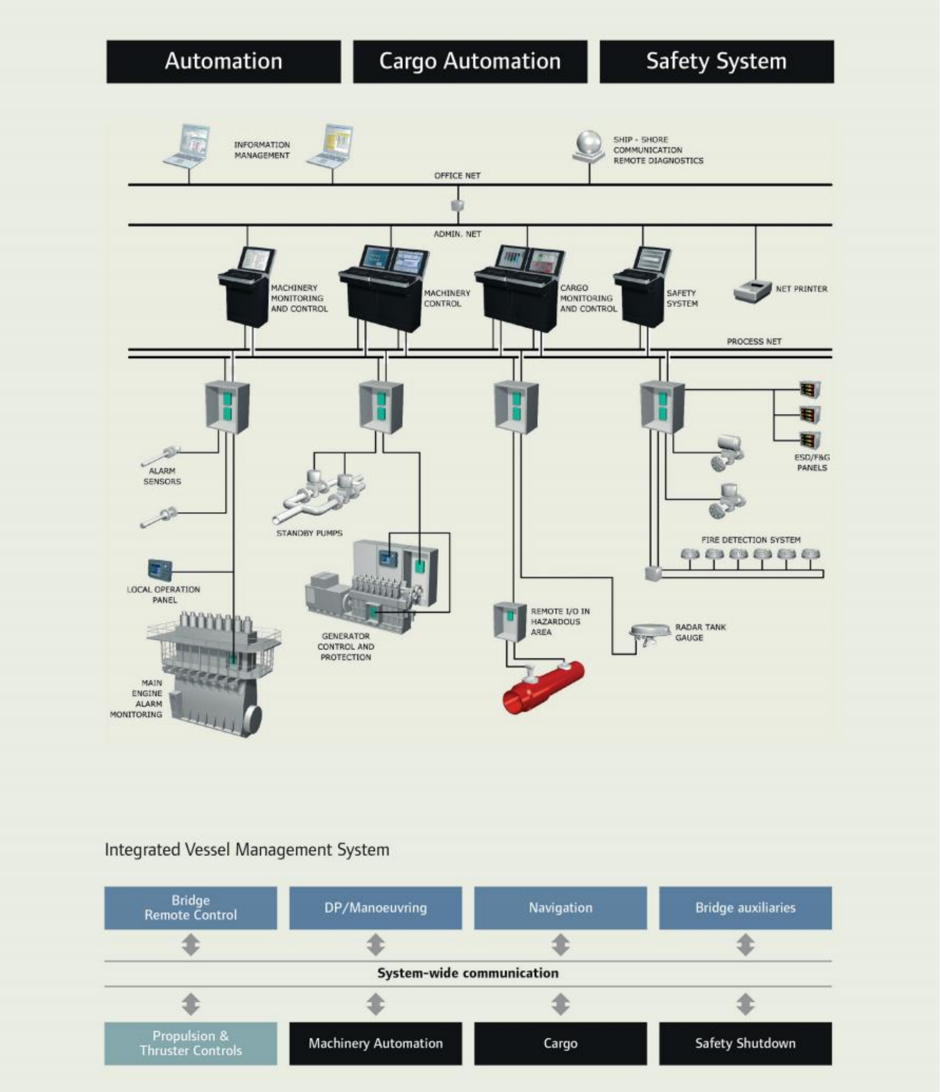


Figure 4. Typical layout for a K-Chief 700 control system

2 Main Solutions Ideas

The project is divided into three technical sub-projects and a sub-project that focuses on budgeting and the saving potential of the technical solutions. The three technical sub-projects are VFD implementation on freshwater system, implementation of automated valves and VFD implementation on seawater system. We will discuss the main ideas for these in this section of the report. The next section, 2.1, will cover some information on power consumption and total pressure head.

2.1 General Information

As you can see in the formula for Power consumption (P) of a centrifugal pump in a closed loop system. The only two independent variables are Flow rate (Q) and Pump Head (H). Meaning that to reduce the power consumption, we must reduce these. The pump head is the total resistance the pump must overcome. The head is usually measured in Bar or in “meters of head”. Meters of head represents a height of an equivalent static column of water. Information on this topic was based on a document titled Calculating the Pump Head by Fluid handling Inc.

$$P = \frac{Q*H*\rho}{367*n}$$

$P = Power\ consumption\ (W)$
$Q = Flow\ (m^3/h)$
$H = Total\ developed\ head\ (m)$
$\rho = Density\ (kg/m^3)$
$n = Efficiency$

The pump head consists of static head, friction head and velocity head. Static head represents the net change in height. The friction head, which is also referred to as pressure drops, occurs when the water flows through any component. These are for example heat exchangers, piping, fittings, and more. The velocity head is the energy required to accelerate water to a higher velocity. In closed loop systems, such as the FW circuit, the starting point is the same as the ending point. Therefore, the starting velocity equals the final velocity, so velocity head is not a consideration.

The freshwater cooling system is a closed loop circuit. The pump is required to transport freshwater from the pontoon level to consumers at the upper deck level, a height difference of approximately 40 meters. Since the system is closed looped, each meter of altitude the water is pumped upwards has an equal drop in height downwards. Therefore, the system is unaffected by static head. The velocity head is not considered in closed loop systems as stated earlier. This means that the total pump head, the resistance the pump must overcome, is entirely the friction head of the system. Where the pressure drops due to friction is from for example piping, heat exchangers, and various fittings. [6] [7]

$$Total\ pump\ head = Friction\ Head$$

As the system stand today, the pump is either operating fully on or fully off. To make the system more energy efficient, we must control the speed of the pump. This can be done by modifying the existing system and installing a Variable frequency drive (VFD) allowing us to control the pump speed.

2.2 VFD implementation on the freshwater system

Controlling the pump with a variable frequency drive (VFD) can reduce energy consumption by regulating the output pressure of the pump. Ensuring sufficient flow through consumers while reducing setpoint pressure can significantly reduce power consumption. Regulating for constant setpoint pressure also gives us the ability to close valves of individual consumers without increasing pressure in the system.

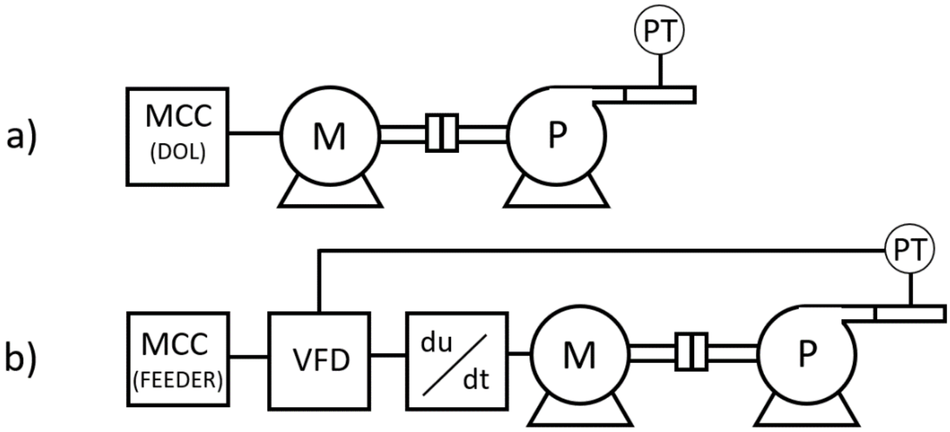


Figure 5. Illustration of the current setup(a) and the implementation of the VFD (b)

2.3 Implementation of automated valves

As the system stands, the pump is operating at a constant full speed. The valves in the system are also intended to be fully open, even though we observed that crew members had manually closed them. The result of closing the valves of consumers is a pressure increase in the whole freshwater system. By using the synergy effect between using a VFD to regulate for pressure we can close valves to reduce flow without increasing pressure. This means we can design a control system for automated flow control for individual consumers of the cooling water.

Our solution idea consists of mounting actuators on existing valves to achieve control over the flow to these consumers. The valve control system will be able to completely cut off inactive consumers. This will lead to a reduction flow, which means the pump must work less to maintain the setpoint pressure. Different consumers may require different control strategies depending on energy savings relative to cost and risk management. This will be discussed in the technical solution for automated valve system.

2.4 VFD implementation on the seawater system

The purpose of the seawater cooling system is to reduce the temperature of the freshwater cooling system. As of now, the system is running at full speed. The solution will be installing a VFD, like the freshwater cooling system. Instead of regulating for pressure, we will be regulating the temperature in the freshwater circuit. Essentially, we want to control the circulating flow of the seawater circuit, depending on the temperature of the freshwater loop. This will substitute the current temperature regulation of the three-way valve. By doing so we will bypass the existing three-way valve, causing all the FW to flow through the heat exchangers, reducing the excess SW power wastage.

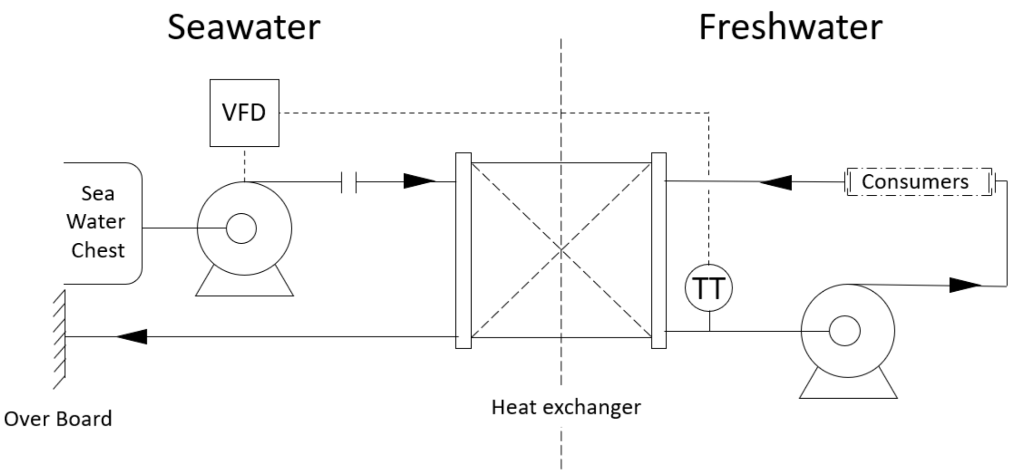


Figure 6. Simplified model, including VFD and temperature transmitter.

3 Freshwater and Seawater VFD Solutions

3.1 General Solution

In our design we have decided to incorporate a distributed control philosophy. The IAS will be responsible for sending start, stop and setpoint reference. While the ABB Drive will have full control over the actual control loop. By doing it this way, we relieve Kongsberg of significant responsibility to make a more redundant system. In the case of a failure in the IAS, the system will continue to operate normally. Additionally, we believe that we can reduce the commissioning costs significantly, due to Kongsberg not having to take the time to finely tune the PID controller. This can be done internally by Odfjell.

We have decided to use the ABB ACS880 VFD due to how simple the drive is to use and commission in the field. Additionally, the software for the Drive is extremely user friendly and free to use. When working on this project we are intending to make the solution simple enough for someone internally in Odfjell Drilling to commission the drives.

Figure 7. Unpacking the ABB ACS880 VFD.

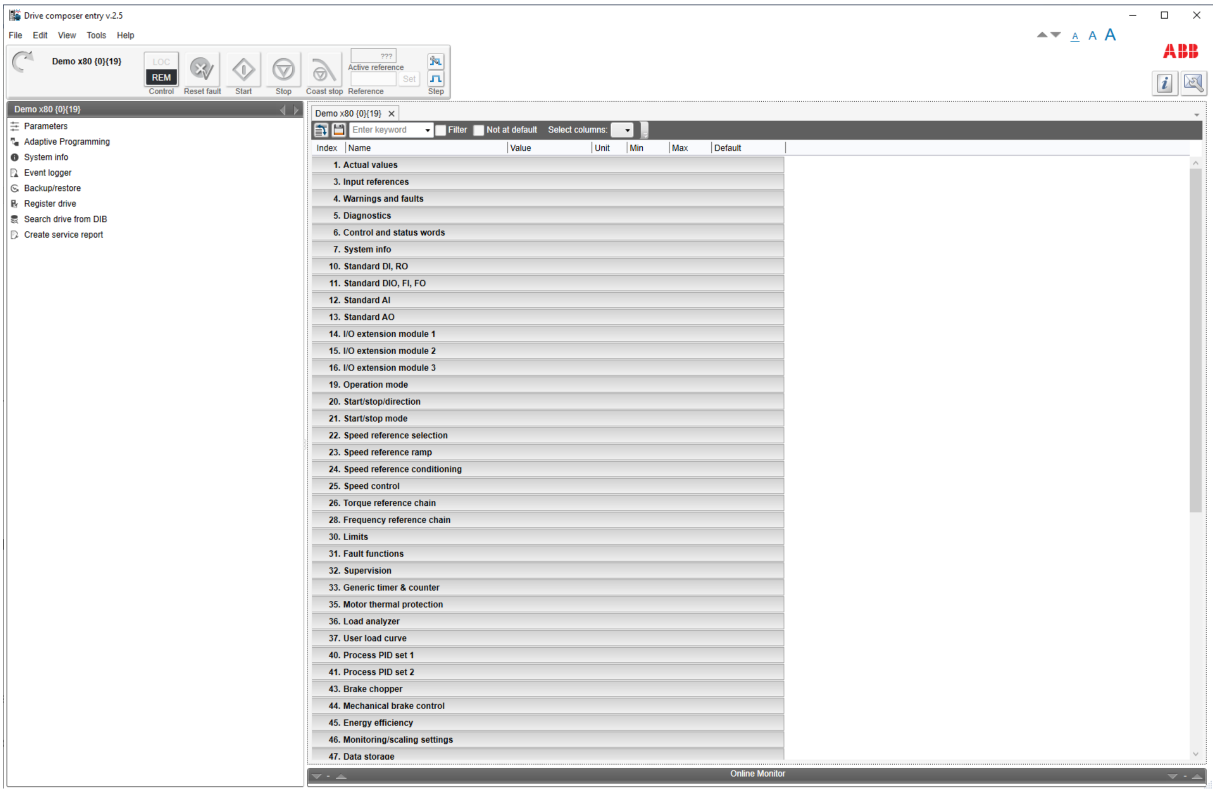


Figure 8. Menu selection of the ABB Software interface.

When we had decided that we were going to go with the ACS880, we had to decide if we wanted to use the wall mounted drives or the floor mounted drives. In our opinion the decision was quite simple. The Floor mounted drives are made in Rittal steel cabinet solutions and are notorious for rusting when placed in harsher conditions. Our intention with this project has always been to make as local as possible. Placing the floor mounted locally in a Seawater pump room would to some degree be irresponsible. The wall mounted drives however are made in plastic with a relatively high IP rating of IP55. The wall mounted drives are also significantly easier to handle due to their smaller frame size.

In addition to the ACS880's being simple to work with they are also relatively cheap. In the case of one or multiple drives failing, it is simply cheaper and more cost efficient to replace the whole drive, rather than having Field Service engineers from ABB come out and repair them. This would not be the case if we chose to use the floor mounted cabinets.

3.1.1 Programming the VFD

A big reason for the use of ABB drives is the integrated adaptive programming feature. It is essentially a simple function block diagram (FDB) programming feature. We will be using this feature to determine the setpoint pressure for the PID controller and the fan control for the Du/dt cabinet.

One of the features we wanted to incorporate into the drive was that the drive was going to continue operating normally at the assigned setpoint, even in the case of a communication loss. To do so we had to create some simple logic to compare the input signal from the PROFIBUS to the last input signal. In the case that the new input signal is smaller than "1" we know that we have had a communication loss due to all the input signals being "0" in the case of a failure. If this happens, the drive will use the old value saved in the data storage parameter in the drive.

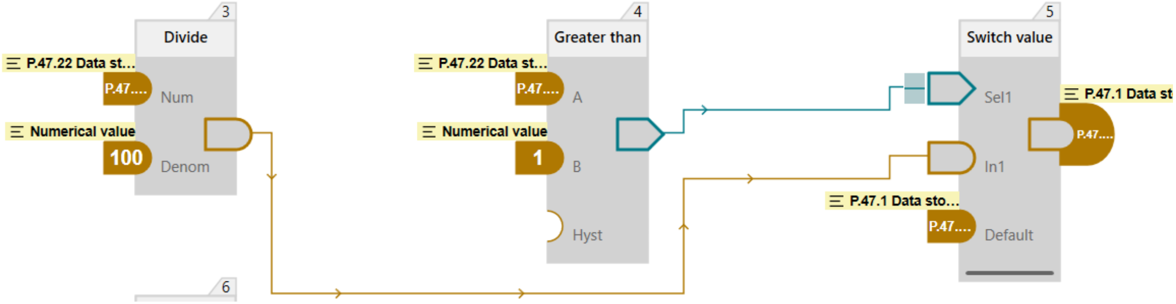


Figure 9. FBD programming with Abb software

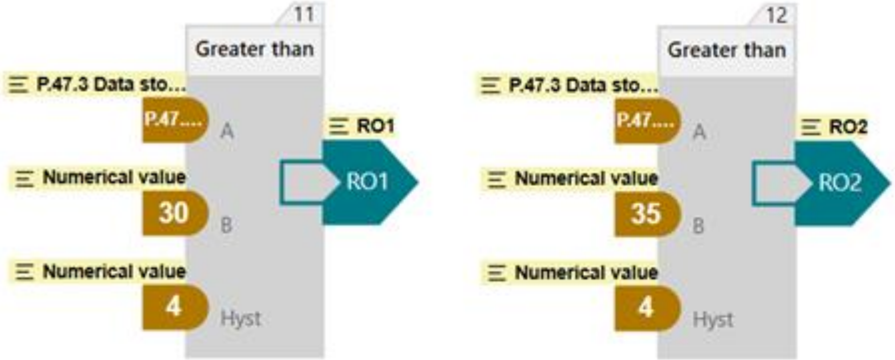


Figure 10. FBD programming for the fans in the du/dt cabinet

3.1.2 PID controller

A PID controller (proportional-integral-derivative controller) is a control loop system that calculates an error value based on the current output value and a chosen setpoint value. The PID controller will correct for this error to decrease it for each loop, until the output value equals the set point value. The correction is calculated as a sum of three different control terms, a proportional, integral, and derivative term. The proportional term corrects the current output value proportional to the target value. As the error approaches zero, so does the correction, meaning that the target value will never be reached. The integral term increases the error value by combining the previous error values, ensuring the controller does not stop before the target is reached. However, this will result in overshoot, as the combined error will not reach zero without going past the target value. The derivative term slows down the increasing error value from the integral term to minimize overshoot.

3.1.3 Communication Protocol

Each quadrant will consist of two Profibus-networks to ensure redundancy. Each network consists of a Kongsberg RCU (remote controller unit), one SW pump VFD, and one FW pump VFD. The Kongsberg RCU will act as the Master, and the VFD's will act as slaves. Additionally, for the VFD to be Profibus compatible we must add a Profibus-DP card to one of the free slots on the drive.

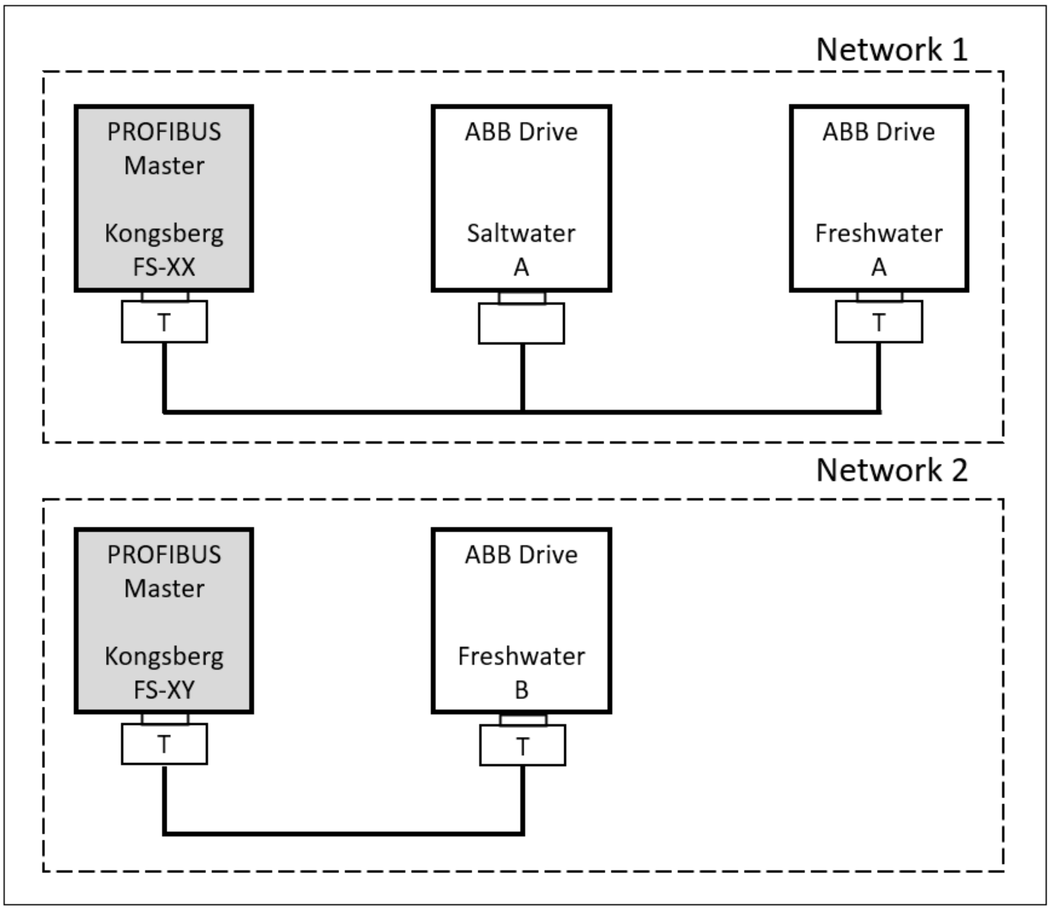


Figure 11. Network setup, divided into two sub-networks for each quadrant.

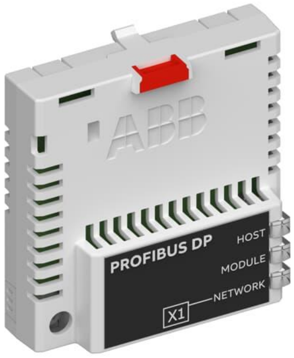


Figure 12. Profibus DP-card to make VFD Profibus compatible

When deciding on the telegram we wanted we were quite clear on the fact that we did not want to change any parameter values (PKW) and that we wanted to be able to access as much process data (PZD) as possible. Therefor we decided to use the PPO 6 telegram, which has no parameter values and 10 process data.

Telegram Name	Cyclic telegram Length
PPO 6	**0 PKW + 10PZD In/Out**

PZD – Process data

PKW – Parameter values

Table 1. Input data for VFD.

Address	Name	Length	Description
FBA Data out 1	Control Word	16bit	See control Word description below. (Start, Stop, Reset)
FBA Data out 2	Pressure reference	16bit	Pressure reference = pressure setpoint in IAS*100. Example: 7.2Bar = 720.

Table 2. Output data for VFD.

Address	Name	Length	Description
FBA Data in 1	Status Word	16bit	See status Word description below.
FBA Data in 2	Speed %	16bit	Range 0-100%
FBA Data in 3	KW output	16bit	Power output = (Value from drive)/10000. Example: 16000/10000 = 1.6kW

Table 3. Control commands sent as 16-bit word from IAS to VFD. Relevant bits are highlighted.

Bit	Name	Description
0 (LSB)	Off1 Control (Start Stop)	True = start, False = stop
1	Off2 Control	ALWAYS TRUE
2	Off3 Control	ALWAYS TRUE
3	Run	ALWAYS TRUE
4	Ramp out zero	ALWAYS TRUE
5	Ramp Hold	ALWAYS TRUE
6	Ramp In zero	ALWAYS TRUE
7	Reset	True = reset alarm and faults
8	Inching 1	ALWAYS FALSE
9	Inching 2	ALWAYS FALSE
10	Remote cmd	ALWAYS TRUE
11	Extr ctrl loc	ALWAYS FALSE
12	User bit0	ALWAYS FALSE
13	User bit1	ALWAYS FALSE
14	User bit2	ALWAYS FALSE
15 (MSB)	User bit3	ALWAYS FALSE

Table 4. VFD status which is sent as 16-bit word to IAS system. Relevant bits are highlighted.

Bit	Name	Description
0 (LSB)	Ready to switch on	True = ready
1	Ready run	True = running
2	Ready ref	NA
3	Tripped	True = tripped
4	Off2 Inactive	NA
5	Off3 Inactive	NA
6	Switch-on inhibited	NA
7	Warning	True = warning
8	At setpoint	NA
9	Remote	True = System in remote mode
10	Above limit	NA
11	User bit0	NA
12	User bit1 (PT sensor failure)	False = Pressure sensor failure. pump stops and stby pump has to start
13	User bit2 (Du/dt cabinet temperature too high)	True = high, alarm needs to be displayed in IAS.
14	User bit3	NA
15 (MSB)		NA

3.1.4 Thermal protection

Thermal protection will be installed to prevent damage caused by overheating. The protection system will consist of built-in thermistors inside the windings of the motor and a FPTC thermistor protection module connected to the ABB VFD. The FPTC has two inputs, a fault input, and a warning input. The fault input triggers the “Safe torque off” function in the drive, limiting all torque generation, essentially stopping the motor. The warning input generates a warning signal to the drive. This signal is purely for indicating a fault and has no other function.

Figure 13. Thermistor motor protection

In the figure below, we can see how the FPTC module must be connected to the motor and the existing STO IO clamps.

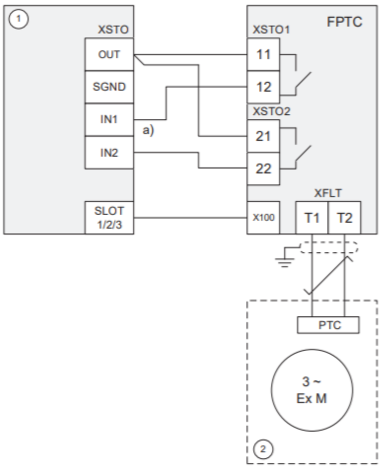


Figure 14. Connection diagram from ABB hardware catalog

3.1.5 Du/dt filter

A VFD typically creates a lot of noise from the drive output, which can be damaging to the motor. A VFD produces a lot of fast rising output voltage when converting the DC power source to an AC output, causing the output voltage to be higher than desired voltage. A typical motor like the one being used in the experiment is not properly isolated to handle the higher voltage, causing additional stress on the motor, cable insulation and motor bearings.

To reduce the risk of damaging the motor we will be using a Du/dt filter. A Du/dt filter uses inductors to reduce the Du/dt-value of the output of the drive, making the outgoing waveforms significantly smoother. During testing on the rig, the motor would most likely not have taken any damage based on the short amount of time it was running through the VFD, but it was a precaution we took for safety.

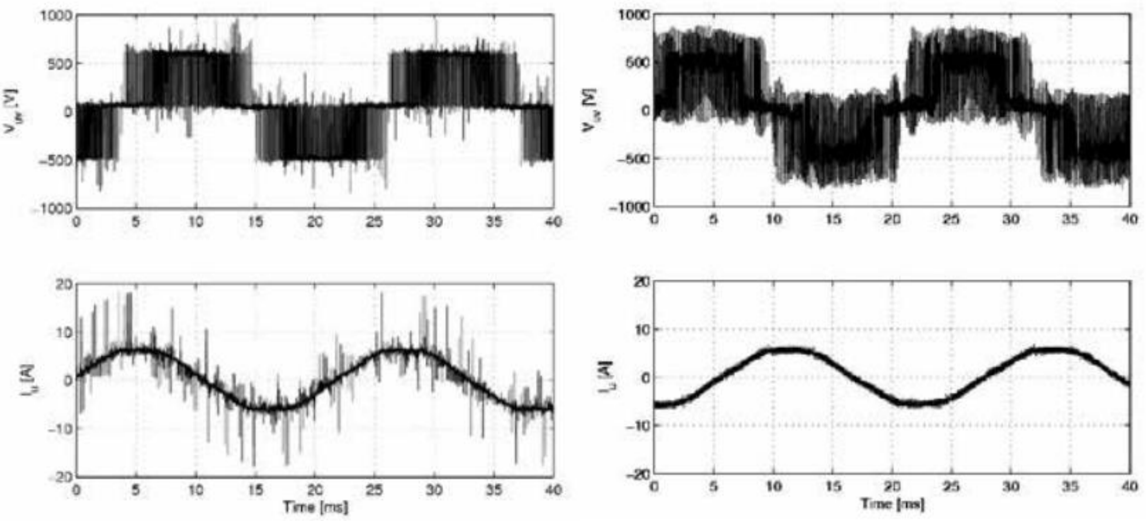


Figure 15. Voltage and current without filter left, and with filter right.

3.1.6 Upgrading motors for VFD applications

When installing a VFD on a motor, certain requirements need to be met to prevent damage on the motor. The motor winding insulation, motor bearings and the pump operating speed range are the major factors that determines if the motor is compatible with a VFD or not. The motor winding insulation needs to be able to withstand the frequency spikes that may come from the VFD, while the motor bearings must be protected from potential common mode voltages. These voltages can potentially build up and discharge through the motor bearings if not properly isolated.

When running a motor through a VFD, the speed of the pump can be set both higher and lower than the baseline pump speed. This requires the motor to be able to provide itself sufficient cooling with the reduced fan speed that comes with reduced rpm. When driven at higher speed, the pump operating speed range must be great enough to not overload the motor, as the increase in power draw is proportional to the speed increase cubed. Taking these requirements into consideration, the current motor on the rig needs to be upgraded to new ones that meets the requirements. [8]

3.1.7 Mechanical protection for ABB Drives

When we initially proposed to install the VFD’s locally in the pump room, the crew were worried that the drives would be exposed to excess mechanical abuse due to the extensive work and service that takes place in these rooms. In order protect the VFD’s from this abuse, we decided to design a simple stainless-steel enclosure.

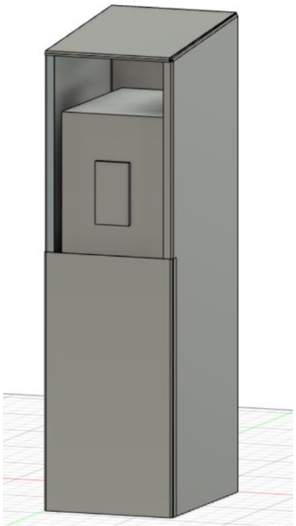


Figure 15. Mechanical protective case for ABB drive

3.2 Freshwater VFD

Onboard Deepsea Aberdeen there are eight main freshwater cooling pumps, two in each pump room. All the pumps will be fitted with Variable frequency drives (VFD) to actively regulate the flow of the FW cooling system by regulating for pressure. The relevant pumps and sensors are listed below:

Tag	Description	Disch. PT
722-PA-001A	FRESHWATER COOLING PUMP PORT FWD	722-PT-103
722-PA-001B	FRESHWATER COOLING PUMP PORT FWD	722-PT-106
722-PA-001C	FRESHWATER COOLING PUMP STBD FWD	722-PT-203
722-PA-001D	FRESHWATER COOLING PUMP STBD FWD	722-PT-206
722-PA-002A	FRESHWATER COOLING PUMP PORT AFT	722-PT-303
722-PA-002B	FRESHWATER COOLING PUMP PORT AFT	722-PT-306
722-PA-002C	FRESHWATER COOLING PUMP STBD AFT	722-PT-403
722-PA-002D	FRESHWATER COOLING PUMP STBD AFT	722-PT-406

3.2.1 Freshwater VFD software

The VFDs for the FW pumps will be controlled by the IAS via Profibus-DP communication. The existing Main/standby pump logic will remain as is. The existing power fault detection is to be eliminated and replaced with pressure fault detection logic. In the following cases below, the main pump is to stop, and the standby pump is to start:

- VFD Tripped
- VFD Pressure fault
- VFD Pressure sensor failure

In the case of a fault, the control room operator has the option to reset the fault in IAS. In the case of communication failure, the IAS is only to start backup pump when a pressure drop is detected, or if manually overridden. Even with a communication failure the VFD should continue to work normally, running on integrated controller unless it has had a power loss.

The VFDs speed will be determined by a pressure controller integrated in the VFD’s software. The pressure setpoint will be written to the VFD by IAS as a 16 bit integer. The VFD will be connected to the relevant PT sensor in series with the IAS, giving both the VFD and IAS access to the same PT data. Speed in percent and power output in kW is to be displayed on IAS control panel. In the case of High Du/dt temp, a warning is to be displayed on control panel and recommended to change drive.

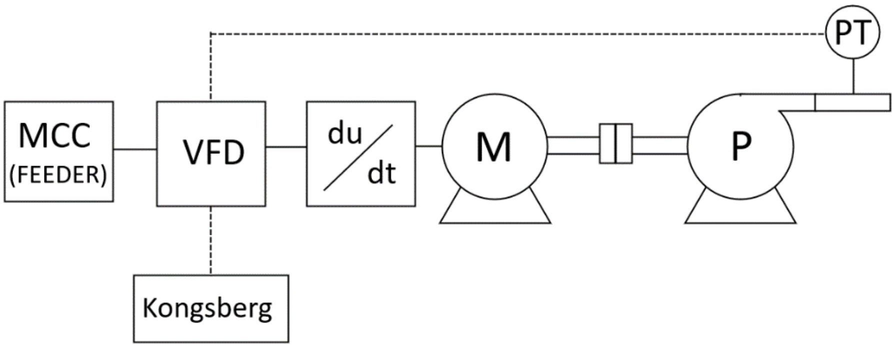


Figure 16. Pressure transmitter used for pump control and fault detection.

3.2.2 Pressure transmitter

For the VFD to obtain the same pressure transmitter signal as the IAS, it was determined that is would be most suitable and cost efficient to connect to the existing pressure transmitter in series with the RCU. By connecting the VFD directly to the PT we can increase the sample rate and eliminate the 100ms delay that would occur if we were to be forwarded the signal from the RCU. See figure below for sensor connection diagram.

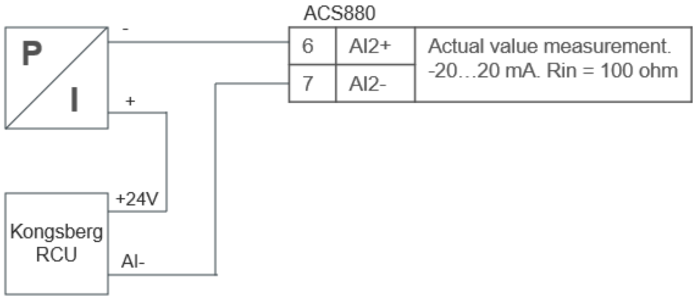


Figure 17. Sensor connection

3.2.3 Du/dt cabinet for FW VFD

Due to ABB not being able to supply a Du/dt filter with a sufficient IP rating for the FW VFD, we had to design out own cabinet solution. The required IP rating for electrical equipment in pump rooms according to DNV GL is IP44 [5], ABB only Supplies Du/dt enclosures up to IP22.

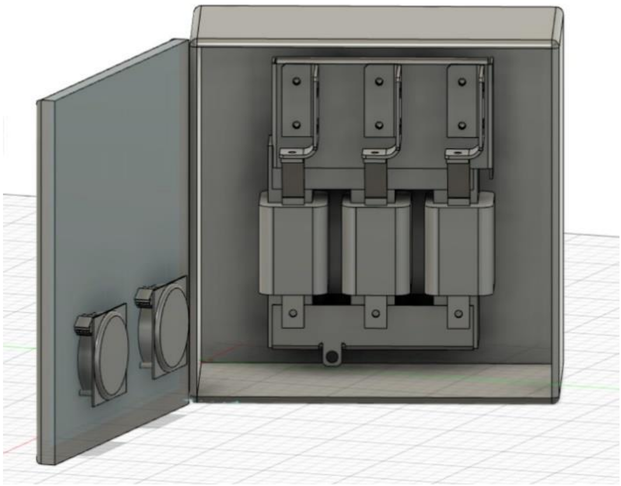


Figure 18. Proposed designed cabinet for Du/dt filter with sufficient IP rating.

Specification for supplier

Description	**Quantity**
Rittal stainless steel 316 cabinet 500x5000x300	1
ABB Du/dt filter FOCH0260-70	1
Rittal 230V fans	2
Rittal exhaust filter	2
Temperature transmitter	1

The proposed design makes it possible for the VFD to control the temperature of the cabinet with the use of the integrated IO’s and relays. The 230V Power from the fans will obtained from the existing space heaters for the old motors. By using this as the power source, the power will come from the same MCC as the motor, eliminating issues regarding getting power from other redundancy groups.

3.3 Seawater VFD

There are eight main seawater cooling pumps. Two in each pump room for cooling the FW cooling system via the central water coolers/heat exchangers. One pump in each quadrant will be fitted with a VFD will be implemented on the SW system to actively regulate the flow of the SW control the FW cooling system temperature.

Tag	Description	Freshwater TT tag.
721-PA-001A	MAIN SEAWATER COOLING PUMP PORT FWD	TBC
721-PA-001C	MAIN SEAWATER COOLING PUMP STBD FWD	TBC
721-PA-002A	MAIN SEAWATER COOLING PUMP PORT AFT	TBC
721-PA-002C	MAIN SEAWATER COOLING PUMP STBD AFT	TBC

3.3.1 Seawater VFD software

The VFDs for the SW pumps will be controlled by the IAS via Profibus-DP communication. The existing Main/standby pump logic will remain as is. The existing low pressure fault detection is to be eliminated and replaced with FW temperature low detection. In the following cases below, the main pump is to stop, and the standby pump is to start:

- VFD Tripped
- VFD Warning
- VFD not able to obtain setpoint temperature.

In the case of a fault, the control room operator has the option to reset the fault in IAS. In the case of communication failure, the IAS is only to start backup pump when a pressure drop is detected, or if manually overridden. Even with a communication failure the VFD should continue to work normally, running on integrated controller unless it has had a power loss.

The VFDs for the SW pumps will be controlled by the IAS via Profibus-DP communication. The motor speed will be determined by a temperature controller integrated in the VFDs software. The Temperature setpoint will be given to the VFD by IAS. The VFD will be connected to a separate Temperature transmitter. The existing temperature transmitter will be used by the IAS to monitor the system. In the case of the VFD not being able to obtain the setpoint, the standby pump is to be started.

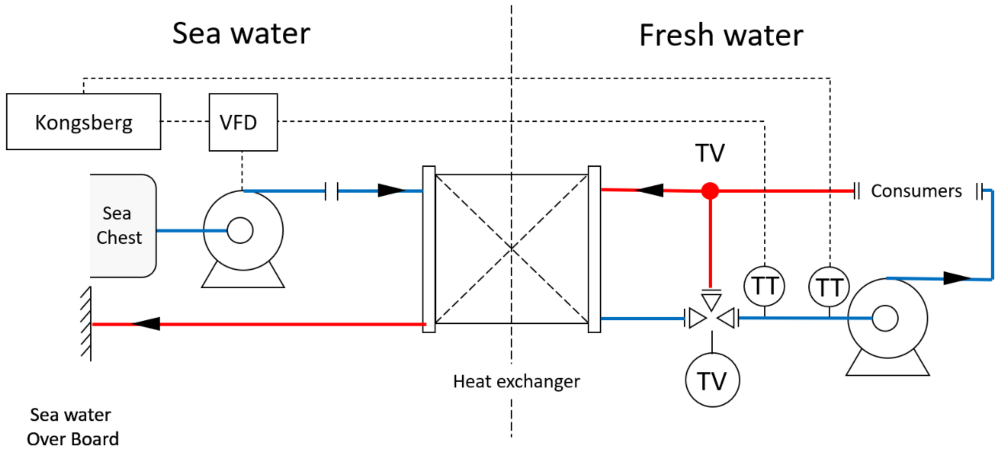


Figure 19. SW sensor setup.

3.3.2 Temperature transmitter

The temperature sensor to be used is an ABB TSP341-N non-invasive temperature sensor. This temperature sensor is mounted on outside of the pipe without the need to drill a hole or shutting down the system. The temperature sensor measures temperature using an algorithm containing the parameters: wall temperature, measuring medium temperature, ambient temperature, medium velocity, pipe diameter and dynamic viscosity. The calculated temperature is sent via a 4-20mA analog signal from a temperature transmitter with a response time of T90 < 30s for rapid changes in temperature. This means the measurement will be within 90% of the actual temperature in less than 30 seconds, see datasheet [9] for information on the ABB TSP341-N. Additionally, the response time of the sensor will also be dependent on the flow in the system. We believe this is a sufficient response time as the system has circulating water that should slow a potential temperature increase.

Figure 20. ABB non-invasive temperature sensor TSP341-N

4 Flow control to consumers

4.1 Introduction

In this section of the report, we will discuss our proposed design for the automated valve system. For more information about specifications of the system please see Appendix. The document is titled *Functional description and design changes to DAB cooling system*.

The implementation of automatic valves can only be applied after the implementation of a VFD, which regulates the speed of the pump to achieve a constant setpoint pressure. As the system stands, using a constant speed pump, the closing of valves will result in a pressure increase. This pressure increase will be counteracted by the VFD, which is regulating for constant pressure setpoint. This allows us reduce flow in pipes by closing the valves. This was also verified during testing on the rig, as discussed later in section 7.4. The result of closing valves is a reduction of the head required to maintain the flow.

Additionally, the friction loss will decrease proportionally with a reduction in flow in a well-designed, closed loop system [7]. Assuming the FW system is a well-balanced and designed system, the reduction of flow should make the system run at a more optimal state regarding efficiency and erosion. In summary, this will allow us to optimize the system by designing a control system for automated flow control for individual consumers of the cooling water.

4.2 Actuator choice

The valves we want to control are quarter-turn butterfly valves. For some consumers we want an actuator to control the valve to a precise position between 0-90 degrees. For other consumers we want an actuator to completely open or close the valve. In both cases we goal is for valve to regulate depending on temperature. According to DNV-GL guidelines for design, found in section 7.4.6, the fail-safe condition for temperature regulating valves in freshwater cooling systems should be fail open [5]. This will ensure no harm on the consumers due to lack of cooling.

When choosing suitable actuators for our project we considered cost of component, installation costs and risk management. We ended up choosing pneumatic powered actuators for our application. The main advantages of pneumatic actuators are their simplicity, they are affordable, and we have easy access to pressurized air. Pneumatic actuators can easily be equipped with fail-safe option. A spring-loaded actuator will be chosen for both applications to mechanically open the valve in case of any detected failure.

We will need two types of pneumatic actuators, one for binary control (fully open or closed) and one for position control. Both will use spring loaded single acting pneumatic actuators. The spring allows the actuator to open the valve in case of failure. For the position control, to regulate the actuator for a setpoint position, we will need an additional positioner component which attaches to the actuator.

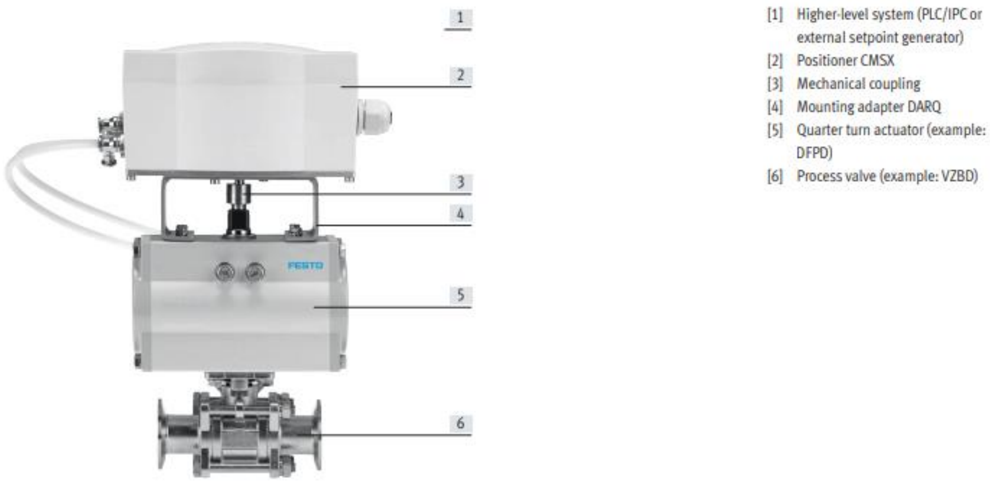


Figure 21. Festo Pneumatic actuator with CMX poistioner.

4.3 The Break Resistor cooler control system

The Break Resistor cooler is a consumer of the cooling system consisting of a resistor which takes excess electric energy that is generated by draw works or anchor winches. This consumer requires different amounts of cooling depending on the activity of the rig. Even with low activity, the break resistor will still need cooling. Therefore, we want dynamic flow control for The Break Resistor cooler. We will achieve this by regulating for setpoint temperature using an existing temperature transmitter within the consumer. The actuator choice is a single acting pneumatic actuator with a positioner. Single acting means the actuator only needs one air intake. The positioner is a control loop that regulates the position from position feedback measurement, which is located within the positioner.

Figure 22. The Break Resistor.

The goal of this control system is to regulate the temperature of the cooling water. The figure shows the control schematic for The Break Resistor control valve. It consists of an inner and an outer feedback loop in cascade. It is important to note that the inner loop is the positioner component which is mounted on the actuator. The system rescieves a setpoint temperature (default is 36 °C). The setpoint is compared to the measured feedback signal to generate a temperature error signal. This error signal goes through the PID controller to genereate a position gain. The position gain is compared to the actual positon of the valve through messurement and the error is sent to the position controller, which adjusts the position of the valve. Ultimately, the control system will dynamically regulate the flow by adjusting the valve position of the consumer depending on a temperature messurement and setpoint.

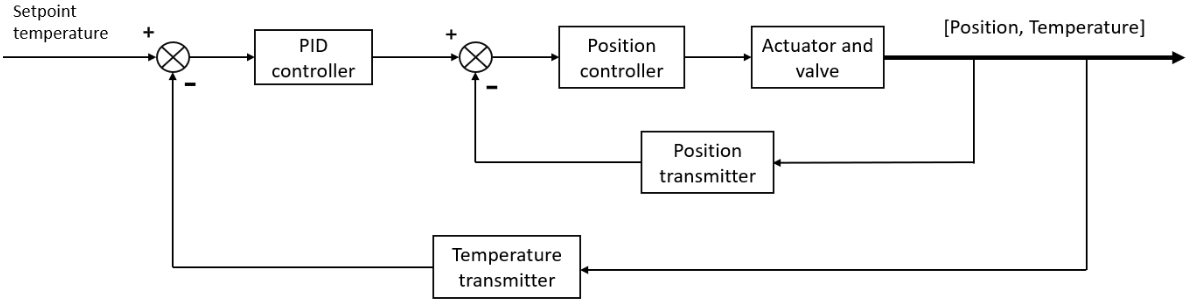


Figure 23. Schematic illustrating control logic and signal flow.

The control room operator can override the temperature setpoint in the IAS system. The operator is also able to open an close the valve with manual ovveride. The standard PID-controller was chosen due to being simple and effective.

4.4 The Anchor Winch cooler control system

There are four different anchor winches, one for each quadrant. The anchor winches are only used when deploying or raising the rigs anchors and will therefore be inactive most of the time. However, when they are in use, they are considered critical consumers and requires sufficient cooling. For this consumer we want to control flow with a binary control strategy, either open or closed, based on a setpoint temperature.

Each anchor winch has an individual closed loop cooling circuit with a heat exchanger towards the main freshwater circuit. Most of the time the local cooling circuit provides enough cooling, but when more cooling is needed the valve on the main freshwater circuit will open and run through the heat exchanger, determined by the temperature in the local circuits. This will be measured by adding a non-invasive temperature transmitter to each of the systems which will constantly signal the current temperature to the IAS. A pneumatic actuator will be added to the main freshwater circuit by each of the anchor winches to control flow through the heat exchanger. The actuator will open the valve by signal from the IAS based on the measured temperature.

The actuators used are spring loaded and set to having the valve normally open. This will ensure that in the event of signal loss, power loss, pressure loss in the pneumatic actuator or if the positional sensor of the valve does not correspond with the valves current setpoint, the valve will always be opened to prevent damage on the anchor winch due to lack of cooling. This event will also send an alarm to the IAS monitoring system.

Figure 24. The Anchor Winch cooling system.

The temperature sensor to be used is an ABB TSP341-N non-invasive temperature sensor. This temperature sensor is mounted on outside of the pipe without the need to drill a hole or shutting down the system. The temperature sensor measures temperature using an algorithm containing the parameters: wall temperature, measuring medium temperature, ambient temperature, medium velocity, pipe diameter and dynamic viscosity. The calculated temperature is sent via a 4-20mA analog signal from a temperature transmitter with a response time of T90 < 30s for rapid changes in temperature. This means the measurement will be within 90% of the actual temperature in less than 30 seconds, see datasheet [9] for information on the ABB TSP341-N. Additionally, the response time of the sensor will also be dependent on the flow in the system. We believe this is a sufficient response time as the system has circulating water in its local cooling circuit, that should slow a potential temperature increase.

4.5 High Pressure Mud pumps

There are four high pressure drill fluid pumps. The FW cooling system consists of two valves, one for pump A and B and one for C and D. We will use the existing running signal from the mud pump drives, to control the already existing valves. The valves will simply open on running signals from the respective mud pumps drives. For closing of the valve is controlled by a timer, which will initiate the closing after the respective pumps have been offline for a specified amount of time. This time variable will be changeable, but it is not important to specify at this stage.

Figure 25. One of four Mud Pumps.

4.6 Water cooled condenser units

There are four water cooled condenser units on Deepsea Aberdeen, one in each quadrant. It Is estimated that these are only active about 5% of the time. These condensers are already fitted with automated valves that close when the system is inactive. However, based on our inspection onboard, it seems as if the bypass valves for the system are open making the valves ineffective. Therefor during the commissioning phase of the project, it is important to close the bypass valse so the automatic valves will work as intended.

Figure 26. Automated valve and bypass for WCCU.

4.7 Chiller units

In the forward cooling system, there are several chiller units. These chiller units are only active less than three months each year during the summer, meaning that supplying continuous cooling to these units are an extreme waste of energy. Therefore, we have decided to simply establish routines to close the main chiller units for the colder temperature periods when the chiller units are inactive. This is relevant for the following units:

Figure 27. Chiller unit.

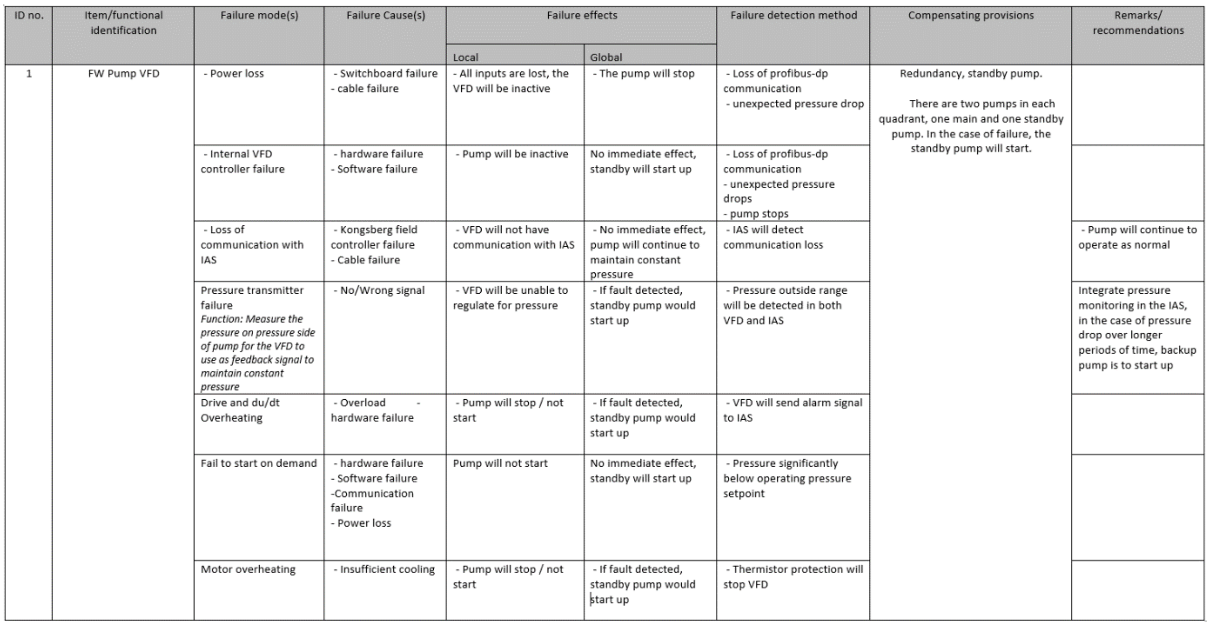
4.8 Risk management and fail-safe

To prevent damage from lack of cooling in the consumers the valves are set to be normally open. In case of failures in the valve control system such as power loss, signal loss, pressure loss in the actuator the spring-loaded actuators will mechanically open the valves. Should this occur, an alarm signal will be sent to the IAS monitoring system. In the case of the binary control valve if the actuator's currently set position differs from the feedback signal of the positional sensor the system will also an alarm.

5 Failure Mode & Effect Analysis (FMEA)

A Failure mode and effect analysis was done to identify how our system can fail and how the system handles. The goal of our system is to be able to fail in any of the identified failure modes and still be operational. This documentation is an important part of the design process. The analysis was performed on all three technical solutions of the project. You can find the documentation for all three FMEAs in the appendix below. To show an example of an FMEA, we used the freshwater VFD pump solution.

The first step of the analysis is to identify failure modes as shown in the third column in the FMEA table below. Typical failure modes are power loss and loss of communication. In the fourth column we identify what causes the failure modes. This can be for example cable failure in the case of power or IAS communication loss. Next, in the fifth column, we identify what effects the failure has locally and globally. Local failure effects meaning how the resulting failure will affect the pump or VFD directly. Global failure effects meaning how the resulting failure will affect the entire system, and what actions will be taken. In the case of a power loss, the backup pump will start automatically. In the case of IAS communication loss, the currently active VFD and pump will continue to run, and the IAS system will detect the failure and notify the operator through an alarm.



ID no.	Item/functional identification	Failure mode(s)	Failure Cause(s)	Failure effects		Failure detection method	Compensating provisions	Remarks/ recommendations
				Local	Global			
1	FW Pump VFD	- Power loss	- Switchboard failure - cable failure	- All inputs are lost, the VFD will be inactive	- The pump will stop	- Loss of profibus-dp communication - unexpected pressure drop	Redundancy, standby pump. There are two pumps in each quadrant, one main and one standby pump. In the case of failure, the standby pump will start.	
		- Internal VFD controller failure	- hardware failure - Software failure	- Pump will be inactive	No immediate effect, standby will start up	- Loss of profibus-dp communication - unexpected pressure drops - pump stops		
		- Loss of communication with IAS	- Kongsberg field controller failure - Cable failure	- VFD will not have communication with IAS	- No immediate effect, pump will continue to maintain constant pressure	- IAS will detect communication loss		- Pump will continue to operate as normal
		Pressure transmitter failure *Function: Measure the pressure on pressure side of pump for the VFD to use as feedback signal to maintain constant pressure*	- No/Wrong signal	- VFD will be unable to regulate for pressure	- If fault detected, standby pump would start up	- Pressure outside range will be detected in both VFD and IAS		Integrate pressure monitoring in the IAS, in the case of pressure drop over longer periods of time, backup pump is to start up
		Drive and du/dt Overheating	- Overload - hardware failure	- Pump will stop / not start	- If fault detected, standby pump would start up	- VFD will send alarm signal to IAS		
		Fail to start on demand	- hardware failure - Software failure -Communication failure - Power loss	Pump will not start	No immediate effect, standby will start up	- Pressure significantly below operating pressure setpoint		
		Motor overheating	- Insufficient cooling	- Pump will stop / not start	- If fault detected, standby pump would start up	- Thermistor protection will stop VFD		

Figure 28. FMEA analysis.

6 Simulating ABB drive software with Siemens PLC

When implementing solutions offshore it can be extremely costly, therefor we decided to test the VFD software in the lab. By doing so, we also eliminate the demand for ABB support during the commissioning phase saving a significant amount of money. We were also able to verify our FMEA and commission procedure that worked as intended. Testing the software in the lab was also a great opportunity to show off our control principle to Odfjell Drilling.

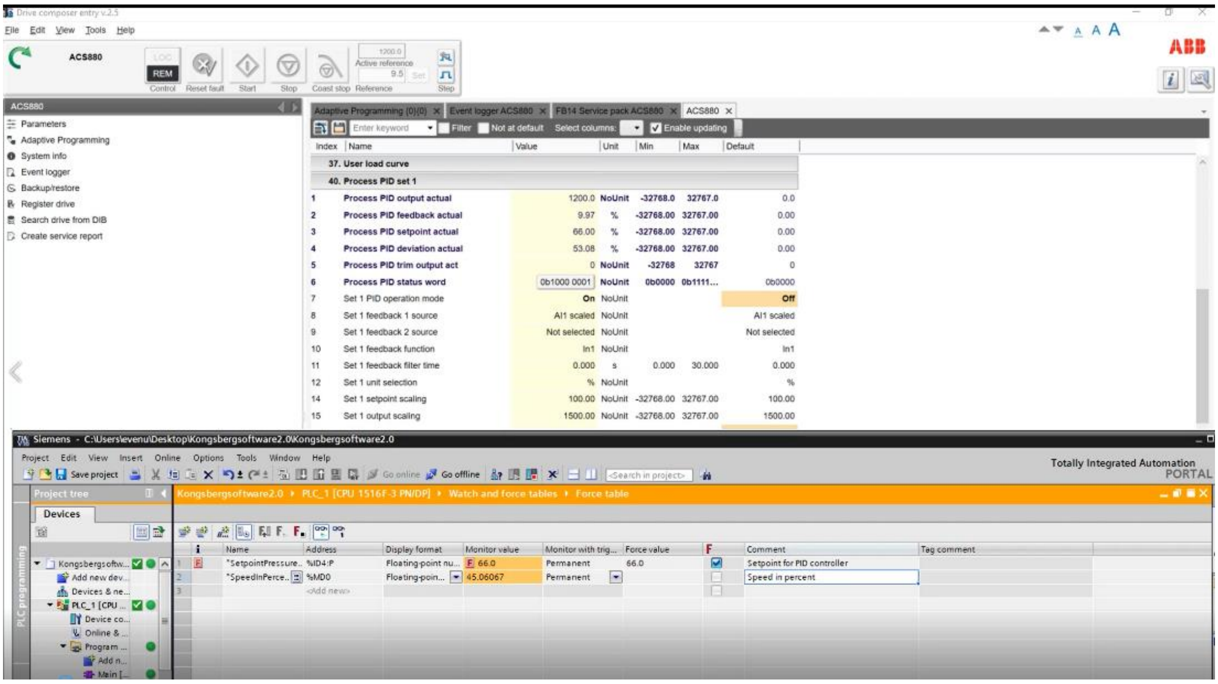
When testing the system, we used a siemens S7-1500 PLC to simulate the role of the Kongsberg RCU. The main purpose of this test was mainly to determine if the control logic would work as intended. Since this is the main priority of the test, we decided that we would not take the duty/standby duty pump algorithm into consideration.

Figure 29. Siemens S7-1500 PLC.

When testing the system, we had limited equipment available. In result, we were not able to setup the test rig with a pressure transmitter, as in the actual system will have. Due to the limited supplies we decided to control the height of water in a tank, using the feedback sensor from an ultrasonic height sensor. The control logic for the VFD with a height measurement instead of pressure measurements will essentially be the same. The goal was to test the functionality of our VFD software, especially the failure mode analysis.

Figure 30. Testing rig to test VFD software.

The Image below shows how we sent the setpoint height to the drive via Tia-Portal and the drive reacts to the change in setpoint. This is how we simulated the functionality of the drive.



Index	Name	Value	Unit	Min	Max	Default
	37. User load curve					
	40. Process PID set 1					
1	Process PID output actual	1200.0	NoUnit	-32768.0	32767.0	0.0
2	Process PID feedback actual	9.97	%	-32768.00	32767.00	0.00
3	Process PID setpoint actual	66.00	%	-32768.00	32767.00	0.00
4	Process PID deviation actual	53.08	%	-32768.00	32767.00	0.00
5	Process PID trim output act	0	NoUnit	-32768	32767	0
6	Process PID status word	0b1000 0001	NoUnit	0b0000	0b1111...	0b0000
7	Set 1 PID operation mode	On	NoUnit			Off
8	Set 1 feedback 1 source	AI1 scaled	NoUnit			AI1 scaled
9	Set 1 feedback 2 source	Not selected	NoUnit			Not selected
10	Set 1 feedback function	In1	NoUnit			In1
11	Set 1 feedback filter time	0.000	s	0.000	30.000	0.000
12	Set 1 unit selection	%	NoUnit			%
14	Set 1 setpoint scaling	100.00	NoUnit	-32768.00	32767.00	100.00
15	Set 1 output scaling	1500.00	NoUnit	-32768.00	32767.00	1500.00

	i	Name	Address	Display format	Monitor value	Monitor with trig...	Force value	F	Comment	Tag comment
1	F	"SetpointPressure..	%ID4:P	Floating-point nu...	F 66.0	Permanent	66.0	☑	Setpoint for PID controller	
2		"SpeedInPerce..	%MD0	Floating-poin...	45.06067	Permanent		☐	Speed in percent	
3			<Add new>					☐		

Figure 31. Abb drive composer PID configuration and TIA-Portal.

7 Testing the feasibility of implementing VSP on FW cooling system

In December 2020 we performed a test on Deepsea Aberdeen. In this test, we implemented a VFD drive on the port aft freshwater pump to allow us to control the pump speed. The goals of the test were to ensure sufficient flow through critical consumers when reducing pump head, establishing a reference output pressure and determine if a VFD controlled pump is practically and economically expedient to implement.

7.1 Setup

The VFD was implemented by using the existing MCC as the power supply for the drive, with a Du/Dt filter connected between the VFD and the freshwater pump. The existing pressure gauge on the pump outlet was used to measure output pressure. The VFD regulated pump speed through a simple PI controller with a reference point in output pressure. This reference point was chosen arbitrarily to 7.2 bar, or a total pump head of about 73 m. During testing, the pump was discovered to vibrate when operating between 850 and 1030rpm. We set a limit of 830 rpm on the pump to prevent damaging the pump and the foundation it is placed on.

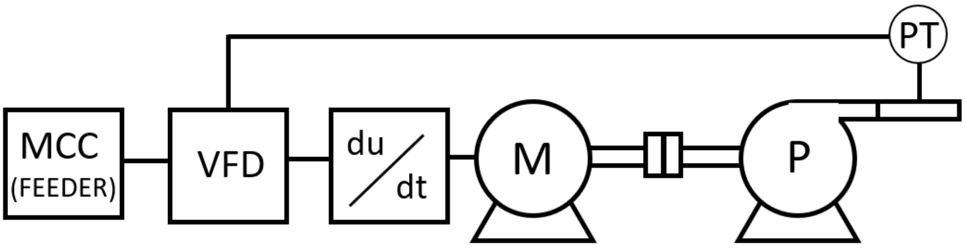


Figure 32. Illustration of the VFD and du/dt filter setup during testing.

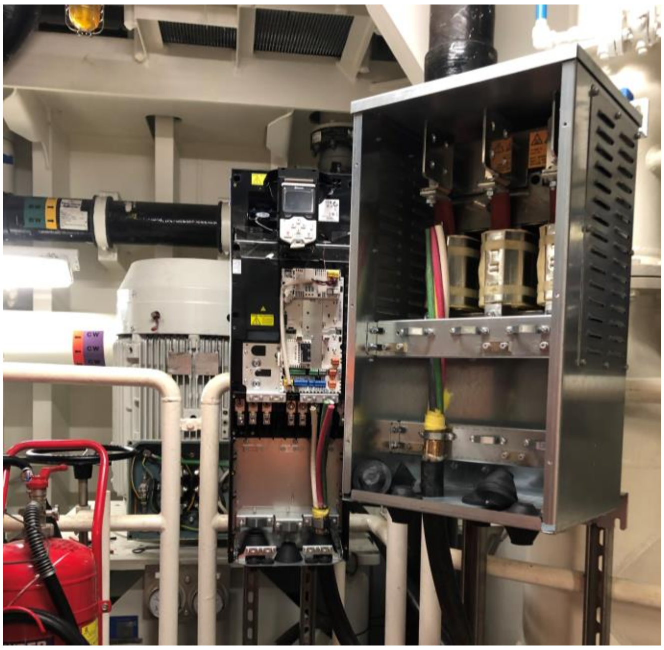


Figure 33. VFD and du/dt filter setup during testing.

7.1.1 Ultrasonic flowmeter

We used a Flexim FLUXUS G601 flowmeter to measure the flow in the pipes carrying cooling water. We chose the G601 flowmeter as it is pre-calibrated and does not require zero-flow calibration. The flowmeter measures flow by mounting two transducers on the pipe. The transducers send ultrasonic signals to each other. They do this by sending the signals through the pipe and fluid by reflecting them on the inner wall of the pipe as illustrated below. Waves sent through the liquid in flow direction has a shorter travel time than signals traveling against the flow. The flow meter uses this difference in transit time of the signals, along with several other parameters like pipe diameter, wall thickness and liquid type, to calculate the flow velocity and volumetric flow rate [10]. We recommended using the sensor in the commissioning phase of the project to verify sufficient flow to individual consumers.

$$Volumetric\ Flow\ Rate = K_{Re} * A * K_a * \frac{\Delta t}{2 * t_\gamma}$$

K_{Re} - Fluid mechanics calibration factor
A - Cross-sectional pipe area
K_a - Acoustical calibration factor
Δt - Transit time difference
t_γ - Average of transit times in the fluid

Figure 34. Volumetric flow rate formula for ultrasonic flowmeter from datasheet [10].

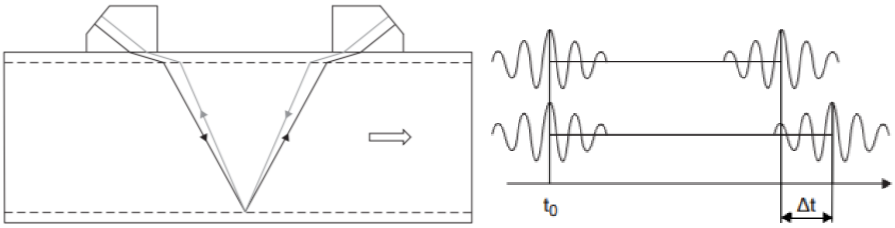


Figure 35. Illustration of ultrasonic flowmeter principle.

7.2 Execution

There are two pumps in the freshwater cooling circuit, one that is active and one that is on stand-by in case of failure. We used the inactive pump to set up the VFD. We began the test by disabling the active pump and enabling the VFD-controlled pump. We then controlled the RPM of the pump with the VFD through the ABB drive composer software. The drive was set to "remote control" to enable the PI-controller to regulate for constant pressure. We then opened and closed the valves on the major consumers. This was done in all combinations while measuring flow through all the critical consumers.

S/N	TAGNO.	Room	Description	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8
3	576-HE-001	M135A wccu room	MCCU	OPEN	Closed	OPEN	OPEN	Closed	OPEN	Closed	Closed
4	431-OJ-001-C	M219	Cooling Unit for dynamic brake (anchor winch)	OPEN	OPEN	Closed	OPEN	Closed	Closed	OPEN	Closed
6	866-EY-030	M147A (engine room)	Braking resistor cooler	OPEN	OPEN	OPEN	Closed	OPEN	Closed	Closed	Closed

Figure 36. Different configurations of opened and closed valves during testing.

7.3 Results

The results of the measurements show that closing or opening valves with a VFD driven pump made little to no difference for the flow, only between 0,1 - 0,3 Bar as the PI controller regulated the pump speed to compensate for the changes. The table below shows the recommended flow through each of the consumers, together with measured flow without VFD implementation and measured flow with VFD implementation.

Table 5. Flow measurements taken during the feasibility test.

Description	TAGNO.	Recommended flow (m^3/h)	Flow without VFD (m^3/h)	Flow with VFD (m^3/h)
Transformer	865-ET-003-C	12.2	18.9	15.0
Drilling Switch Board	867-HE-S03	21.5	34.8	26.0
Service Air Compressor	733-KC-001-B	14.2	11.4	9.6
HP Mud Pump A	325-BK-101-A	79.0	87.0	N/A
WCCU for FCU & Cooling Coil	576-HE-001	57.0	46.0	47.0
Starting air compressor	731-KB-001-A	11.4	8.6	8.2
Cooling Unit for Dynamic Brake (anchor winch)	431-OJ-001-C	75.0	85.0	60.0
Inside -> outside	N/A	34.5	49.0	35.0
Breaking Resistor Cooler	866-EY-030	63.0	105.0	60.0
Braking Resistor for AHU Winch	314H1-EZ001	10.5	9.9	7.6
Cement Package	371_BI001	52.7	50.0	32.0

Looking at the recommended flow compared to the non-VFD driven pump, the current system provides too much flow through six of the measured consumers. This is both cost inefficient and unhealthy for the system in the long run, as it was designed for the freshwater temperature to reach around 36 degrees, but it currently runs significantly colder. After enabling the VFD, the new measurements shows that the old flow values that were above recommended has now been pushed more in line with the recommended values, most notably the breaking resistor cooler. However, some of the flow values has now gone below the recommendations, the anchor winch, and the cement package.

7.4 Test discussion and conclusions

Before the test, there was some uncertainty around closing the valves. We were unsure if closing a valve would affect other consumers on the rig by disrupting the flow distribution. After observing that opening and closing valves had little to no impact on the system when controlling the pump through the VFD, our hypothesis to utilize automated valve control on some consumers to reduce the overall flow throughout the cooling system was validated. Closing valves to inactive consumers would reduce the pump speed required to uphold the set output pressure for further energy and cost savings. This automated valve control system is described in section 5 of the report.

As for the power usage of the pump, we observed a major decrease in power consumption after enabling the VFD. As the figure below shows the reduction from 106kW to 24kW, a 77% power reduction. Since this power usage reduction comes solely from installing a VFD on the pump, it serves as a baseline power reduction estimate and gives a good indication of how big the potential savings could get when enabling more power saving solutions.

Figure 37. Power consumption before (left) and after (right) implementing pressure regulator.

We also noticed that the VFD controlled system reduced the noise levels near consumers. This was also confirmed by a Schlumberger crew member, who had complaints about water hammering in the pipes and the excess pressure in the system. We assume that the reduction in water hammering is a good indicator that the system is operating at more optimal conditions than before.

The flow rates after enabling the VFD has mostly been reduced to be more in line with the recommended flow or stayed consistent at the same levels as before enabling the VFD. The exceptions are the anchor winch, breaking resistor, and cement package.

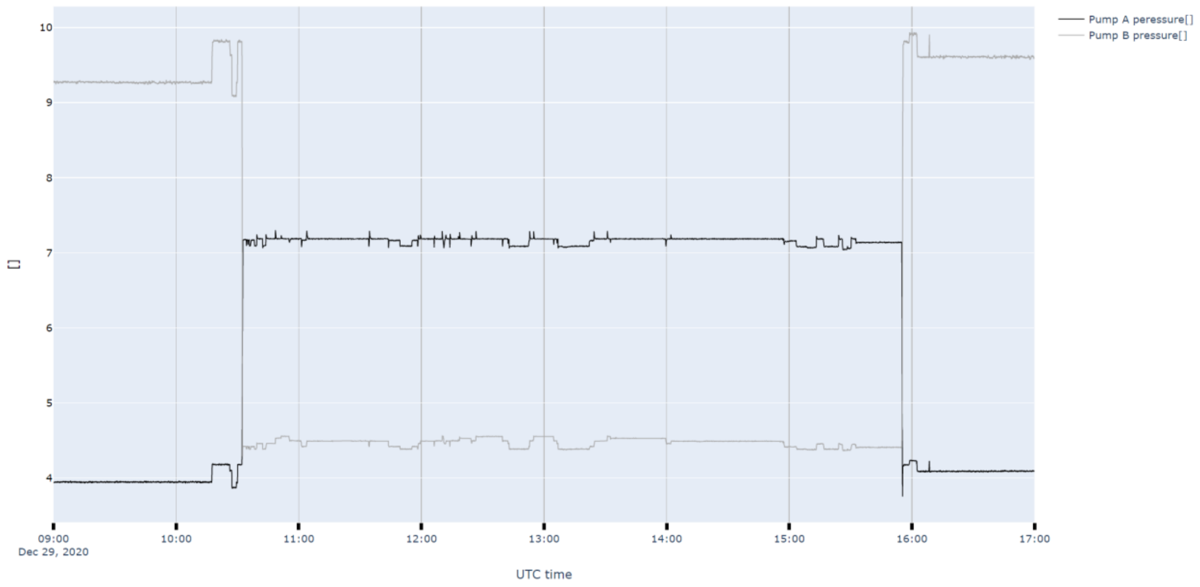


Figure 38. Pressure data from the pumps discharge side during testing.

The anchor winch has a recommended flow rate of 75, a current flow rate of 85, and a flow rate of 60 after enabling the VFD. This shows that the current flow rate is well above the recommended flow rate. As for the reduced flow rate of 60, we believe it to be sufficient as the anchor winches all have a local closed loop cooling circuit with a heat exchanger towards the main cooling system. This local circuit enables the anchor winches to operate longer before needing additional cooling from the main circuit. The anchor winches are also rarely in use. If this proves to be against documentation and requirements, a solution for increasing flow rate while the anchor winch is running needs to be developed.

While measuring the cement package we reached the set rpm limit of 830 rpm. This caused the flow to be lower than it would have been without the rpm limit enabled. Thus, flow measurements for the cement package cannot be taken accurately before the pump foundation has been reinforced so that the rpm limit can be removed. The rpm limit can clearly be seen on the graph in figure below, where output pressure drops below 7.1 bar.

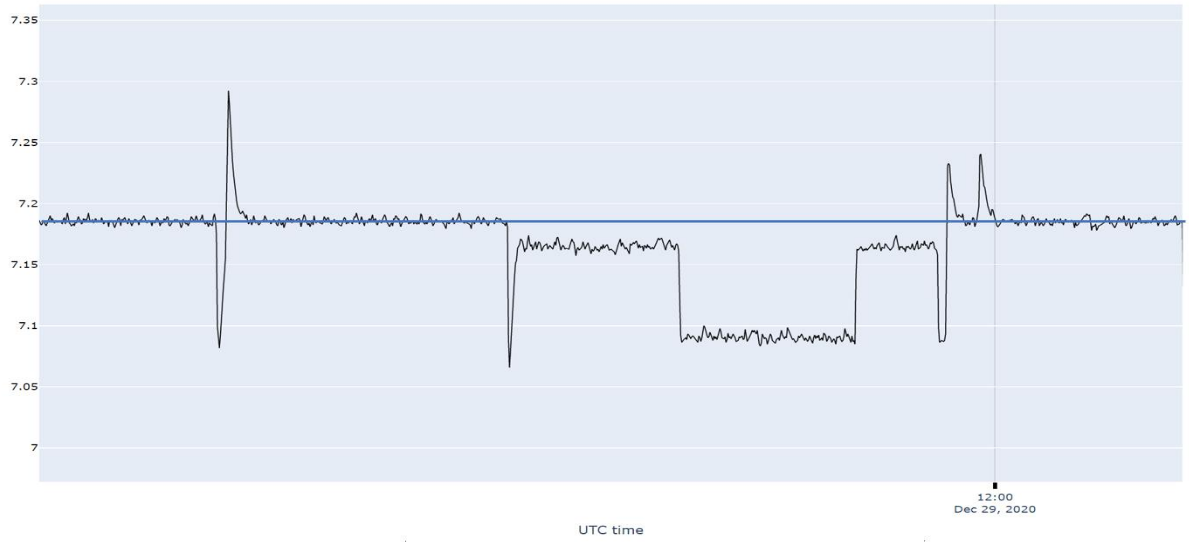


Figure 39. Pressure data from discharge side, with RPM limit

Overall, we were very happy with the results of the test. We had an immediate reduction in power consumption and there was a big reduction of the noise in the system, which is a good indicator that the system is operating in a better state. Additionally, we saw that closing individual consumers had a minimal effect on flow to other consumers which was one of the most important aspects of the test. The test was also a great way to get an understanding of the existing system and the work involved in installing the system in the future.

8 Energy and cost saving potential

8.1 Energy saving potential in the FW cooling circuit

When calculating the potential energy saving potential in the FW cooling circuit, we did it in two stages. The first stage where we considered the pressure drops in the system and the second stage where we look at the reduction in flow after VFD implementation. When doing the calculations, we used the pressure determined during the testing phase and the list of required flow to the individual consumers from hydraulic balance simulation done by the shipyard. By doing this we get an initial savings from the system, just by lowering the pump head. Additionally, the combined efficiency between power loss in motor, cable, and pump was estimated to approximately 93% based on data from the test onboard.

To calculate the power saving potential by implementing the VSP, we simply reduced the pump head from 50 meters to 27m in the formula below. Based on the data we collected while onboard the vessel we could quickly compare and conclude that this is an efficient way to determine the energy saving potential. In the table below you can see the power savings, consumption before and after in each quadrant.

$$P = \frac{Q * H * \rho}{367 * n}$$

Table 6. Energy Savings on VFD FW

	Original power consumption (kW)	Power consumption after reduced pressure (kW)	Power savings after reduced pressure (kW)
Port Aft.	108.5	54.0	**54.5**
STBD Aft.	107.7	54.8	**52.9**
Port Fwd.	111.3	56.8	**54.5**
STBD Fwd.	112.8	59.1	**53.7**

To calculate the power savings from closing individual consumers, we simply used the new pump head and the design flow to the individual consumer, combined with average time active. In the table below you can see the average time active and the calculated power savings. for the different consumers that we will be implementing some sort of flow control on.

Table 7. Savings potential for Valve control Port Aft

Consumers	Time active (%)	Average flow reduction(m^3/h)	Energy savings (kW)
Anchor Winch cooling unit	1	74.3	6.5
HP Mud Pump A	20	61.0	5.4
HP Mud Pump B	20	61.0	5.4
Engine room WCCU	5	54.2	4.8
Cement package	10	47.4	4.3
Break Resistor cooler	10	56.7	5.0
	Sum:	354.5	31.2

Table 8. Total calculated energy savings.

	Power savings after reduced pressure (kW)	Power saving from flow control (kW)	Total savings (kW)
Port Aft.	54.5	31.2	85.7
STBD Aft.	52.9	26.7	79.6
Port Fwd.	54.5	36.6	91.1
STBD Fwd.	53.7	33.2	86.9
Total:	**215.6**	**127.7**	**343.3**

8.2 Energy saving potential in seawater cooling circuit

In this study, the energy saving potential is hard to determine due to not have a sufficient pump curve, but we are able to determine the required mass flow. The system is designed to operate with 32 °C seawater temperature, but during this analysis the SW mass flow is based on the average seawater temperature between Orkney and Utsira, as it is where the rig has just secured its next contract. The average seawater temperature for this area is 8.6 °C. [11]

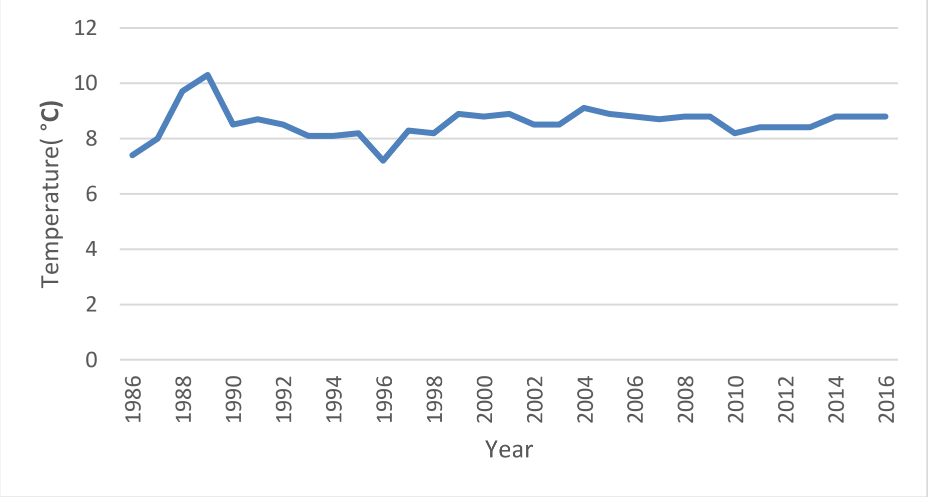


Figure 40. Seawater temperature between Orkney and Utsira between 1986-2016. [11]

The calculations to determine the mass flow required to provide sufficient flow are based on the heat generated form the individual consumer, and the amount of cooling needed to obtain the FW setpoint temperature of 36 °C.

Table 9. Average flow savings for SW cooling system

Corner	FW flow (m3/h)	FW temperature (°C)	FW Heat (kW)	SW Flow (m3/h)	SW Flow savings (%)
Port. AFT	266	75	6155	159	82.33%
STBD. AFT	209	57	2524	90	90.00%
Port. FWD	172	52	1651	67	92.56%
STBD. FWD	233	49	728	74	91.78%

These calculations are based on average theoretical flowrate and average theoretical heat in the FW circuits. We have also used a simplified model for the heat exchanger, so it could easily be calculated to give us a decent estimate of the flow needed to cool it down. The calculation method was also verified using the datasheet and cross validating the values given.

8.3 Seawater Simulation

To get a better picture of the potential savings on the seawater system, we decided to create a simulation using data from earlier wells drilled on similar rigs. We gathered data from Odfjell in the given time intervals, for three temperature sensors to do our calculations. The seawater temperature, the freshwater cooling input and output temperature. With these three datapoints and the parameters of the heat exchanger we were able to calculate the energy absorbed by the heat exchanger, and how much flow that was required to do the same amount of cooling.

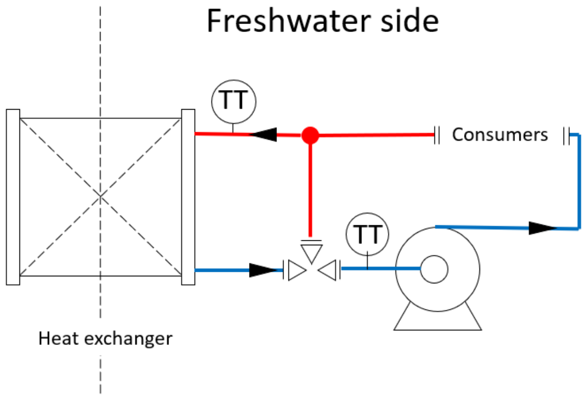
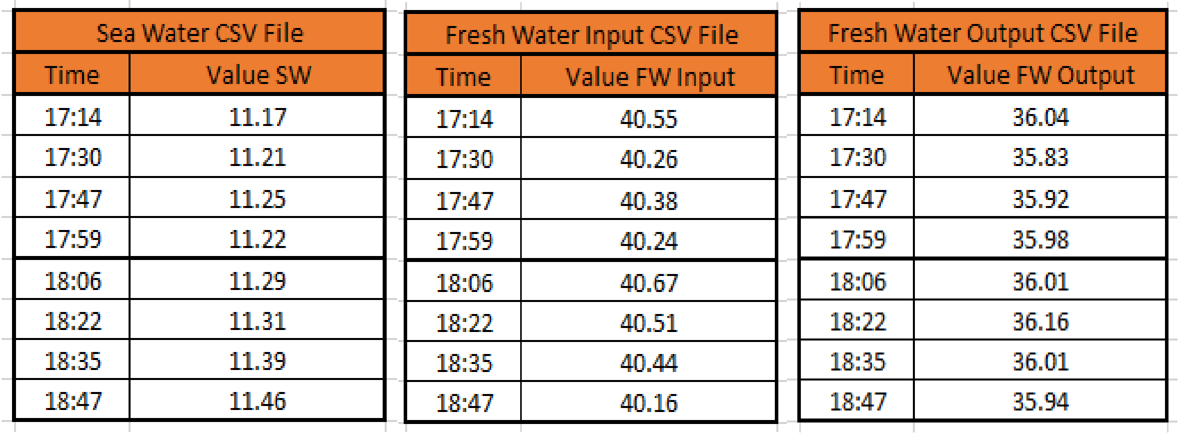


Figure 41. Illustration of sensor locations in the FW system

8.3.1 Data Collection



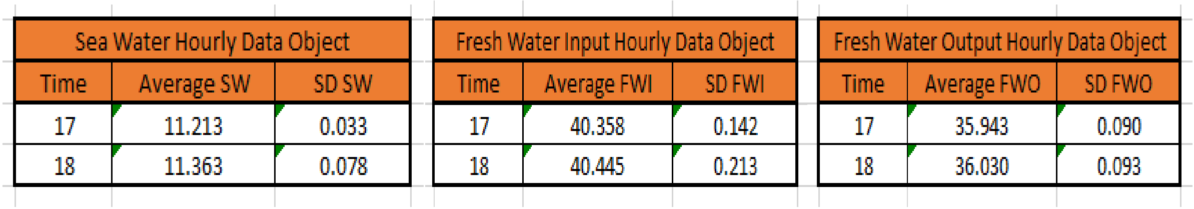
Sea Water CSV File	
Time	Value SW
17:14	11.17
17:30	11.21
17:47	11.25
17:59	11.22
18:06	11.29
18:22	11.31
18:35	11.39
18:47	11.46

Fresh Water Input CSV File	
Time	Value FW Input
17:14	40.55
17:30	40.26
17:47	40.38
17:59	40.24
18:06	40.67
18:22	40.51
18:35	40.44
18:47	40.16

Fresh Water Output CSV File	
Time	Value FW Output
17:14	36.04
17:30	35.83
17:47	35.92
17:59	35.98
18:06	36.01
18:22	36.16
18:35	36.01
18:47	35.94

Figure 42. Illustration of data we received.

The software starts reading a CSV file for each sensor containing a list of time and temperature into memory. After all this data is formatted into the software, we do a simple reduction into hourly averages, while also calculating the standard deviations to check that the simplification is reasonable.



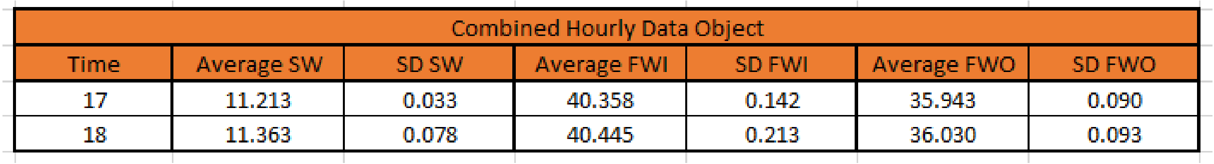
Sea Water Hourly Data Object		
Time	Average SW	SD SW
17	11.213	0.033
18	11.363	0.078

Fresh Water Input Hourly Data Object		
Time	Average FWI	SD FWI
17	40.358	0.142
18	40.445	0.213

Fresh Water Output Hourly Data Object		
Time	Average FWO	SD FWO
17	35.943	0.090
18	36.030	0.093

Figure 43. Illustration of processed data in our software

After this we take each of the three new lists consisting of hourly averages and combine them. In the case of a missing datapoint from one of the sensors, we decided to just ignore that hour and proceed. This results in a full list of each hour having an average value and the standard deviation for all the sensors.



Combined Hourly Data Object						
Time	Average SW	SD SW	Average FWI	SD FWI	Average FWO	SD FWO
17	11.213	0.033	40.358	0.142	35.943	0.090
18	11.363	0.078	40.445	0.213	36.030	0.093

Figure 44. Illustration of processed data combined into a single datatype.

8.3.2 Calculations

Having all the variables from the data collection and being able to specify the attributes of the heat exchanger we were able to create a function that gave us the calculated freshwater output temperature for each hour.

This could be written as $^{\circ}\mathrm{C} = f(SWflow)$

But we already had the desired output, so we had to turn the equation to solve for flow, which was a challenging task. Instead, we created an iterative approximation algorithm that gave the temperature as feedback and reduced or increased the flow accordingly.

8.3.3 Conclusion

The results of the calculations show that the variation in temperature each hour is minimal, and the simplification into hours seems like a reasonable way to study the system. There is also an extreme reduction in flow needed when operating in the North Sea, as we expected because of the system being built to handle worst case scenarios, in the warmest parts of earth, and then some.

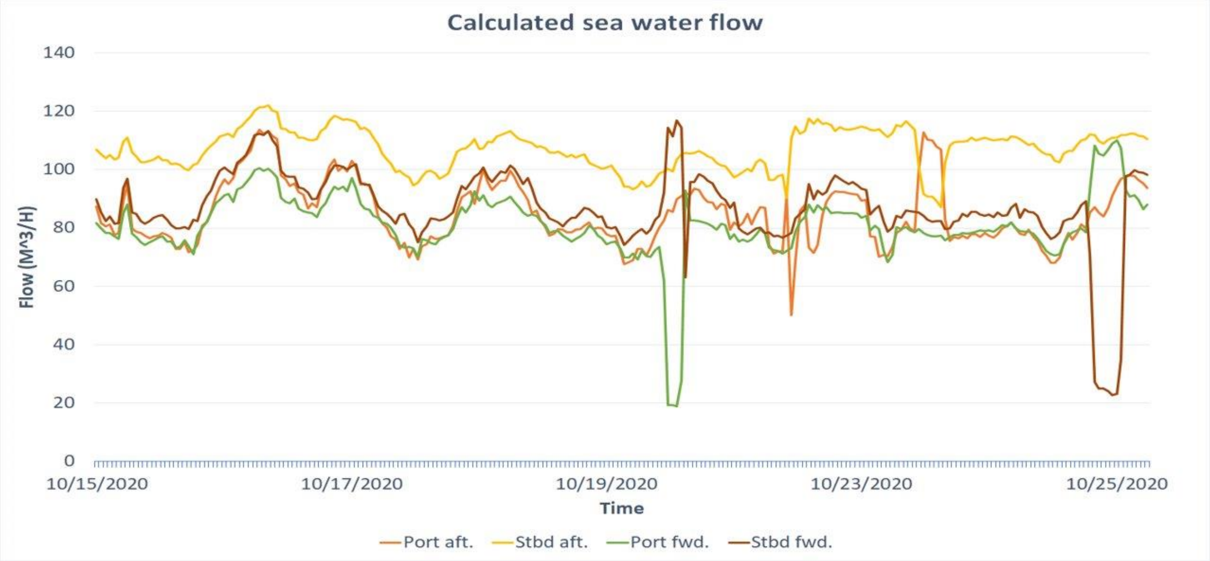


Figure 45. Simulation of SW flow

8.4 Total savings

Based on the simulations on the SW cooling system and the calculations on the FW cooling system we have calculated the potential savings. All these calculations are based on the generators using 200g of diesel per kWh of energy produced and a diesel price of 524 USD per tonne. In addition to the cost of diesel, we have also considered the environmental taxes in Norway. See tables below for prices, constants, exchange rates and costs to produce energy used in the calculation.

Table 10. Diesel cost related values used for calculation

Entry	Value
Diesel MGO (USD/T)	524
Diesel MGO (USD/L)	0.45
CO2-fee (NOK/L)	1.27
NOx-fee (NOK/KG)	23.48
Exchange rate (NOK/USD)	8.42
Density (SG)	0.86
NOx g/kWh (g/kWh)	8.6
Diesel consumption (g/kWh)	200

Table 11. Cost of energy

Price	Value
Co2 tax ($USD/kWh)	0.030
NOx tax ($USD/kWh)	0.024
Fuel price ($USD/kWh)	0.090
Total price ($USD/kWh)	0.144
Total price (NOK/kWh)	1.210
Yearly ($USD/kWy)	1259
Yearly (NOK/kWy)	10 603

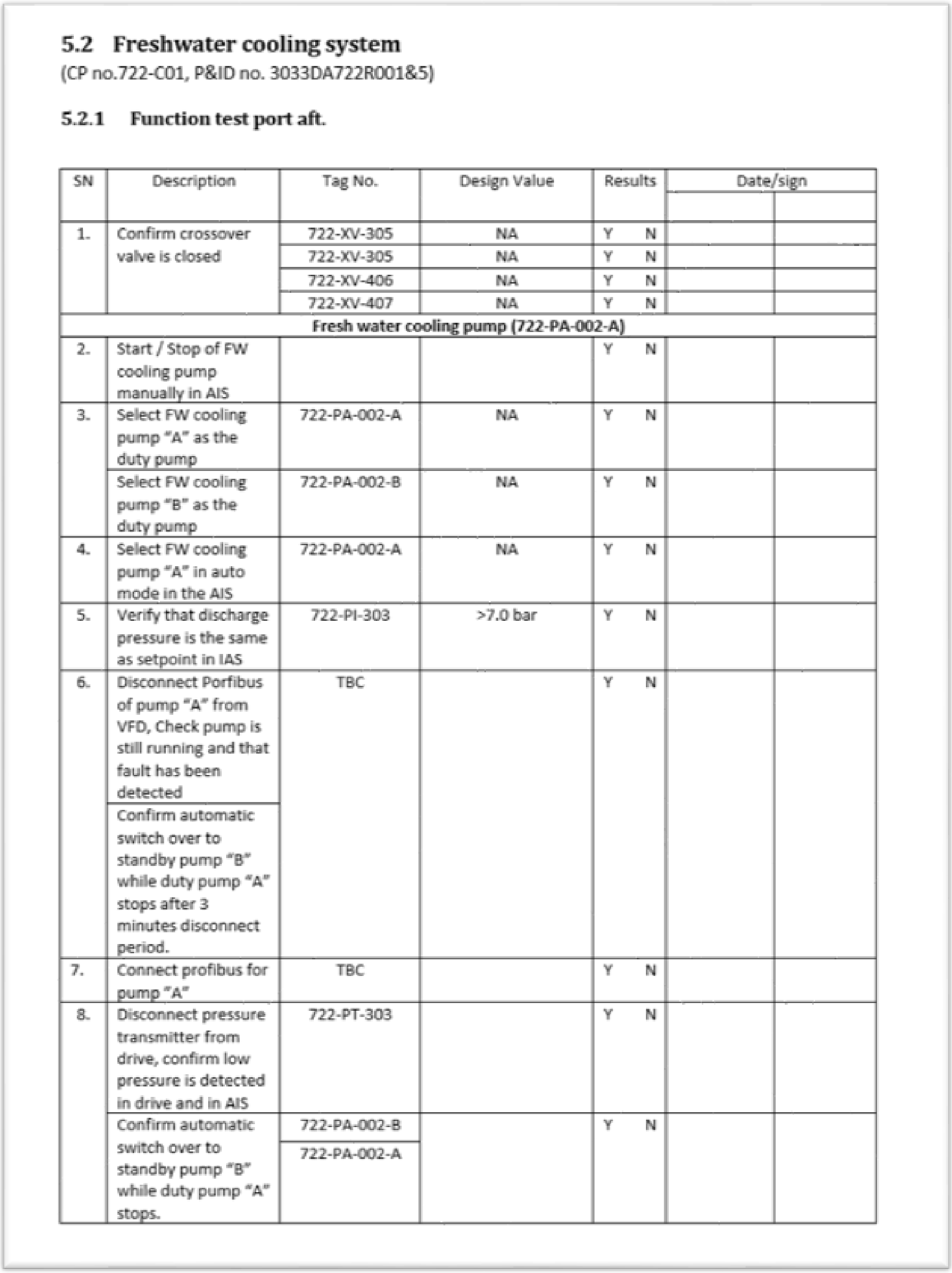
The total savings both costs related, and emissions related are listed in the table below. It is important to understand that these costs will change both with exchange rate and the yearly increase in emissions taxes. As the Norwegian government plans to increase these rates the coming years.

Table 12. Potential savings overview

Reduction each year	Calculated savings
Diesel (Tonnes)	1030
Co2 (Tonnes)	3266
NOx (Tonnes)	44
Cost (NOK)	7 600 000

9 Commissioning Procedure

The objective of the commissioning procedure is to give clear instructions for the activities to be carried out to complete the necessary steps to complete the upgrades features to the central cooling system. We have made a document that goes into all details of the procedure, titled *DAB Central Cooling System Commissioning Procedure*. The commissioning procedure is an essential part in showing and proving the functionality of the system internally in Odfjell drilling but also to DNV-GL who are responsible for the quality assurance and risk management of the vessel.



5.2 Freshwater cooling system

(CP no.722-C01, P&ID no. 3033DA722R001&5)

5.2.1 Function test port aft.

SN	Description	Tag No.	Design Value	Results	Date/sign	
1.	Confirm crossover valve is closed	722-XV-305	NA	Y N		
		722-XV-305	NA	Y N		
		722-XV-406	NA	Y N		
		722-XV-407	NA	Y N		
Fresh water cooling pump (722-PA-002-A)						
2.	Start / Stop of FW cooling pump manually in AIS			Y N		
3.	Select FW cooling pump "A" as the duty pump	722-PA-002-A	NA	Y N		
	Select FW cooling pump "B" as the duty pump	722-PA-002-B	NA	Y N		
4.	Select FW cooling pump "A" in auto mode in the AIS	722-PA-002-A	NA	Y N		
5.	Verify that discharge pressure is the same as setpoint in IAS	722-PI-303	>7.0 bar	Y N		
6.	Disconnect Porfibus of pump "A" from VFD, Check pump is still running and that fault has been detected	TBC		Y N		
	Confirm automatic switch over to standby pump "B" while duty pump "A" stops after 3 minutes disconnect period.					
7.	Connect profibus for pump "A"	TBC		Y N		
8.	Disconnect pressure transmitter from drive, confirm low pressure is detected in drive and in AIS	722-PT-303		Y N		
	Confirm automatic switch over to standby pump "B" while duty pump "A" stops.	722-PA-002-B 722-PA-002-A		Y N		

Figure 46. Snippet of Commissioning Procedure document

10 Discussion

While testing there were a couple points of concerns that needs to be addressed before implementing the solution. These concerns include vibrations in the pump, Cement unit not getting sufficient flow during testing, and uncertainty around the engine room getting sufficient cooling.

10.1 Vibrations in freshwater pump

During the test we notice vibrations in the pump in the rpm range 850-1030RPM. This is due to the pump structure not being designed for that specific frequency range. This meant that we had to implement an RPM limit of 845 RPM to avoid the motor running in the vibration area. This also meant that during the experiment the Mud Pump and cement unit had to be closed during the test to obtain a sufficient output pressure from the pump to sufficiently supply the other consumers. We know for certain that this range is where the pump is going to be operating in therefor the structure needs to be reinforced for the pump to be VFD driven. Odfjell Drilling's structural people take care of this issue.

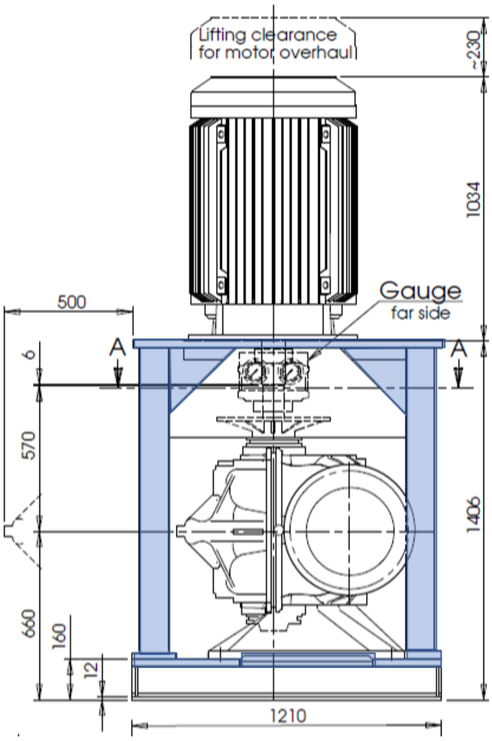


Figure 47. FW cooling pump structure

To determine if the vibrations in the pump were structural or due to the pump characteristics, we decided to do a simple modal analysis of the motor stand. A modal analysis determines at which periods a structure naturally resonate based on its stiffness. By determining the motor stands natural frequency we can determine if the structure is the main cause of the vibrations.

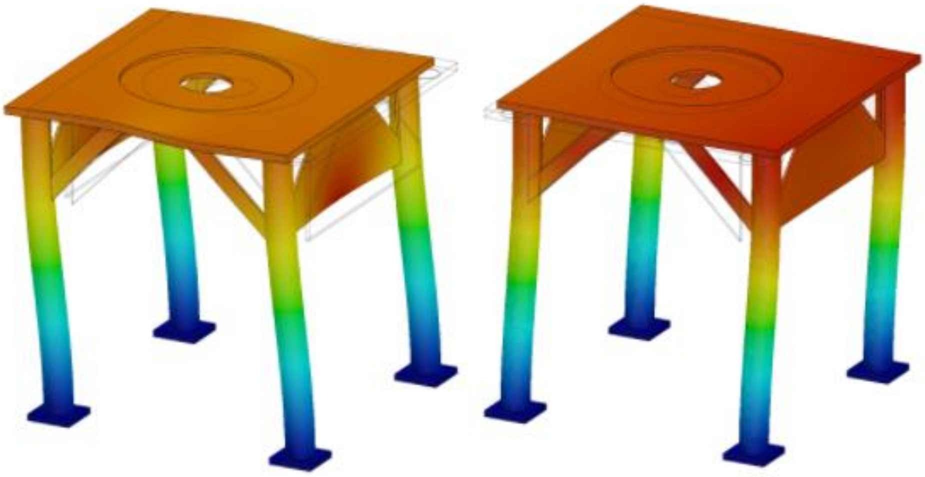
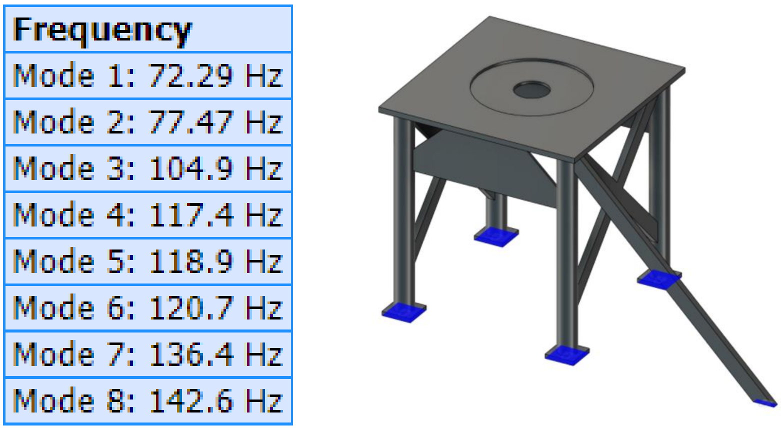


Figure 48. 41.78Hz and 48.25 Hz Total Modal Displacement



Frequency
Mode 1: 72.29 Hz
Mode 2: 77.47 Hz
Mode 3: 104.9 Hz
Mode 4: 117.4 Hz
Mode 5: 118.9 Hz
Mode 6: 120.7 Hz
Mode 7: 136.4 Hz
Mode 8: 142.6 Hz

Figure 49. Reinforced structure

In the simulation we found two frequencies within the operating speed from 0 to 60 Hz. These frequencies also corresponded to the speeds which we experienced vibrations at. We then did a simple suggestion when it comes to reinforcing the structure to get an example where the natural frequency is higher than the operating frequency as shown in figure 61 above.

10.2 Cement unit not getting sufficient flow

During the test, the Cement package - 371_BI001 was not getting sufficient flow. We are not certain, but we believe that the cause of this is the RPM limit we set on the VFD to avoid the frequencies that the pump vibrated at. This means that the motor could not reach the speed required to reach the setpoint pressure of 7.2 Bar.

Another cause of the insufficient flow could be that the setpoint pressure is too low and would have to be increased to get the minimum sufficient flow. If this is the case, then we would have to implement a function that increases the pressure when the cement package is active. This is something that will have to be determined during commissioning with the use of flowmeter. If this is the case, we could implement a solution which increases the setpoint pressure when the cement unit is active.

Figure 50. Cement package

10.3 Uncertainty around diesel engines

During the test, the flow to the engine was not measured. The engines cooling system Is quite complex and includes a freshwater preheating system. The flow to the engine needs to measure during commissioning to make sure the engine has sufficient cooling.

By reducing the flow of the total system, the water will have more time in contact with the consumers. The result of this is that the temperature of the return water will be higher than in the current system. Our understanding of the system is that the diesel engines cooling water is in series with the rest of the consumers, on the return side. This means that the warm return water from the rest of the consumers passes through the engines. A special case when every consumer is open, and is working at 100% load, we may feed too warm water into the engines. We will have to do more research on the specific functionality and requirements of the diesel engines cooling system.

Figure 51. Engine and generator

10.4 Uncertainty around seawater sub-system

We have not tested the seawater pump and we do not have sufficient pump curves to determine the power consumption when implementing a VFD. The decision to go forward with the saltwater system is a decision that must be taken by Odfjell Drilling.

10.5 FW temperature exceeding max design temperature.

When conducting the calculations for flow on the seawater side, we noticed that the FW temperature exceeded the design temperature for the heat exchanger of 70°C. These calculations were based on the average theoretical flow rate, and heat generated by consumers based on their average running time. These calculations were based on the maximum possible heat generated by the consumers and believe that this is a highly unlikely scenario, and do not believe it will be a problem when the system is implemented.

11 Conclusion

The aim of the project was to gain a better understanding of centralized cooling systems and propose a solution for optimizing the system onboard one of Odfjell drillings vessels. At the start of the project consisted mostly of reading system drawings and building a general understanding of the system and its behavior.

The project started in December 2020, where we preformed flow tests on the system to get a better understanding. We quickly realized the potential in improving the efficiency as the initial results were very promising. The solution ideas, from an automation standpoint, are relatively simple. When factoring in the scale of the system and all the safety requirements surrounding it, the project quickly becomes complex.

When designing the solution for this project, we wanted to make the solution as simple and robust as possible. This was done so that Odfjell Drilling could commission the project without being dependent on of support from ABB or other equipment suppliers, which would drive to cost up greatly. Using feedback from our supervisors in Odfjell Drilling, as well as testing with a VFD in the lab at HVL, we believe we have come to an effective solution to the problem.

During our bachelor project we were informed by Odfjell that our solution was to be implemented. Two members of our group will continue to further develop this project and work on commissioning. The upgraded system is set to be in operation in late summer 2021.

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Appendix A. Project documentation

With this report there is attached a zip file called user documentation. This contains:

- Freshwater cooling pump software description
- Seawater cooling pump software description
- Central cooling system commissioning procedure
- Functional description of changes to central cooling system