Optimise sea water cooling on SSAV Tiradentes

By installing frequency converters on the seawater cooling pumps

Thesis

Author: Levien J.M. Verboven
Study year: 4
HZ University of Applied Sciences
Coach: A. de Groot
Place: Middelburg
Date: 17-04-2023
Version number: 2.0

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Image on front page: OOS Tiradentes. OOS international, 2018.

Samenvatting

OOS International is een in Nederland gevestigde internationale offshore dienstverlener voor accommodatie, scheepsmanagement en zwaar hijswerk. OOS levert hooggekwalificeerde constructiediensten binnen de olie- en gasindustrie. De OOS Tiradentes is een Semi-Submersible Accommodation Vessel (SSAV), dat plaats biedt aan 580 personen. Een 3D-gecompenseerde 'gangway' is geïnstalleerd om mensen te verplaatsen tussen de OOS Tiradentes en het platform van de klant. Dynamic Positioning (DP) wordt gebruikt om de positie naast de platforms te behouden.

Het schip is momenteel in bedrijf nabij de Braziliaanse kust. Dit gebied wordt bestempeld als een gematigd klimaat, wat betekent dat de regenval en de temperatuurverschillen tussen de seizoenen niet groot zijn. De voorschriften voor veilig gebruik in "Dynamic Positioning" modus op de OOS Tiradentes schrijven voor dat ten minste drie van de zes hoofdmotoren moeten draaien. Aangezien niet alle motoren voortdurend en niet bij volle belasting draaien, hebben de koelwaterpompen meer koelcapaciteit dan nodig. Door op de zes koelwaterpompen frequentieregelaars te installeren kan het toerental van de elektromotor worden verlaagd, wat leidt tot een lager energieverbruik. Dit kan brandstof besparen en de levensduur van mechanische onderdelen in de pomp verlengen door lagere mechanische belastingen.

Deze studie is een aanbeveling aan OOS International voor het optimaliseren van het koelwatersysteem met behulp van frequentieregelaars, en beantwoordt de vraag: "Wat is de verwachte return on investment van de gekozen installatie van frequentieregelaars op de zeewaterkoelpompen?".

Voor deze studie zijn deskresearch en kwantitatief onderzoek gecombineerd. VFD-berekeningen op de OOS Tiradentes tonen aan dat gewoonlijk slechts 30 procent of minder van de gepompte koelcapaciteit effectief wordt gebruikt. De brandstofbesparing na installatie van de frequentieregelaars wordt geschat tussen €64.747,54 en €77.462,26 per pompconfiguratie per jaar.

Voor de zes pompen die zullen worden uitgerust met VFD's werd de upgrade berekend op materiaalkosten, installatie en manuren. De kosten voor deze conversie wordt geschat op €509.734,19. De Return on Investment is berekend op basis van vier modellen en duurt in het slechtste geval ongeveer 15 maanden.

Abstract

OOS International is a Netherlands-based international offshore service provider for accommodation, ship management and heavy lifting. OOS provides highly qualified construction services within the oil and gas industry. The OOS Tiradentes is a Semi-Submersible Accommodation Vessel (SSAV), which can accommodate 580 people. A 3D-compensated 'gangway' is installed to transfer people between the OOS Tiradentes and the client's platform. Dynamic Positioning (DP) is used to maintain position next to the platforms.

The vessel is currently in operation near the Brazilian coast. This area is labelled as a temperate climate which means the rainfall and temperature differences between seasons is not significant. The regulations for safe operation in "Dynamic Positioning" mode on the OOS Tiradentes describe that at least three of the six main engines must be running. As not all engines are running all the time and not at full load the cooling water pumps have more cooling capacity than needed. By installing variable frequency drives on the six cooling water pumps the RPM of the electric motor can be reduced, this leads to lower energy consumption. This can save fuel and prolong the life of mechanical parts in the pump due to lower mechanical stresses.

This study is a recommendation to OOS International on optimizing the cooling water system using variable frequency drives, and answers the question, " What is the expected return on investment of the opted installation of variable frequency drives on the seawater cooling pumps?”.

Desk-research and quantitative research were combined for this study. VFD calculations on the OOS Tiradentes show that usually only 30 percent or less of the pumped cooling capacity is effectively used. Fuel savings after installing the variable frequency drives are estimated between €64,747.54 and €77,462,26 per pump configuration per year.

For the six pumps that will be equipped with VFDs, the upgrade was calculated on material costs, installation, and man-hours. The cost for this conversion is estimated at €509,734.19. The Return on Investment is calculated based on four models and in the worst-case scenario it takes around 15 months.

Preface

In this thesis information is provided regarding the following question "What is the expected return on investment of the opted installation of variable frequency drives on the seawater cooling pumps?". This thesis completes my bachelor's degree for becoming a maritime engineer. The research was carried out for OOS International B.V., and it consists of the possibility to install Variable Frequency Drives (VFD's) on six cooling water pumps used for cooling six diesel generators and three thrusters.

Graduating has been an interesting challenge with ups and downs, but all have made me stronger than I was before. For that I would like to thank several people who motivated and helped me during the entire process. Firstly, I would like to thank OOS International for the internship and the possibility to visit the OOS Tiradentes for almost five months, embarking and disembarking with a helicopter and the multicultural crew with whom I have pleasantly worked together with on huge and sophisticated systems. This was an experience in which I have learned a lot and it will remain an extraordinary memory forever. Secondly, I want to thank my company internship supervisor P. Pattenier and my HZ supervisor A. de Groot for their guidance.

At last, I would like to thank my family and my girlfriend for supporting me throughout my studies at the HZ University of Applied Sciences.

I hope you enjoy reading.

Levien Johannis Marinus Verboven
Middelburg, 17 April 2023.

Index

List of abbreviations

Abbreviation	Meaning
A/C	Air-condition
AC	Alternating current
CRAAP	Currency, Relevance, Authority, Accuracy and Purpose
DC	Direct Current
DNV-CG	Den Norsk Veritas – Class Guidelines
DP-3	Dynamic Positioning 3
DU/DT	Peak-voltage filter
EMC	Electromagnetic Current
ESD/PSD	Emergency shutdown
FMEA	Failure Mode Effect Analysis
FPSO	Floating Production and Storage and Offloading
FW	Freshwater
HT	High temperature
HVAC	Heating, Ventilation and Airconditioning
I/O cabinet	Input/Output cabinet
IAS	Integrated Automation System
IEC	International electrotechnical commission
IGBT	Insulated Gate Bi-polar Transistor
IP-rate	Internal Protection rate
kW(h)	kilowatt(hour)
LT	Low temperature
LV SWBD	Low voltage Switchboard
MC	Mechanical completion
MDO	Marine diesel oil
NEK	Norwegian electrotechnical Committee
OOS	Overdulve Offshore Services
P&ID	Piping & Instrumentation Diagram
PLC	Programmable logic controller
PMS	Power management system
PT-100	type of temperature sensor
PWM	Pulse-width modulation
QSP	Quality survey plan
ROI	Return on Investment
RPM	Rounds per minute
RTD	Resistance temperature detector
SHF	Sheath halogen free
SSAV	Semi-submersible Accommodation unit
SW	Seawater
VAT	Value added taxes
VFD	Variable frequency drive

1. Introduction

General information:
The OOS Tiradentes is equipped with a diesel-electric propulsion system. The power is generated by six MAN 12V 32/40 diesel engines divided over three engine rooms supplying six azimuth thrusters located in the pontoon area. In each pontoon three azimuth thrusters are installed with a maximum load of 4400 KW. In each thruster room one, two and six there are three seawater cooling pumps installed in combination with 2 heat exchangers. This is for High temperature and Low temperature cooling water. The extra pump is a backup pump and can feed water to the LT and HT heat exchanger in case of failure. The Freshwater side of the LT cooling water system is used for cooling two engines and one azimuth thruster including auxiliaries. The freshwater side of the HT cooling water system is used for cooling two engines. This means three thrusters have a separate cooling water system. This research will only discuss the six seawater cooling pumps used for cooling 6 engines and three thrusters.

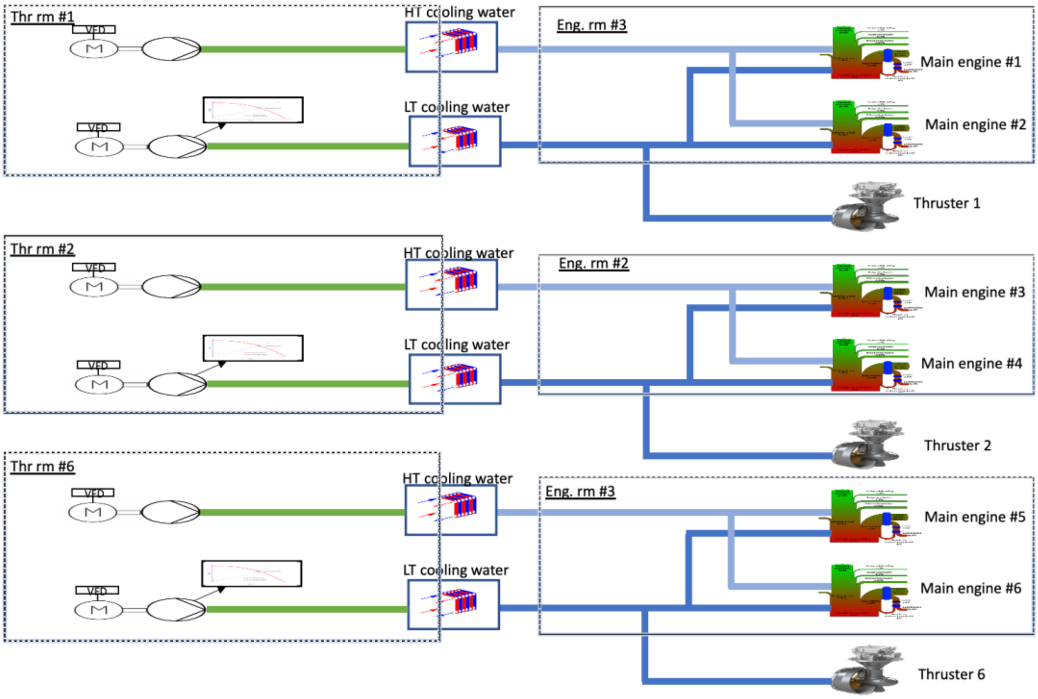

Figure 1 Overview of the six cooling pumps that will be discussed in this research. The idea is to upgrade the motors with variable frequency drives (VFD'S) as seen in the figure. (L.J.M. Verboven, 2023)

The issue:
The OOS Tiradentes is a Semi-Submersible Accommodation Vessel (SSAV) operational in Brazil. The ship is relatively new but still there are several options to optimize. In this research the seawater cooling system is opted for a potential upgrade by installing Variable frequency drives on a total of six seawater cooling pumps. This project was early postponed due to the lack of budget for research, parts, and construction at that time.

The OOS Tiradentes is in operation if the telescopic gangway allows personnel to go back and forth between the OOS Tiradentes and the platform of the client. To stay alongside a client's platform the vessel makes use of dynamic position to maintain the required position. The power consumption of this propulsion system is mainly determined by the surrounding environmental conditions. When connected to the client's platform most of the time the power consumption of the Engines and

Azimuth Thrusters is low because most seasons the weather is gentle, and the current is relatively low (The Brazil Current, n.d.).

Due to Dynamic Positioning 3 (DP3) regulations it is mandatory to always run engines below 50 percent load when in DP mode. The OOS Tiradentes has three engine rooms and while in DP mode in each engine room at least one of the two engines must be running. The LT and HT cooling water pumps are designed for cooling both engines when running at 100% load with an outboard seawater temperature of 35 degrees. Most of the time only one engine is running, and the seawater temperature is below 35 degrees. To prevent too much cooling of the engine this cooling water is bypassed and not flowing through the HT and LT heat exchangers. This means that the water pumped through the bypass is wasted energy. Another way of regulating the cooling water temperature while minimizing wasted energy is by adjusting the quantity of cooling water that is pumped. The best way to achieve this is by installing variable frequency drives on the seawater cooling pumps. By installing variable frequency drives OOS International would like to reduce fuel costs and emissions.

Objectives:
This research is a recommendation to OOS International on optimizing the cooling water system on the OOS Tiradentes by installing variable frequency drives. The goal is to minimise fuel costs, emissions and enhance the operational conditions of the cooling pumps. To get a better understanding of optimising a cooling water system by using VFD’s on a DP-2 or DP-3 system a hypothesis of such conversion is described in this research.

Main Question:

What is the expected return on investment of the opted installation of variable frequency drives on the seawater cooling pumps?

Sub Questions:

1. Which additional parts should be ordered for the opted installation of variable frequency drives?
2. What are the expected total expenses for the opted installation of the variable frequency drives?
3. What is the expected new power consumption of the cooling water system after installing variable frequency drives?

The main question is supported by three sub questions. All the theories available and relevant for this research is covered in the theoretical framework. This framework contains all the regulations, expenses and calculations based on models and profiles what will result in answering the questions.

Preconditions:
To realize this opted installation of variable frequency drives it will have to meet several conditions. The system must be built with the lowest expenses possible, Future maintenance of new installed parts must be taken into consideration and the system must be standardized, safe and redundant. The opted installation should be carried out with as little downtime as possible.

Reading guide:
The first chapter begins with the commissioning regulations for installing a variable frequency drive on an electrical a-synchronic motor. In the second chapter the design properties and the needed software and hardware for such system is investigated. In the third chapter the expenses are calculated for the software/hardware, installation costs and commissioning costs. In the fourth chapter a forecast of the fuel savings is calculated. In the fifth chapter the expenses and savings are compared and based on different models the return of investment is calculated. The conceptual framework in chapter 2.6 is a visual representation of the research steps that have been taken to answer the main question.
The method is used to describe how the correct data is acquired to reach a conclusion based on results from research on board the OOS Tiradentes.
The results describe all the costs and energy calculations for this VFD conversion. The discussion reflects the calculations in the results. Also the validity and uncertainties are discussed such as the reliability of fuel costs in the future. The conclusion and recommendations cover the results of the main and sub-questions from this research.

2. Theoretical framework

In this theoretical framework all relevant concepts, definitions, models, theories that are related to the main research question and sub-questions are described.

2.1 Requirements for a commissioning process on an Offshore unit.

DNV-CG-0170 “Offshore classification projects – testing and commissioning” is a class guideline which outlines the general best practices that lead to effective testing and commissioning of new modifications of systems on board in nine steps. As the opted upgrade of installing variable frequency drives on the seawater cooling system is in step 1 it is important to know what requirements the class society have for commissioning this system. DNV-CG-0170 is applicable to testing and commissioning activities onboard classed mobile offshore units e.g., drilling accommodation and FPSO. The OOS Tiradentes is a Semi-Submersible accommodation vessel meaning the class guideline is applicable. The total commissioning process consists of nine steps and each step will be described below.

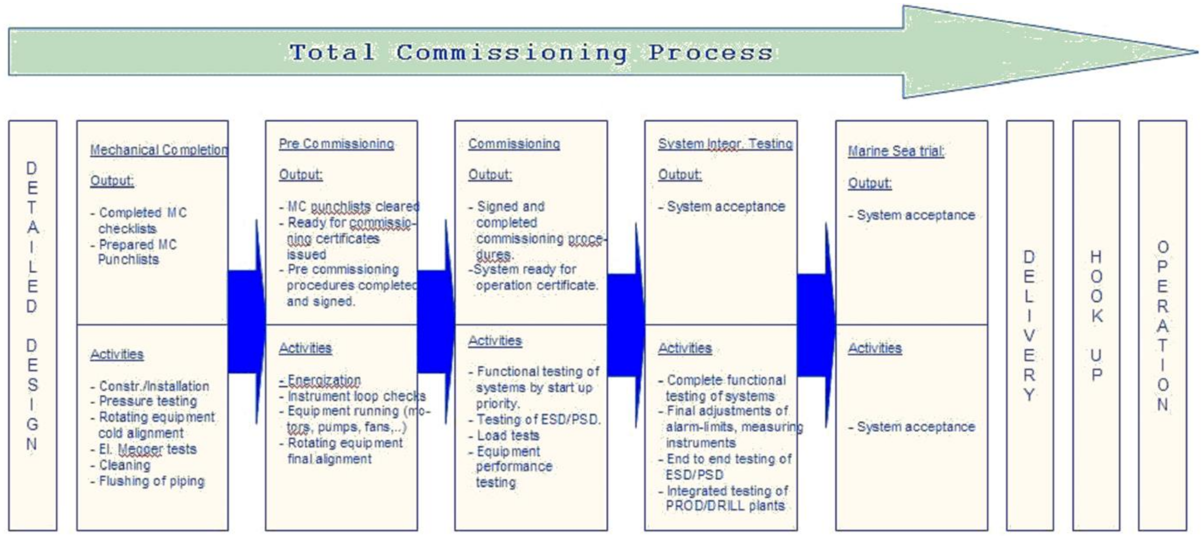

Figure 2 Total commissioning process described in nine steps (DNVGL, 2015)

Detailed design

“When entering into the final stages of any project, the detailed design is expected to be fully completed, reviewed and approved” (DNVGL, 2015) If the design is not done in a satisfactory manner this can result in problems when testing and commissioning. Eventually this will result in loss of valuable time or additional costs.

For this research the first step is to design new electrical diagrams and if needed adjust old electrical diagrams. In these electrical diagrams the type of wires, type of VFD and if needed extra components are shown (for example DU/DT filters.). The new drawings must comply with class society regulations, As the frequency drive is an electrical component, offshore standards DNV-OS-D201 “Electrical installations” guidelines must be followed to avoid difficulties in the following commissioning steps. The electrical drawings will give insight in how to wire up the new system into the already existing Integrated Automation System (IAS), More detailed information about connecting the VFD controls to the IAS system is described in paragraph 4.1.

Mechanical completion

The mechanical completion stage is the construction period of the system. In other words, the system is built as defined in the detailed design. After finishing the construction, a mechanical completion checklist is performed. The class survey maintains oversight by doing unscheduled surveys. The quality survey plan (QSP) lists certain activities of MC where the presence of a surveyor is mandated. For this research the Cable installation and Low Insulation testing are MC checks where a class society surveyor is mandated. The performed tests verify that the added parts to the cooling water system are installed correctly and evidence of the required certification of equipment must be verified.

Pre-Commissioning

The pre-commissioning phase is a phase where normally the DNV Surveyor does not attend. In this stage the functional operability of the equipment part or full system is verified. This stage of testing requires energising of equipment and introduction of fluids in cooling piping systems. By 'trial and error' testing the last problems can be solved before the commissioning phase.

In this phase the VFD's are tested in local control and remote control. The variable frequency drive controls the a-synchronic motor by adjusting the frequency in the stator of the electric motor. As the torque will differentiate as an effect of this variation of frequency in the stator the rotor will change its rotational velocity (Select Electricalent, 2021). The Variable frequency drive can be operated in local control or remote control. Adjusting the RPM on the control panel located on the VFD is called local control. This is possible by first pushing the button "Hands on" and then the RPM can be adjusted by using the "raise or lower" buttons. When the RPM settings of the VFD are controlled from the engine control room this is called remote control. Remote control is possible by pushing the "Remote" button on the VFD and then the control signals are sent to an Input/Output cabinet (I/O cabinet). The I/O cabinet sends multiple signals from different systems to the "console engine control room" This is an Acoustic/optical signal unit. The signals from sensors and control systems are displayed on this console. Kongsberg (manufacturer of Dynamic Positioning systems for Offshore vessels) made it possible by applying software and hardware to interpretate these signals and if needed send a signal back to a specific system or give an alarm when a received signal from a I/O cabinet is concerning for safe operation of the vessel. This is done by an acoustic alarm combined with a visual reading on the engine control room console display. Kongsberg has programmed the system that when alarms are received that have an immediate danger on safe operations the "Integration Automation System" can shut down engines, thrusters, open and close breakers and start or stop pump configurations to maintain safe operation of the vessel. When the conversion of installing VFD's on the seawater cooling pumps are done first in local control safe operation must be achieved. After local control is sufficient the system must maintain a safe operation in remote control. This means that the IAS needs to be tuned in such a way that the system automatically follows the correct steps after receiving input signals from the VFD and sending output signals, temperature sensors and pressure sensors in the cooling water system. To clarify this Kongsberg system the next paragraph is a simple example of k-chief control system (Marine automation system, K-Chief 700 – Kongsberg Maritime, n.d.).

Simple example of K-chief system (K-chief is system of field station to IAS system)
The two lube oil pressure sensors mounted on the main engine both read out a pressure of 1 bar and the normal operating pressure is 5 bar for the engine. The I/O cabinet will receive this reading and send it to the integration automation system (IAS). The IAS will interpret this as immediate danger and will send a signal back to the I/O cabinet to activate an emergency shutdown of the Engine. Furtherly an alarm is sent to the engine control room console to inform the process operator. To prevent black-out the IAS system will give a signal to another I/O cabinet to start an extra engine. After this the Power management system (PMS) comes into play. The PMS is part of the IAS and will manage the breakers of the Busbar. It will open the breaker of the stopped engine and close the breaker of the started engine. At the same time the RPM of the extra engine is adjusted to synchronize before closing the breaker as this is necessary to prevent complete black out on the busbar.

The new cooling water system including the VFD controls must be connected to k-chief including visualisation on the ECR console. This service must be provided by Kongsberg. In paragraph 4 “results” more about the visualisation of the new system is explained.

Commissioning

When the Pre-commissioning phase is completed meaning the system is working sufficiently based on the trial-and-error principle, a class surveyor will come on board to test the system and make sure that after tuning the system all parts contributing to the conversion are working sufficiently and in operating limits.

System integration testing

System integration testing is testing and commissioning of more than one system. In this phase all systems related to the converted system are in operation while testing the cooling water system. The System integration test is often carried out during the marine sea trials and proves compliance with project requirements. This testing covers at least the complete functional testing of systems across equipment boundaries, Final adjustments of alarm-limits and measuring instruments, end to end testing of ESD/PSD.

Operation

In this phase only regular maintenance is needed to keep the system in operational conditions. A maintenance scheme must be followed based on manuals of the parts in the converted system. In this phase usually no class and statutory items.

2.2 Understanding of Parts needed for conversion

In this paragraph knowledge is obtained about the minimum requirements for the additional parts. First the type of variable frequency drive is discussed. The variable frequency drive must have features that are critical for safe operation in a DP-3 vessel. When a suitable VFD type is selected the type of cables for power supply is discussed. The next section discusses the additional type of sensors that must be installed and how to connect the sensors to the IAS. In the last section the control units and power supply units needed for connecting the VFD and the additional sensors to IAS are verified. The location of the additional added parts including the amount of cable for the conversion are shown in the results paragraph 4.1.

2.2.1. Variable frequency drive

The VFD is a type of motor controller that drives an electric motor by varying the frequency and voltage of its power supply (Danfoss, 2023). The Variable Frequency is comprised of three main components: A rectifier, DC link, and an Inverter. The rectifier converts the Alternative Current (AC) to Direct Current (DC) The DC link supplies voltage to the drive from the rectifier and inverter, the DC link stores power converted by the rectifier. Capacitors in the DC link absorb the remaining AC Ripple and deliver smooth DC voltage (see Figure 3). This DC voltage is converted into an AC voltage by switching transistors in the inverter and sent to the motor.

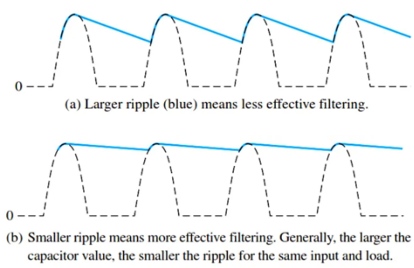

Figure 3 Filtering AC ripple using capacitors

The Variable Frequency Drive varies the output frequency by switching transistors connected to either the positive or negative DC bus (Select Electricalent, 2021). The inverter is controlled by a PLC programmable controller. There are different types of inverters and PLC programmable controllers available on the market. The most common VFD configurations used in cooling water systems and ventilation systems are equipped with Intermitted Gate Bi-polar transistors (IGBT) inverters and controlled by a PLC using Pulse Width Modulation (PWM). Figure 4, here below shows a block diagram of a VFD consisting of the three main components and necessary auxiliary components.

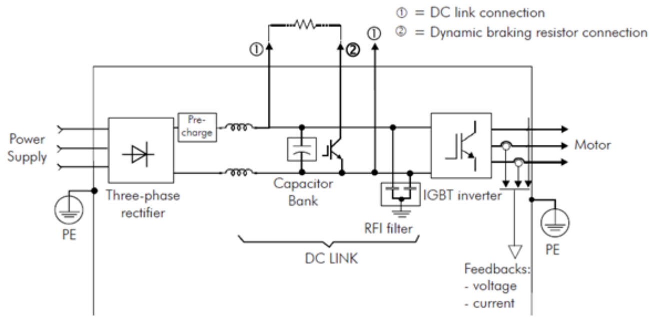

Figure 4 Block diagram of variable frequency drive

As the cooling water system is a critical system for safe operation the system must be reliable. Features like “Coasting and Flying start” increase the reliability of the VFD controlled cooling water system. Furtherly the VFD must be integrated in the Kongsberg K-chief system. The following signals are sent from the VFD to the I/O cabinet to ensure K-chief can act accordingly based on the operation status of the VFD:

-*Remote function*
-*Electric motor running feedback*
-*remote start/stop function*
-*Electric motor speed feedback*
-*Electric motor speed Set (remote)*

After multiple prices are known obtained by brochures and the feasibility of multiple VFD’s are discussed the most suitable VFD is selected and is shown in paragraph 4.1.

2.2.2. Cables

The electric cable is an insulated conductor provided with a protective coating. It is made by a metal part, generally copper which is covered with an insulating material. Conductor and insulation form the core of the cable. A cable can be made up of one or more cores. From the outside, it is protected by a sheath. The first section discusses the minimum requirements for the power supply cable between the VFD and Electric motor. The second section discusses the minimum requirements of the communication cables between the VFD and I/O cabinet.

Correct type of Power supply cable.

The type of power supply cable must be an armoured cable (EMC cable) as the VFD power is more sensitive to corona discharge. The cables will be installed in the thruster rooms meaning that enhanced mechanical protection and electrical screening is required. The flexibility class of the cable must be high to be able to bend the cable in narrow spaces. Below a list of the minimum requirements for the cable based on IEC regulations.

-Conductor flexibility	Flexibility Class 5
-Halogen free	IEC 60754-1
-Rated voltage	600V/1200V
-Fire retardant	IEC 60332-3-22
-Flame retardant	IEC 60332-1
-Gasses toxicity	No
-Gasses corrosivity	IEC 60754-2
-Smoke density	IEC 61034

The Outer sheath can consist of two types “SHF 1” or “SHF 2” as described by NEK 606 norm. SHF 1 consists of a thermoplastic fibre and SHF 2 consists of ethylene vinyl acetate which is a multi-functional elastomer. SHF 2 cable is softer and more flexible than SHF 1. In offshore systems it is most likely to use type SHF 2 for the outer sheath (Incore-cables, 2023).

The size in square millimetre depends on the amount of current that is passing through the wire. First the internal current is calculated by a load on the electric motor of 82,8 kilowatts.

$$P_{total} = \sqrt{3} \times I_n \times V_{ll} \times PF \times \eta$$
$$I_n = \frac{P_{total}}{\sqrt{3} \times V_{ll} \times PF \times \eta}$$
$$I_n = \frac{82800}{\sqrt{3} \times 690 \times 0{,}85 \times 0{,}94}$$
$$I_n = 86{,}7\ A$$

$\mathrm{I_n}$ = nominal current
$\mathrm{V_{ll}}$ = Voltage between phases
PF = Power factor
η = efficiency of electric motor

Now the Power losses in the cable can be calculated. There are two types of losses in the cable. The biggest losses are created by currents passing through the cable. The second type are dielectric losses. These losses are created by a change in electric fields inside of the insulation. In grid calculations these losses are most of the time neglected (Phase to phase, n.d.). This means we will only calculate the losses because of currents passing through the cable.
The resistance in a cable is based on the following formula.
$R = \rho * L * A_{size}$
$A = \pi * r^2$
As the formula shows the resistance will increase proportional to the length and thicker wire will have less resistance. The data sheets of cables most of the times will give the resistance in the cable per kilometre at a temperature of 20 degrees.
Research shows on a different DP-vessel named Acta Centaurus where Variable frequency drives are installed on the seawater cooling system cable type MPRXCX is used (Acta Centaurus, 2019). This type of wire meets the requirements as described in terms of fire resistance, flexibility, and rated voltage. The data sheets of these cables type state the following:

Table 1 Cable type and specifications (L.J.M. Verboven, 2023)

Cable type (3-phase square millimetre)	Specifications needed for calculations
MPRXCX Flexiship 3x35	-Voltage: $0.6/1.2\ kV$ -Maximum Amps: $110A$ -Resistance: $0.554\ Ohm/km$ -Price per metre: 73,4 euro

Omvlochten halogeenvrije scheepskabel

Flexibel MPRXCX® FLEXISHIP

mm2	1-aderig	3-aderig	KG
35	24.700,-	73.400,-	EJ
50	32.300,-	96.300,-	EJ
70	41.200,-	135.000,-	EJ
95	54.300,-	177.000,-	EJ
120	65.700,-	228.000,-	EJ
150	80.200,-		EJ

Figure 5 price list for MPRXCX Flexiship armoured cable (NPL15, 2022).

Cable glands and cable lugs
For the connection of the main power supply cable lugs are mounted on the cable to connect the drives to the electric motor. To protect the power connections cable glands are installed to cover the cable lugs.

2.2.3. Control units

The OOS Tiradentes has the following types of Kongsberg marine automation systems installed on board:

1. Kongsberg Positioning (K-Pos) which is used for position keeping using azimuth thrusters.
2. Kongsberg Safe (K-Safe) which is used for Fire and Gas systems.
3. Kongsberg Chief (K-Chief) which is used for power management, Auxiliary machinery control, Ballast/bunker monitoring and control, Cargo monitoring and control

The cooling water pumps are described as Auxiliary machinery by Kongsberg and must be connected to I/O cabinets (Field stations). The Field station send and receive data from the IAS system.
For the sensors and from the VFD unit to the field station cabinet communication cable is used to send and receive signals about the status of the system. For every engine room cabinet about 50 meter of communication cable is required. The ordering costs depend on the amount of cable needed and the price per meter of cable.

Figure 6 Picture of field station on the OOS Tiradentes (L.J.M. Verboven, 2022).

Figure 7 RCU502 and RMP420 installed in Field station (L.J.M. Verboven, 2022).

2.2.4. PT-100 (temperature sensor)

The most used temperature sensor on the vessel is a PT-100. This Resistance Temperature Detectors (RTD) are a class of sensors that change resistance when the temperature of the medium the sensor is inserted in changes. This change of resistance is proportional to temperature. Platinum is a basic element with the chemical symbol Pt. The resistance of platinum at zero degrees is exactly 100 Ohm. That is how the name for the temperature sensor PT-100 is found.

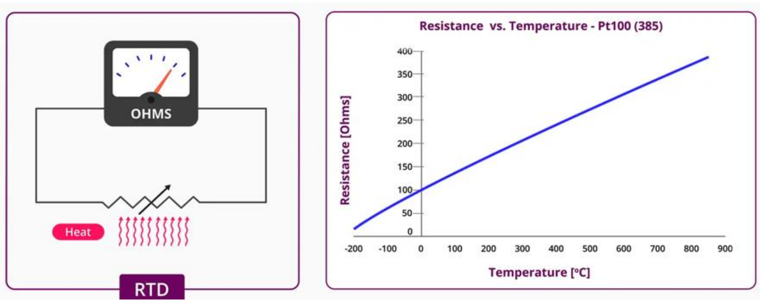

Figure 8 Block diagram of a RTD and the linear relation between temperature and resistance of the PT-100 (Sommer, 2022)

The PT-100 must be installed on the freshwater outlet pipe. The best option is to locate it as close as possible to the heat exchanger to minimise the dead-time as much as possible. To mount the sensor a socket must be installed on the freshwater outlet pipe. A total of 6 PT-100 Sensors and 6 sockets must be ordered for the conversion.

2.3 Calculations of expenses related to the conversion

Desk-research and research on board the OOS Tiradentes is done to receive more information about the quantity of parts needed for the conversion. In the pre-liminary research the costs of parts per piece is put in paragraph 4.2. Manhours for installation and commissioning are described in paragraph 2.3.1. In paragraph 2.3.2. day rates of the working personnel are discussed.

2.3.1. Installation and commissioning costs

Manhours

The calculation of man hours in the shipping industry is often based on weight/gross tonnage of the ship. For repairs on ships other factors are present. For example, system density (the quantity of installations per unit of available space) brings a different calculation then used for new shipbuilding. For an average calculation we can use some manuals on calculating manhours. Both calculate manhours in an engineering approach, based on many past projects. Since the OOS Tiradentes is located close to the Gulf Coast, manhours of available electricians and workers in that region, must be compared with European wharfs and contractors. It is determined that the average performing productivity for the Gulf Coast area is 30% less (Page, 1999). This is possible due to more difficult environmental working conditions. Therefore, when Butlers' (2012) manual: 'Guide to Ship repair estimates in Man hours' is used, 100/70 = 40 percent more manhours are added. Besides of this calculation help, experience in projects/repairs on the OOS Tiradentes and similar projects, is indispensable to estimate whether the cost figure is realistic or not. Practices of the chosen (local) project-crew or shipyard will partly be translated into more or less manhours, as a result a small part of the calculation will be a theoretical philosophy.

1. Manhours for placing the VFD and PT-100 sensor.

For installing the pocket of the PT-100 sensor the work scope consists of welding a socket on the pipe and afterwards hot tapping the line to install the PT-100 sensor. Small hot tapping machines are available to rent or buy. The purchase value is around 800 euro.

2. Manhours needed for installing cable tray for cables

Table 6.9 Man-hours for installations of cable tray per metre (perforated steel cable tray, including brackets and fastenings)

Size (mm)	*Man-hours per metre*
75	0.95
100	1.05
150	1.25
225	1.50
300	1.75
Bends	Each bend to be rated at three times that of 'per metre'

Figure 9 Man-hours for installations of cable tray per metre (Butler, 2012).

The diameter of the cable is 100 mm. The man-hours for installing one metre of cable tray are 1,05 hours/m as seen in Figure 9.

3. Manhours needed for installing cable from VFD to Electric motor.

To attach main power to the VFD's there must be some redirecting of existing cable

Main part of the job is the cabling and the installation of cable tray. Cable's will be attached to walls and be sunken in the floor. Butler provides a special Chapter on Electrical works containing tables for Manhours on Cabling, and for the installation of cable tray (Butler, 2012).

Manhours for cabling depend on type; weight and size of cable; flexibility of cable and access. Manhours per meter are shown in Figure 10. Manhours for installation of cable tray are present in Figure 9. For working on heights above three meters five percent more working hours must be taken into consideration, above five meters ten percent more working hours are added. installing two similar cables in one cable tray the manhours are reduced by 15 percent (Butler, 2012).

Table 6.7 Man-hours for installations per 100 metres of rubber-insulated, or similar, armoured flexible cable, braided in bronze or steel, basket weave

Area (mm^2)	*2 core*	*3 core*	*4 core*	*5 core*	*6 core*
1	28	36	40	45	51
1.5	29	39	51		
2.5	46	59	67		
4	53	67	74		
6	74	86	92		
10	82	90	94		
16	86	93	99		
25	90	95	109		
35	95	99	120		
50	99	112	141		
70	104	132	164		
95	109	141	180		
120	128	167	205		
150	132	176	218		
185	154	205	256		
240	196	261	326		
300	254	352	440		

Figure 10 Man hours for installing cable (Butler, 2012).

The cable is 35 square millimetre cable with 3 cores meaning 99 working hours are required for installing 100 metres of armoured flexible cable.

4. Manhours needed for connecting VFD to IAS including tuning.

Extra Installation details for connecting VFD read-out and command cables that must be connected to the IAS system have to be discussed with Kongsberg.

5. Costs of class society in terms of inspections and changes in new certified drawings.

As a change in a critical system is made a new DP system FMEA must be performed by a company that is certified by a class society. Normally this DP system FMEA is performed every 5 years. This FMEA and the costs for commissioning, surveyor attendance in commissioning steps, and changing P&ID drawings and cable diagrams conform relevant regulations.

2.3.2. Day rates / salary

According to The Complete Guide (2023) a field service technician without experience earns an average of BRL$1,630 per month, in this matter the technician is preferably experienced for 10 years or more, some of the crew must be able to communicate in English and the person must have the correct licenses and certificates for performing the job safely while working in an offshore environment. As shown in Figure 11 a field service technician with 10-15 years' experience earns BRL$3,920 per month. Offshore it is common practice to work based on a day rate and negotiate variables such as overtime percentages in the contract. Also, skills and experience may increase salary. The average day rate of a field service technician with 10-15 years' experience is around BRL$130. For this research the estimated day rate is BRL$550, based on the scope of work, the required experience and mandatory licenses and certificates. BRL$550 is around 100 euro in 2023. Meaning the price per hour is 12,50 euro.

Figure 11 Salary of field service technician in brazil (The Complete Guide, n.d.).

2.4 Fuel savings after conversion

In this paragraph the efficiency of the centrifugal pump after the conversion is theoretically described using different models and profiles. The pressure, flow, and load of the centrifugal pump with fixed RPM versus variable RPM is described by using the pump characteristics. The fixed RPM of the electric motor is currently 100 percent load.

Fuel savings are achieved in this conversion when the heat is transferred more efficient whereas the seawater pump is using less power. In Figure 12 a simplified heat transfer diagram is shown to get a better understanding of the heat transfer between the seawater and freshwater for each engine room.

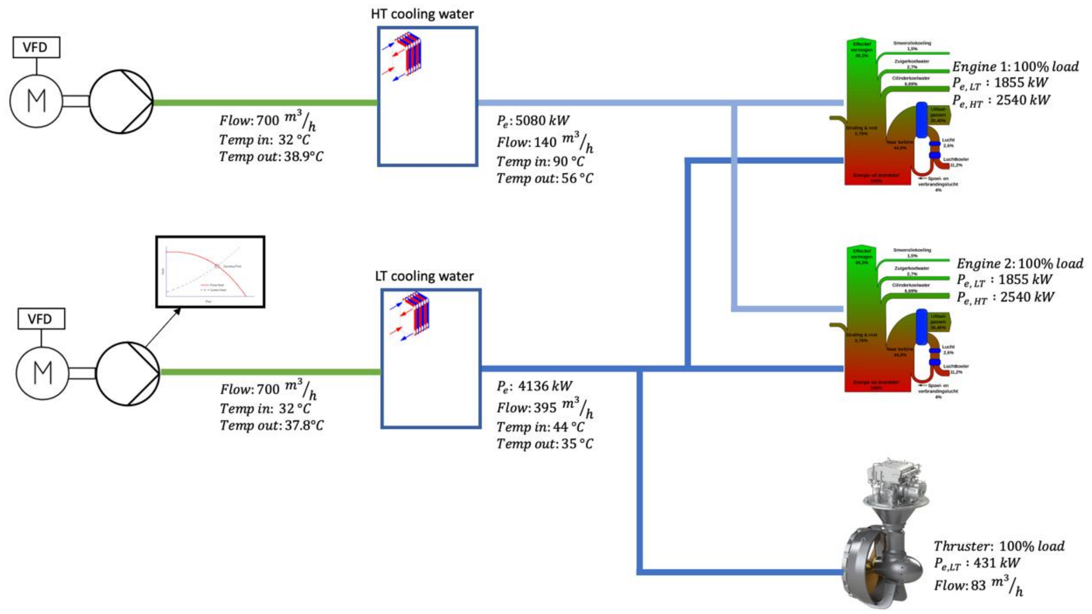

Figure 12 Simplified overview of SW for supply vs Demand on FW system at 100% load (L.J.M. Verboven, 2023).

The thrusters and main engines are operating at variable load meaning the heat transfer varies as well. The Three-way valve in the FW system regulate the heat transfer that the temperature of the FW operates stays in operational limits. The SW supply can be significantly reduced when the load on the Main Engines and Thrusters are low. The next section will give a short explanation on how the load on the engines and thrusters is determined.

Pump curve (Efficiency at different RPM)

For the HT and LT seawater cooling pump the pump characteristics are provided by the pump manufacturer. When adjusting the rpm of the pump the following three formulas are useful.

$V_e' = V_e \times (\frac{n'}{n})$ $\quad$ $P'_{man} = P_{man} \times (\frac{n'}{n})^2$ $\quad$ $P'_e = P_e \times (\frac{n'}{n})^3$

As seen in Figure 13 the HT and LT seawater pump is designed at the following characteristics.

1. $flow\ (V_e) = 700\ {m3}/_{h}$ $\quad$ 2. $pressure\ (P_{man}) = 2.5\ bar.$
3. $RPM\ (n) = 1850$ $\quad$ 4. $abs.power\ (P)_e = 64.07\ kW$

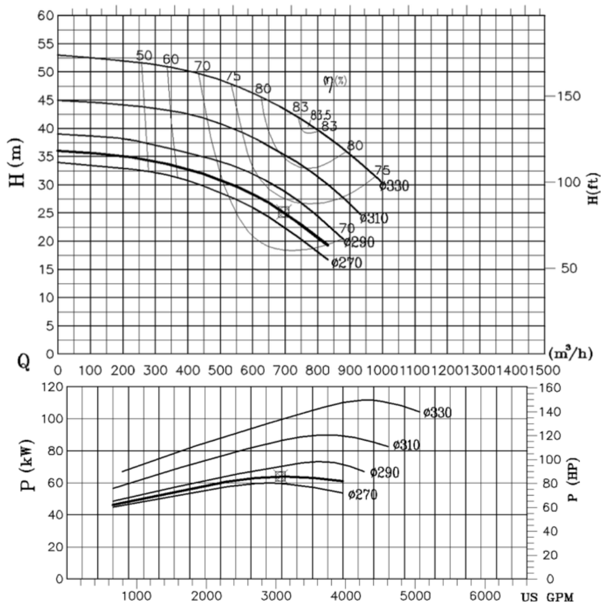

Figure 13 Pump curve and absorbed power of HT LT SW cooling pump (Azcue pump manual).

Table 2 New parameters based on pump curve at lower RPM (L.J.M. Verboven).

N (%)	N (rpm)	Flow (M3/h)	Pressure (bar)	Abs. Power (kW)	Abs. power (%)
100	1850	700	2.5	64,07	100
90	1575	630	2,025	46,71	72,9
80	1400	560	1,6	32,8	51,2
70	1225	490	1,225	21,98	34,4
60	1050	420	0,9	13,84	21,6

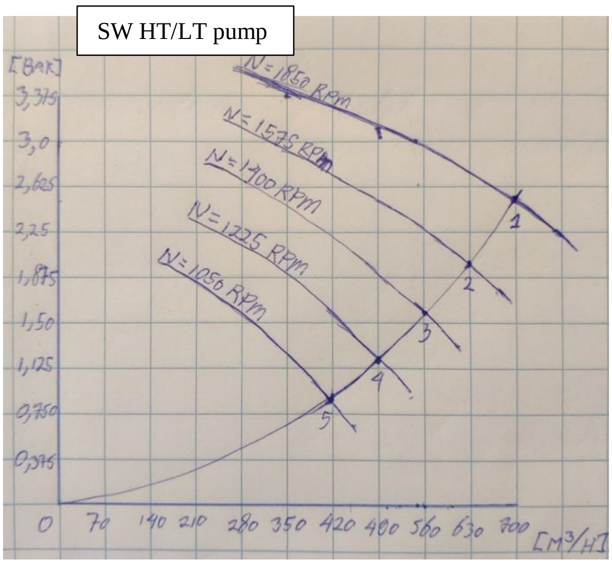

Figure 14 Pump curve for seawater HT/LT pump (L.J.M. Verboven, 2022).

In Figure 14 the new pump curve at different RPM is shown, the results are summed up in Table 1. At 60 percent RPM the pressure of the system is 0.9 bar the system must always operate over 1 bar meaning the minimum RPM of the pump must be above 65 percent. In Figure 14 the new pump characteristics at different RPM are described.

The absorbed power is not yet the total power consumption because resistance in the electric motor, cables and motor control must be taken into consideration. In a simplified block diagram, the train of parts containing losses is shown. This efficiency train can be used in Paragraph 4 "Results" to calculate the total efficiency and power consumption of the pump configuration.

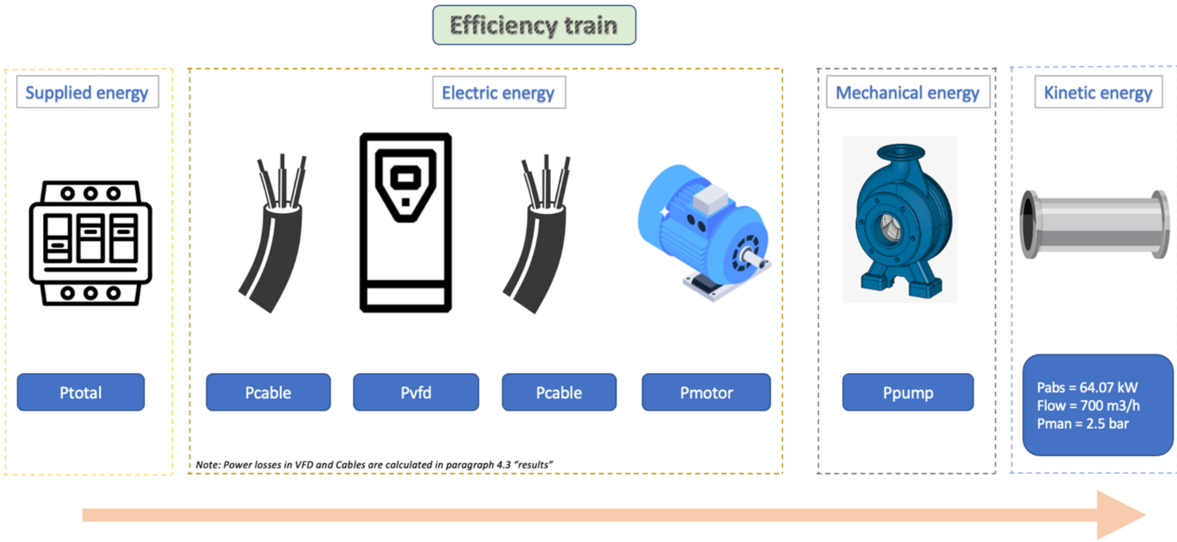

Figure 15 Efficiency train (L.J.M. Verboven, 2023).

The cable from the VFD to the LV SWBD rooms located on the Lower Deck are 50mm^2 cables. The resistance in these cables is also taken into consideration in the power losses calculations as well as the new installed cables. The cable losses are calculated as shown in this example.

Example:
A three phase cable of 35 mm^2 (R=0,554/km) is connected between the VFD and Electric Motor. The cable has a total length of 25 metres and must supply a power of 82,8 kW to the electric motor. What are the power losses in the cable?

$$R_{cable} = \frac{25}{1000} \times 0{,}554 = 0{,}01385\ Ohm$$

$$I_n = \frac{82800}{\sqrt{3} \times 690 \times 0{,}85 \times 0{,}94} = 86{,}7\ A$$

$$Uverlies = 86{,}7 \times 0{,}01385 = 1{,}2\ V$$

$$1{,}2 \times 86{,}7 = 153\ Watt\ per\ phase$$

In the results the total power losses of all the cables together are calculated and will be compared to the power losses when the current is less so the power losses in the cables is also less. With the new current the new power losses can be calculated.

2.5 Return on investment

According to Beattie (2022) “ROI measures the probability of gaining returns from investments”. This is expressed in this equation as:

$$ROI = \frac{Total\ revenue}{Total\ cost} \rightarrow \quad ROI = \frac{Energy\ savings\ per\ year}{Costs\ for\ opted\ conversion}.$$

The fuel consumption on board the OOS Tiradentes is calculated by dividing the generated power of the Main Engines in kWh and the Fuel consumption in litres.
The energy savings per year are calculated based on yearly saved euros with the following formula:

$$\text{Yearly savings} = P * B * P_e$$

Pe = Price of fuel for 1 kWh $\frac{€}{kWh}$
P = nominal power of the motor in kW based on the four load models calculated in paragraph 4.3.
B = operating time of the motor in hours per year.

The fuel price per kWh on the OOS Tiradentes is calculated in paragraph 4.4 based on the average load while in DP-3 mode near the Brazilian coast. At different environmental conditions the fuel price per kWh can be different. According to OOS (L. Overdulve, personal communication, 2022) the contract with Petrobras is extended until at least 2025 meaning for this research the fuel price per kWh as shown in paragraph 4.4 is valid.

2.6 Conceptual framework

The conceptual model is based on the main question followed by three sub questions supported by imported topics that are discussed in this report to find possible answers to the questions.

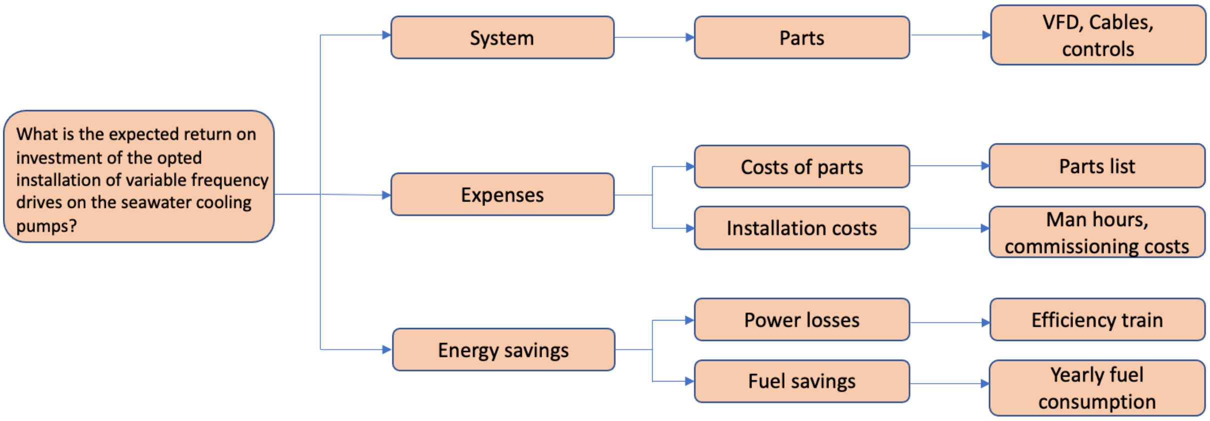

Figure 16 Conceptual framework. (L.J.M. Verboven, 2023)

3. Method

For this thesis internal desk research, external desk research and quantitative research are used. Internal desk research is done on enquiries, manuals, Piping- and Instrumentation Diagrams (P&ID), cable diagrams, internal experts, thesis proposal/start-up and different valuable sources received from OOS International. Examples of used external desk research are brochures, Scientific research platforms, educational books, external experts. Quantitative research is performed in sub-question 1, 2 and 3 for estimating costs, expenses, and Return on Investment of the opted conversion.

3.1 Method per sub-question

1. **Which additional parts should be ordered for the opted installation of variable frequency drives?**

Constructed on P&ID's and drawings of the thruster rooms a new conversion plan for the opted installation was added to the original designs see Appendix 4. Based on desk research, and research on board the OOS Tiradentes and for four weeks on the Acta Centaurus, which already have this opted conversion in service, the additional parts in the VFD configurations on electric pumps were described.

2. **What are the expected total expenses for the opted installation of the variable frequency drives?**

The quantity was substantially based on the new conversion plan such as the length and type of cable, the type of VFD and sensors. The Labour hours are based on paragraph 2.2. using a calculation model created by Butler (2012). The day rates for able personnel are based on cost calculations of earlier projects on board the OOS Tiradentes. For the costs of parts in paragraph 4.2 a table the same as Table 4.

Table 3 Expenses table for additional parts needed for opted VFD conversion.

Total costs of parts	Remarks	Pieces needed	Price per piece	Incl. Transport and Import costs (80%)
EMC Cable 35 mm2	Cable between VFD and el. Motor			
Cable gland M 35	For protection of cable connections			
Communication cable	Between VFD and Field Station, CAT 6.			
VFD motor controller	Maximum output at least 82.8 kW			
VFD Filter	Du/DT filter			
Auxiliary VFD related parts	Remote control and read-out functions.			
PT – 100 Sensor	Installed after Heat exchanger			
Pocket for PT-100	No remarks			
TO BE CONTINUED IN RESULTS				

3. **What is the expected new power consumption of the cooling water system after installing variable frequency drives?**

Based on the cooling water system specifications the heat balance graph was designed (See Figure 12). The heat balance graph was made to have a better understanding in the cooling supply and demand. The resistance of the cables, VFD's, pumps and electrical motors were calculated by pump manufacturer details, manuals, electric motor plates, cable datasheets and desk research. This to see how much loss there is in the system's components in logical order. By making an efficiency train and heat balance graph the fuel consumption per kWh (as described in paragraph 3.5) and the fuel savings were estimated.

Return on Investment
The expected return on investment was for a big part calculated based on the answers from sub questions 2 and 3. In these sub questions it was calculated what the expenses and consumption were and weighted against the costs of installation the ROI could be calculated. Further prices that were needed to calculate the ROI were found in inquiries, quotations, pricelists, and third-party information.

3.2. Reliability and validity

Reliability and validity are ways of demonstrating and communicating the rigour of research processes and the trustworthiness of research findings. This trustworthiness depends on several research features: the initial research question, how data are collected including when and from whom, how they are analysed, and what conclusions are drawn (Roberts, P., & Priest, H., 2006). The data in this research is validated by operational data of the vessel OOS Tiradentes in service in Brazil. This data consisted of the power consumption of the main engines and the seawater cooling pumps and azimuth thrusters in various environmental conditions.

3.2.1. Reliability

The following forms of research are concluded for this thesis: internal- and external desk research and quantitative research. The internal research consisted of email contact and meetings with the technical department working in the office from OOS International B.V. External desk research was performed through sources such as brochures, manuals, pricelists, inquiries, academic work, and professionals from within the field. The combination of having both internal and external sources helped the reliability of this research by having multiple points of view and information sources. The reliability of the external sources is checked through the CRAAP test (Currency, Relevance, Authority, Accuracy and Purpose) (Research Guides: Evaluating Sources: The CRAAP Test, n.d.).

3.2.2. Validity

To increase the validity of this thesis data is checked by email contact and meetings as well as comparisons to data of OEM manuals and information from the shipyard. This collaborative work ensured that the information was double-checked and consequently validified.

4. Results

The results describe the most important findings of the conducted research. The results answer the main- and sub questions.

4.1 Understanding of parts needed for conversion

VFD

A suitable VFD is the ACS880-01-098A-7 ABB. This VFD has a maximum power output of 90 kW and has all essential features built in. “These features include as standard a choke for harmonic filtering as well as options like a brake chopper, EMC filter and communication protocol adapter, functional safety, external output filters and I/O extension modules” (ABB, 2023). The VFD without additional options is listed on the market for 13.640,00-euros incl. VAT (wiautomation, 2023). The additional options needed must be discussed with ABB and Kongsberg. The frequency converter is rated with Internal Protection (IP) 21. When placing the VFD inside a cabinet this IP rating is not a problem. When the VFD is mounted to the wall in the thruster rooms an IP rating of 21 is not sufficient. The solution for this problem is that the drive offering includes enclosure classes up to IP 55. In this VFD conversion the VFD with an IP-21 class is built inside a cabinet. A total of six VFD and three cabinets must be ordered for this conversion. In other scenarios it is possible that mounting the VFD to the wall is less expensive than installing a cabinet. For the additional options for the VFD a limit of 5000-euro incl. VAT is taken into consideration. The cabinet will cost around 2000-euro incl. VAT per piece. For shipping and importation costs OOS reached out to a Logitec specialist (importation company) for regular parameters for shipment of mechanical parts such as pumps and electrical equipment. The following parameters can be used:

1. Aliquote for importation to Brazil	65%
2. Air freight cost (5 days to delivery)	17.5%
3. Sea freight cost (35 days to delivery)	7.5%
4. Customs cost	0.5%

Price VFD	= 13.640 * (1/1,21)	= 11.272,7 euro (21% Tax return in the Netherlands)
Price adding features		= 5000 euro
Total		= 16.272,7 euro

Total costs after importation and shipping for 1 VFD unit including additional controls:

Air freight = 16.272,7 * (1+0,65+0,05+0,175) = 30.511,31 euro.

Sea freight = 16.272,7 * (1+0,65+0,075+0,05) = 28.884,04 euro.

The efficiency of this type of VFD is given by ABB as shown in Figure 17.

Operating Point Frequency / Current	Absolute Loss	Relative Loss	Efficiency
0 / 25 %	471 W	0.4 %	93.1 %
0 / 50 %	639 W	0.5 %	95.0 %
0 / 100 %	963 W	0.8 %	96.2 %
50 / 25 %	497 W	0.4 %	96.4 %
50 / 50 %	701 W	0.6 %	97.3 %
50 / 100 %	1141 W	1.0 %	97.8 %
90 / 50 %	795 W	0.7 %	98.3 %
90 / 100 %	1416 W	1.2 %	98.5 %
Temperature Rating:	Maximum 40 °C		

Figure 17 VFD efficiency at different Operating Point Frequency / Current. (ABB brochure, 2023)

I/O Cabinet / Visualization.

To install the PC cable and the PT-100 sensor cable the following channels can be used to connect the VFD controls:

- Thruster room#1: (SW pumps HT#3 and LT#3). FS201/RMP420/U2 spare channels 25-32;
- Thruster room#2: (SW pumps HT#2 and LT#2). FS202/RMP420/U2 spare channels 21-24, 25, 29-32;
- - Thruster room#6: (SW pumps HT#1 and LT#1). FS206/RMP420/U2 spare channels 21-24, 25, 28-32;

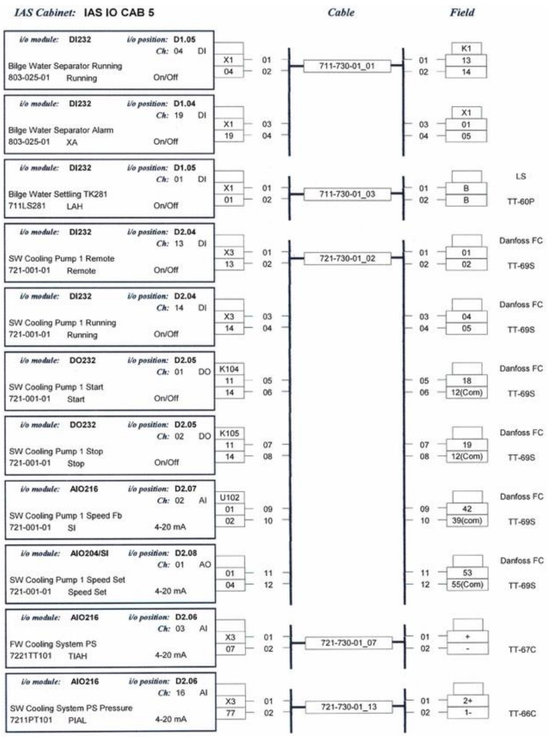

Figure 18 example of a IAS IO Cabinet with channels reserved for VFD

In Figure 18 a wiring diagram for a VFD connected to a Field station is shown. Based on research on the OOS Tiradentes and Acta Centaurus the time that Kongsberg need to connect the communication cables is estimated and used in the ROI calculation. To have more specific price details an enquiry for the installation costs must be created in collaboration with Kongsberg.

In Figure 19 the visualisation of VFD control on seawater cooling system on a K-chief system. The blue circle represents the load of the VFD. In this figure the load of each VFD is 50 percent. As shown is the pump in auto mode, for the OOS Tiradentes it must be possible to start and stop the pump and put it in auto or manual mode.

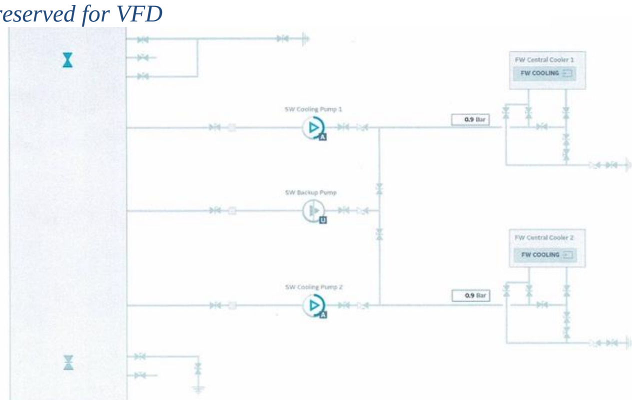

Figure 19 Visualisation of VFD control on seawater cooling system

Power supply cable and cable-tray

For each thruster room the length of power supply cable and cable tray is estimated based on visual inspection on the OOS Tiradentes and use of drawings from the Thruster room. By using Butler's (2012) manhour calculations, the estimated manhours needed per thruster room is calculated. Table 5 and 6 is for thruster room 1, table 7 and 8 for thruster room 2 and table 9 and 10 for thruster room 6.

Table 4 Thruster Room 1 cable length + working hours

Power supply cable between VFD and El. Pump	HT Pump	LT Pump
Cable length in metres x-axis	3,44	0,8
Cable length in metres y-axis	2	0,81
Cable length in metres z-axis	0,5	0,4
Total cable length in metres (multiplied by 1,5)	8,91	3,015
Working Hours for cable installation	8,91	3,015

Table 5 Thruster Room 1 total working hours cable tray installation

Cable tray for power supply cable	HT + LT
Cable tray length in metres	6,5
Cable tray bends	7
Working Hours for cable installation	6,825
Extra time for bends	3,3075
Total working hours for cable tray installation	10,1325

Table 6 Thruster Room 2 cable length + working hours

Power supply cable between VFD and El. Pump	HT Pump	LT Pump
Cable length in metres x-axis	4,225	0,65
Cable length in metres y-axis	3,95	3,95
Cable length in metres z-axis	4,02	4,02
Total cable length in metres (multiplied by 1,5)	18,2925	12,93
Working Hours for cable installation	18,2925	12,93

Table 7 Thruster Room 2 total working hours cable tray installation

Cable tray for power supply cable	HT + LT
Cable tray length in metres	15
Cable tray bends	8
Working Hours for cable installation	15,75
Extra time for bends	3,78
Total working hours for cable tray installation	19,53

Table 8 Thruster Room 6 cable length + working hours

Power supply cable between VFD and El. Pump	HT Pump	LT Pump
Cable length in metres x-axis	3,259	0,55
Cable length in metres y-axis	2,03	0,81
Cable length in metres z-axis	0,5	0,5
Total cable length in metres (multiplied by 1,5)	8,6835	2,79
Working Hours for cable installation	8,6835	2,79

Table 9 Thruster Room 6 total working hours cable tray installation

Cable tray for power supply cable	HT + LT	
Cable tray length in metres	6	
Cable tray bends	7	
Working Hours for cable installation	6,3	hours
Extra time for bends	3,3075	hours
Total working hours for cable tray installation	9,6075	hours

4.2 Calculations of expenses due to the conversion

For thruster room 1 all parts needed for the conversion are put in an excel file and prices are attached as to best knowledge. As the VFD cabinet will be placed relatively close to the electric motor the costs are less than the costs for thruster room 2. Costs for thruster room 1 is shown in Table 11, thruster room 2 in Table 12 and thruster room 6 in Table 13. The 2 marked rows are uncertain and is a forecast but the actual costs must be discussed with Kongsberg. For now, €2000 for thruster room 1 and 6 and for thruster room 2 it is €2300.

Table 10 Cost calculation Thruster Room 1

Thruster Room 1					
Specifications	**remarks**	**pieces needed**		**Price**	
Price for insulated shield plate on el. Motor		2	pcs	€	2.570,04
Price for installing bearing on el. Motor		n/a		done by OOS crew	
Price for CAT 6 cable (... metres)	Field station 201	50	meter	€	47,70
Price for 1 VFD including controls (DU/DT filter, start/stop, LOTO ft. etc.		2	set	€	61.022,62
Price for PT-100 sensor		2	pcs	€	198,00
Price for sensor Pocket		2	pcs	€	93,60
Total price in euro's for installation of cable(tray) including additional parts		n/a		€	2.170,14
Costs for installation of VFD Cabinet		n/a		€	100,00
Costs for installation of 2 VFD unit		n/a		€	300,00
Costs for rewiring cable from LV SWBD to VFD.		n/a		€	500,00
Costs for connecting cables from VFD to FS		n/a		€	500,00
Costs to Kongsberg for connecting VFD to AIS system		n/a		€	1.500,00
Cable-ties (1000 pcs)	250 mm x 3.6 mm	1	pcs	€	46,80
Cable-ties (1000 pcs)	360 mm x 4.8 mm	1	pcs	€	78,03
Cable gland		2	pcs	€	306,00
Cable lugs		12	pcs	€	97,20
Total		n/a		€	69.530,13

Table 11 shows that the total costs for upgrading 2 pump configurations in thruster room 1 is €69.530,13.

Table 11 Cost calculation Thruster Room 2

Thruster Room 2					
Specifications	**remarks**	**pieced needed**		**Price**	
Price for insulated shield plate on el. Motor		2	pcs	€	2.570,04
Price for installing bearing on el. Motor		n/a		done by OOS crew	
Price for CAT 6 cable (... metres)	Field Station 202	50	meter	€	47,70
Price for 1 VFD including controls (DU/DT filter, start/stop, LOTO ft. etc.		2	set	€	61.022,62
Price for PT-100 sensor		2	pcs	€	198,00
Price for sensor Pocket		2	pcs	€	93,60
Total price in euro's for installation of cable(tray) including additional parts		2	pcs	€	5.505,34
Costs for installation of VFD Cabinet		n/a		€	100,00
Costs for installation of 2 VFD unit		n/a		€	300,00
Costs for rewiring cable from LV SWBD to VFD.		n/a		€	1.200,00
Costs for connecting cables from VFD to FS		n/a		€	800,00
Costs to Kongsberg for connecting VFD to AIS system		n/a		€	1.500,00
Cable-ties (1000 pcs)	250 mm x 3.6 mm	1	pcs	€	46,80
Cable-ties (1000 pcs)	360 mm x 4.8 mm	1	pcs	€	78,03
Cable gland		2	pcs	€	306,00
Cable lugs		12	pcs	€	97,20
Total				€	73.865,33

Table 12 shows that the total costs for upgrading 2 pump configurations in thruster room 2 is €73.865,33.

Table 12 Cost calculation Thruster Room 6

Thruster Room 6					
Specifications	**remarks**	**Pieces needed**		**Price**	
Price for insulated shield plate on el. Motor		2	pcs	€	2.570,04
Price for installing bearing on el. Motor		n/a		done by OOS crew	
Price for CAT 6 cables	Field Station 206	50	meter	€	47,70
Price for 1 VFD including controls (DU/DT filter, start/stop, LOTO ft. etc.		2	set	€	61.022,62
Price for PT-100 sensor		2	pcs	€	198,00
Price for sensor Pocket		2	pcs	€	93,60
Total price in euro's for installation of cable(tray) including additional parts		2	pcs	€	2.078,73
Costs for installation of VFD Cabinet		n/a		€	100,00
Costs for installation of 2 VFD unit		n/a		€	300,00
Costs for rewiring cable from LV SWBD to VFD.		n/a		€	500,00
Costs for connecting cables from VFD to FS		n/a		€	500,00
Costs to Kongsberg for connecting VFD to AIS system		n/a		€	1.500,00
Cable-ties (1000 pcs)	250 mm x 3.6 mm	1	pcs	€	46,80
Cable-ties (1000 pcs)	360 mm x 4.8 mm	1	pcs	€	78,03
Cable gland		2	pcs	€	306,00
Cable lugs		12	pcs	€	97,20
Total				€	69.438,72

Table 13 shows that the total costs for upgrading 2 pump configurations in thruster room six is €69.438,72.

Travel expenses

Table 13 Travel expenses to OOS Tiradentes

Type of worker	Persons	Travel expenses (From … to OOS Tiradentes	Total travel expenses
Field technicians	3	€ 800,00	€ 2.400,00
Class society	2	€ 1.500,00	€ 3.000,00
Kongsberg technician	1	€ 1.500,00	€ 1.500,00
Total			€ 6.900,00

Class society costs

Table 14 Class society costs

Commissioning process	Attendance of surveyor	€ 25.000,00
PI&D	Renewing drawings for HT / LT cw system.	€ 10.000,00
Total		€ 35.000,00

Total costs

Total costs parts and installation costs	€	212.834,19
Travel expenses	€	6.900,00
Class society costs	€	35.000,00
Kongsberg additional costs	€	5.000,00
Excpected downtime costs	€	250.000,00
	€	509.734,19

The total expenses for this VFD conversion on all six pump configurations are €509.734,19.

4.3 Fuel savings after opted installation of variable frequency drives

Fuel costs

OOS International does not have a standing agreement with Petrobras for buying MDO, therefore the worldwide MDO market prices are mostly leading in terms of the price OOS International must pay (R. de Haas (Chief Engineer on OOS Tiradentes), personal communication, September 2022).
As shown in Figure 20 the global average bunker price is fluctuating, from prices as low as 262,75 US$/MT in April 2020 to prices as high as 1.131 US$/MT in June 2022. These fluctuations in price will affect the energy savings from the VFD conversion.

Figure 20 Global average bunker price in US$ per Metric Tonne.

Suppose the price of 1 metric tonne is 750 US$ (taken January 27, 2023)

$$Tonnes\ to\ litres = \frac{1000}{0,86} = 1163\ litres$$

750 US$ for 1163 litres of MDO. The price for 1 litre is $\frac{750}{1163} = 0,6449\ US\$$

As seen in Table 15 the main engine use 0,2336 litres per kWh.
The total price for 1 kWh is 0,2336*0,6449 =0, 15 US$/kWh = 0,14 Euro/kWh
(Density MDO = 860 kg/m^3)

Table 15 Fuel consumption per kWh on the OOS Tiradentes Source: OOS Tiradentes (2022)

Fuel/energy consumption				
Fuel consumption /24h			30	m3
Energy production by engines				
	Average load kW	Hours running	Total kWh	
DG1	1600	14	22400	
DG2	1600	10	16000	
DG3	2000	24	48000	
DG4	0	0	0	
DG5	0	0	0	
DG6	1750	24	42000	
		Total	128400	
Consumption per kWh			0,2336449	l/kWh

Fuel Savings

To find an answer to the power consumption of the pump configuration the kinetic energy can be calculated using the rpm, flow, and pressure. In Table 16 the kinetic energy, flow and pressure are calculated at 100, 90, 80, 70 and 60 percent rpm. The flow and pressure from the pump at 100 percent flow are given by the pump manufacturer.

Table 16 RPM, effective power, flow and pressure of SW Cooling water pump

RPM (%)	RPM	Kinetic power	flow	pressure
n' (%)	n'	Pe' (kW)	Ve' (m3/h)	Pman' (Bar)
60	1050	13,83912	420	0,9
70	1225	21,97601	490	1,225
80	1400	32,80384	560	1,6
90	1575	46,70703	630	2,025
100	1750	64,07	700	2,5

From kinetic energy to total supplied energy all mechanical and electrical losses must be added to the kinetic energy. In Table 17 the new power consumption after added losses of mechanical energy, electrical motor, VFD and cable. The Efficiency of each part is the following: centrifugal pump is 86%, electrical motor is 93% VFD is between 98,5 and 93 percent and the cable losses are calculated in table 15.

Table 17 Power consumption at 100, 90, 80, 70 and 60 RPM after all losses from VFD, pump, electric motor and cables.

Kinetic energy	mechanical energy	electrical motor	VFD	cable	Total supplied energy
kWh	n = 0,86	n = 0,93	See operating point	$I^2 * R$	kWh
13,83912	15,7765968	16,88095858	17,89381609	17,9716013	18
21,97601	25,0526514	26,806337	28,14665385	28,3391157	29
32,80384	37,3963776	40,01412403	41,61468899	42,03540053	43
46,70703	53,2460142	56,97323519	58,68243225	59,51901196	60
64,07	74,43	79,6401	80,8347015	82,42210302	82,8

The cable losses will decrease exponentially when less current is flowing through the wire. To calculate these losses in Table 18 the Resistance and the current through the wire at 4 different operating conditions is determined. The total cable losses are added in Table 17 to determine the total supplied energy. When the VFD is installed, and the load is 100 percent the cable losses will be higher compared to the cable losses before the conversion.

Table 18 Cable losses in kWh at 21, 33, 50, 71, 100 percent load

Cable losses at different current									
35 mm2 cable	0,554	ohm/km	total length of cable	54,621	metres	Average length per VFD	9,10	metres	0,015 Ohm
50 mm2 cable	0,483	ohm/km	total length of cable	1000	metres	Average length per VFD	166,67	metres	0,242 Ohm
								total	0,257 Ohm
100	% load	78,65	1587,40	1,587	kW per VFD				
71,54	% load	57,10	836,58	0,837	kW per VFD				
50,24	% load	40,49	420,71	0,421	kW per VFD				
33,66	% load	27,39	192,46	0,192	kW per VFD				
21,20	% load	17,41	77,79	0,078	kW per VFD				
For extra details check theoretical framework Chapter 2									

Table 19 Power consumption in kWh and price at 21, 33, 50, 71, 100 percent load

Power consumption						
	daily (24h)		monthly (28 d)		Yearly (365 d)	
load	kWh	Price per day	kWh	Price per day	kWh	Price per year
21% load	431,32	€ 60,38	12076,92	€ 1.690,77	157431,23	€ 22.040,37
33 % load	680,14	€ 95,22	19043,89	€ 2.666,14	248250,65	€ 34.755,09
50 % load	1008,85	€ 141,24	28247,79	€ 3.954,69	368230,11	€ 51.552,22
71% load	1428,46	€ 199,98	39996,78	€ 5.599,55	521386,54	€ 72.994,12
100% load	1978,13	€ 276,94	55387,65	€ 7.754,27	722017,62	€ 101.082,47
Without VFD	*1947,21*	*€ 272,61*	*54521,99*	*€ 7.633,08*	*710733,09*	*€ 99.502,63*

In Table 19 the power consumption and the fuel costs per day, month, and year at 21, 33, 50,71 and 100% load is shown (Including VFD). The last row of Table 19 describes the total costs for fuel per year of one pump configuration without VFD.

In Table 20 savings of one pump configuration at 21%, 33%, 50% and 71% load. For example, the yearly savings at 33% load is 99.502,63 – 34.755,09 = €64.747,54 Besides the fuel costs also the fuel savings in kg can be calculated. To produce one kWh of energy on the OOS Tiradentes the main engines use 0,198 kg MDO as shown in paragraph 2.5.

Table 20 Savings through one VFD at 21, 33, 50, 71 percent load

Savings through 1 VFD		Based on 0,34 euro / kWh	
	daily savings	monthly savings	Yearly savings
load	euro	euro	euro
21% load	€ 212,23	€ 5.942,31	€ 77.462,26
33 % load	€ 177,39	€ 4.966,93	€ 64.747,54
50 % load	€ 131,37	€ 3.678,39	€ 47.950,42
71% load	€ 72,63	€ 2.033,53	€ 26.508,52
100% load	€ -	€ -	€ -

4.4 Return on investment

In Figure 21 the Return on Investment is shown at 71, 50, 33 and 21 percent load. As shown is the Return on investment in all 4 models below one year. As the expected lifespan of the VFD components is at least 10 years and the OOS Tiradentes is planned to stay in operation for quite a while meaning this opted conversion is profitable.

Table 21 Return on investment at 71, 50, 33 and 21 percent load for all six VFD (L.J.M. Verboven, 2023)

Return of investment (6 VFD, total costs - savings)			Based on kWh price on SSAV Tiradentes	
			0,15 euro / kWh	
Year	71% load	50% load	33% load	21% load
2024	-€ 509.734,19	-€ 509.734,19	-€ 509.734,19	-€ 509.734,19
2025	-€ 350.683,10	-€ 222.031,69	-€ 121.248,95	-€ 44.960,63
2026	-€ 191.632,00	€ 65.670,81	€ 267.236,29	€ 419.812,93
2027	-€ 32.580,91	€ 353.373,31	€ 655.721,54	€ 884.586,49
2028	€ 126.470,18	€ 641.075,81	€ 1.044.206,78	€ 1.349.360,05
2029	€ 285.521,28	€ 928.778,31	€ 1.432.692,02	€ 1.814.133,61

Figure 21 is the values from Table 21 expressed in a diagram. As the load on the VFD is expected to be between 33 and 21 percent load the ROI will be between the yellow and green line.

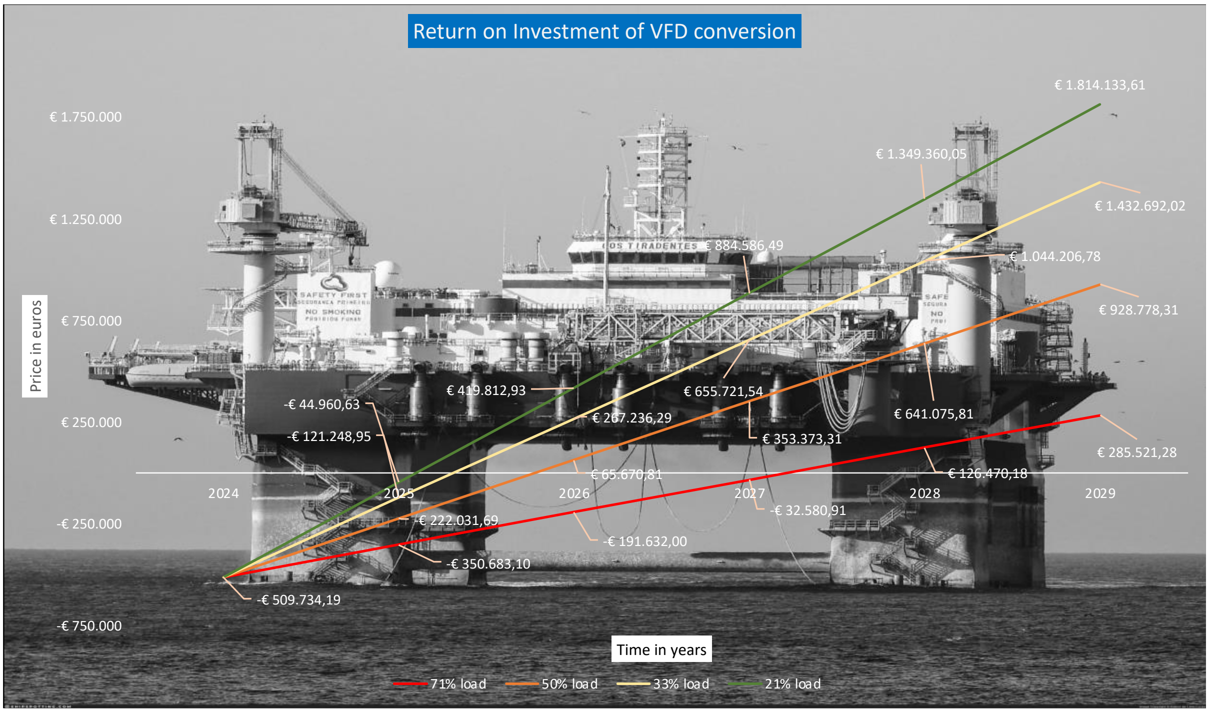

Figure 21 Return on Investment for the six VFD at 71, 50, 33 and 21 percent load (L.J.M. Verboven, 2023)

Emissions

The emissions consist of 3,206 grams CO_2 per gram marine diesel oil according to an LCA study by the International Maritime Organization, IMO (Krantz, 2016). So, if one kg of diesel is consumed by the main engines 3,206 kg of CO_2 is produced. According to Ecotree (n.d.) "one tree absorbs 25 kg of CO_2 in one year". If the main engine consumes around 8 kilograms of MDO one tree can absorb the CO_2 emissions within a year. As seen in Table 22 in one day already around 250-300 kg of fuel per day is saved per pump configuration. In one day on all six pump configurations, it is possible to reduce (1258 – 432) * 6 = 5,0 tonnes of carbon emissions. In one year when the average load is 33% on all six pumps a total of (157,36 – 54,10) * 365 = 37.690 trees can be used to capture other emissions in a world towards zero carbon emissions.

Table 22 Daily consumption for one pump configuration (L.J.M. Verboven, 2023)

Daily consumption for one pump configuration				
Load (%)	Power (kWh)	MDO (Kg)	CO2 emissions	Trees
21	431,32	85,62	274,49	34,31
33	680,14	135,01	432,83	54,10
50	1008,85	200,26	642,02	80,25
71	1428,46	283,55	909,06	113,63
100	1978,13	392,66	1258,86	157,36

5. Discussion

This research regards the feasibility, expenses, and the estimated return of investment of the opted installation of variable frequency drives for the seawater cooling pumps. Eventual difficulties for the opted conversion, installation costs, costs of parts and the savings in terms of fuel are discussed to create a better understanding of the feasibility and return of investment of the opted VFD conversion. This research addresses the preliminary research and the possibilities that arise when installing VFD on the seawater cooling pumps.

Previous research on this topic was not found. However, a lot of new DP-vessels have VFD installed on cooling water pumps and supply/exhaust fans meaning it is common practice to install VFD’s on DP vessels. To enlarge the reliability and validity of this research internal experts and external experts from the OOS Tiradentes and Internal experts from the Acta Centaurus such as Service engineers, Electricians and Chief engineers have been requested to check the estimated costs and savings for the opted VFD conversion.

P&ID, manuals and a visual inspection on sight are used to map out the configuration without VFD. Then based on lay-out drawings and cable diagrams and brochures and desk research on man hours an excel file is created to estimate the quantity of parts needed and the costs of parts. This Hypotheses has limitations due to the lack of information regarding on costs for Class society and Kongsberg. The fuel saving calculations at different RPM are highly accurate as all equations used are based on simple physics and mathematically correct. The Return on Investment is highly dependable on the fuel price per kWh.

Further research should be conducted in collaboration with Kongsberg and Class Society to integrate and commission the VFD conversion safe and reliable. Kongsberg must specify costs for the software, additional hardware, Installation costs, and eventual warranties. Class Society must attend several commissioning steps and help with change of management in terms of P&ID and cable diagrams.

In this research an estimated downtime cost is added to the total expenses. The price of this downtime cost can be calculated more specific when a date is set for the installation and commissioning of the six VFD’s. The most favorable option would be to carry out this project while the rig is already in the bay for other maintenance to spread the downtime costs over the ongoing projects.

The fuel costs have a significant influence on the ROI. In this research the day rate of the fuel price is taken in 2023. When OOS will sign a new contract with Petrobras or another company it is possible to negotiate a fixed fuel price. For example, the following two years the fuel price per tonnes is 750 US$. When this fixed fuel price is known this parameter can be used inside the excel file to calculate the new ROI. Furtherly it is very important to know the location and scope of work for upcoming projects for the OOS Tiradentes. More severe weather conditions or more difficult DP-operations require more load on the cooling water pumps. The calculations in this research are based on the weather conditions in Brazil. As Petrobras is still willing to extend the contract with OOS it means that when the VFD’s are installed in 2023 at least the first 5 years in Brazil enough fuel can be saved to make this conversion feasible. This is possible because the calculations show that the load, under these environmental conditions, on the cooling water pumps will not be above 33% load.

6. Conclusions & Recommendations

During the research, an attempt was made to find an answer to the main question. The main question is: "What is the feasibility, expenses, the estimated return of investment of the opted installation of variable frequency drives for the seawater cooling pumps?"

1. **Which additional parts should be ordered for the opted installation of variable frequency drives?**

It is concluded that the modifications needed for the current design are: Installing shielded bearings on the electric motors, installing a cabinet including a VFD and additional electrical equipment, Installing cable and cable tray for power supply and controls. The system must be integrated in the K-chief system and commissioned for operational use. Drawings and diagrams must be updated after the conversion.

2. **What are the expected total expenses for the opted installation of the variable frequency drives?**

The total costs for upgrading the seawater cooling system with six VFD will cost €509.734,19. This is a summation of all the costs of parts, man-hours, downtime, travel expenses, commissioning fees, and visualization in k-chief system. The list of parts and installation costs and other expenses are shown in paragraph 4.2.

3. **What is the expected new power consumption of the cooling water system after installing variable frequency drives?**

Electrical and mechanical losses in the seawater cooling system such as the VFD, pump, electric motor and power supply cables are determined to calculate the new power consumption. The new power consumption at 100, 90, 80, 70 and 60 percent rpm of the pump configuration is found and multiplied by the fuel prices per kWh on the OOS Tiradentes. In most conditions the pump will have a new rpm between variating between 60 and 70 percent of the nominal rpm (1750 rpm). The power consumption at 60 percent rpm is 18,0 kW and at 70 percentage 28,3 kW and the nominal load is 82,4 kW. In brazil the expected power consumption will be between 60 and 70 percent.

If the OOS Tiradentes is in DP-operations one pump configuration will run between 60 and 70 percent rpm the seawater cooling system will remain within operational standards as the pressure and flow is still sufficient. In 1 year, one pump configuration can have a revenue of euros when the electrical motor is running at 60 percent rpm (18,0 kW). At 70 percent rpm (28,3 kW) in 1 year the total revenue is €161.080. In total the modification is performed at six pump configurations. For this calculation a price of 0,14 euros per kWh is used based on fuel consumption per kWh on the OOS Tiradentes.

4. **What is the expected return on investment of the opted installation of variable frequency drives on the seawater cooling pumps?**

Figure 20 show the Return on Investment of the 4 different rpm of the six pump configurations. In the most favorable condition, the ROI is around 12-15 months if the operating conditions of the cooling pumps will remain the same as in Brazil. As most of the time the load on the Main Engines is low it is forecasted that at under all circumstances the VFD conversion on the six seawater cooling pumps is profitable.

Together with energy savings less stress on mechanical parts and noise and vibration reduction and need less maintenance on cleaning of seawater strainers. The only negative part is that through AC ripple the busbar has more harmonic distortion. Although it is not expected that this harmonic distortion will cause problems as the power consumption of the VFD is relatively low compared to other consumers on the busbar.

The opted VFD conversion is, based on this research and research on other similar cooling configurations on different vessels, feasible and profitable within one year. For this matter it is recommended to perform this upgrade in the upcoming bay visit. Especially in a world towards zero carbon emission, OOS International can make a great step into more sustainable operations.

After installation and commissioning a maintenance scheme and an instruction form on how to properly operate the upgraded cooling water system must be created for optimal use of the system. When the vessel is underway using high load on all thrusters it is possible that from the engine control room on the k-chief display the setpoint of the VFD's must be adjusted to maintain enough cooling capacity for the main engines and thruster. When back in DP-mode the setpoint of the VFD can be reduced again to save as much energy as possible.

On the OOS Tiradentes more systems have a-synchronic electric motors installed on board. At these systems such as the Reverse osmosis plant, supply/exhaust Fans, pre-heat units, HVAC units etc., the installation of a VFD unit may result in fuel and emission savings. Further investigation on these systems is recommended to verify if VFD conversions is profitable.

To reduce costs of parts, it is favourable to buy most parts in Brazil to reduce importation and transportation costs. To reduce downtime costs the opted VFD conversion must be installed during a major maintenance project to share the downtime costs. As the cooling water system is a critical system on the vessel it is necessary to create partial blackout to install the VFD cables and instrumentation safely.

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Appendix 1

Total overview of thruster room 1, 2 and 6

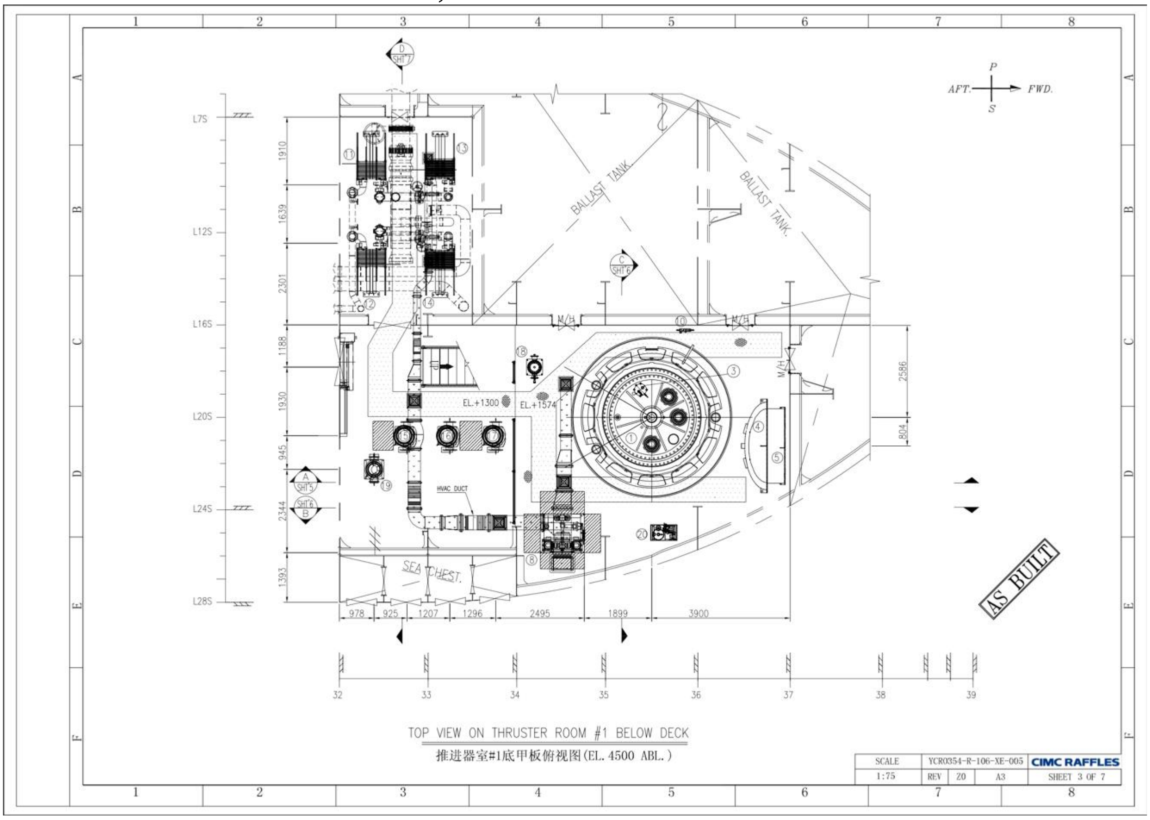

Figure 22 Top view of Thruster Room #1 Source OOS International (2022)

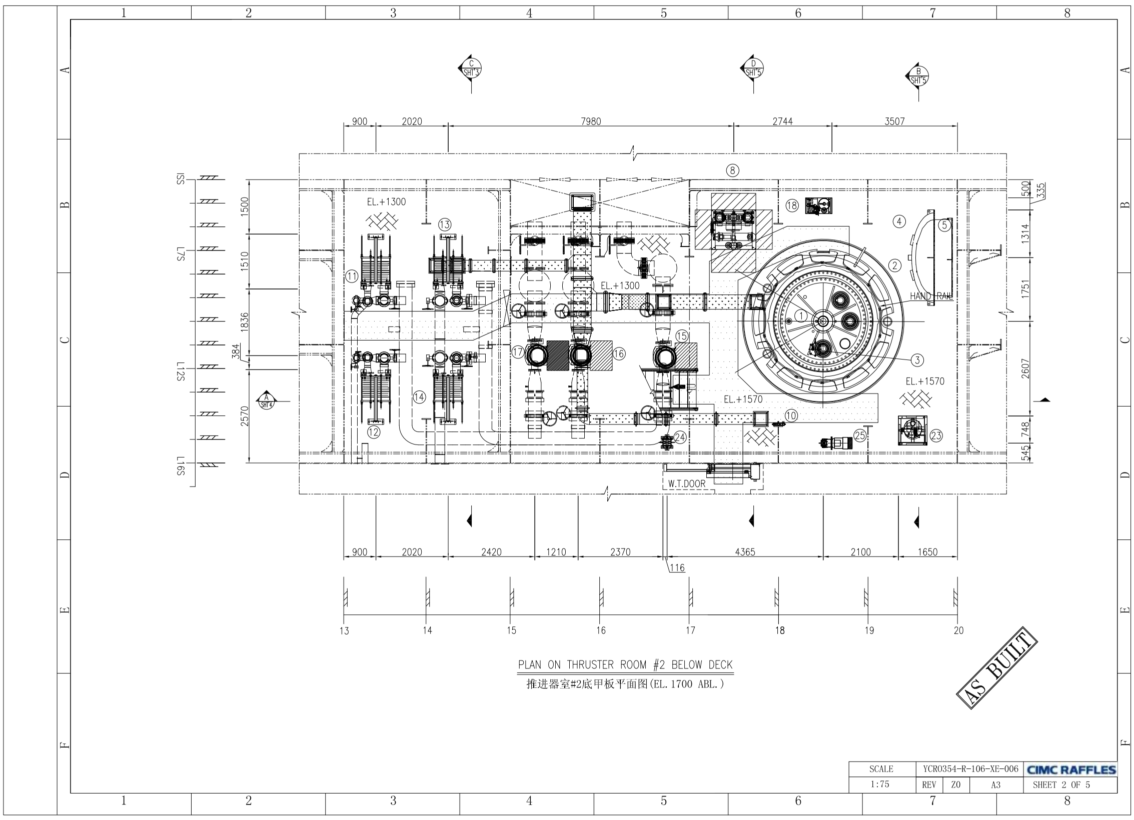

Figure 23 Top view of Thruster Room #2 Source OOS International (2022).

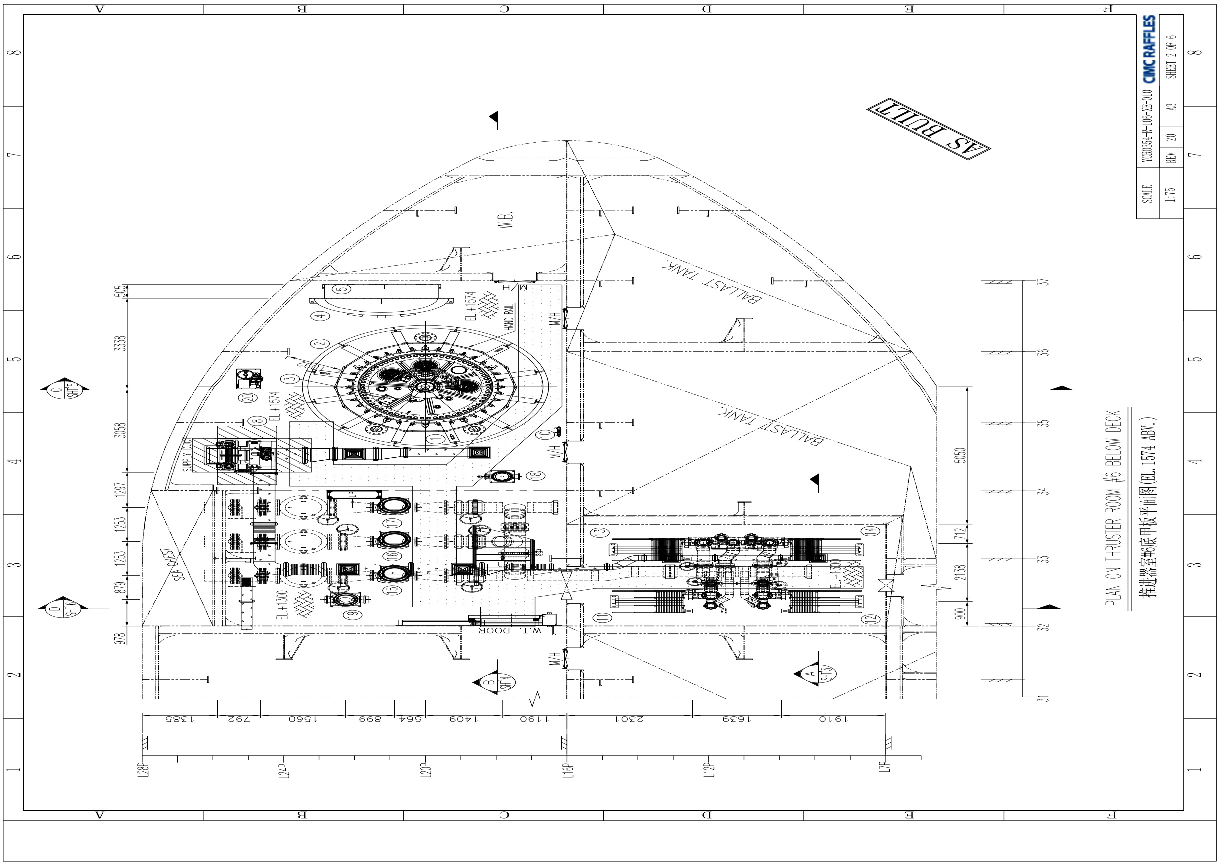

Figure 24 Top view of Thruster Room #6 Source OOS International (2022).

Appendix 2

Pictures of Thruster Room 1,2 and 6

Figure 25 Thruster Room 1 LT HT pump 3 (Starboard side pontoon). Source L.J.M. Verboven (2022)

Figure 26 Thruster Room 1 LT HT pump 3 (Starboard side pontoon). Source L.J.M. Verboven (2022)

Figure 27 Thruster Room 2 HT LT pump 2 (Starboard side pontoon) Source L.J.M. Verboven (2022)

Figure 28 Thruster Room 2 HT LT pump 2 (Starboard side pontoon) Source L.J.M. Verboven (2022)

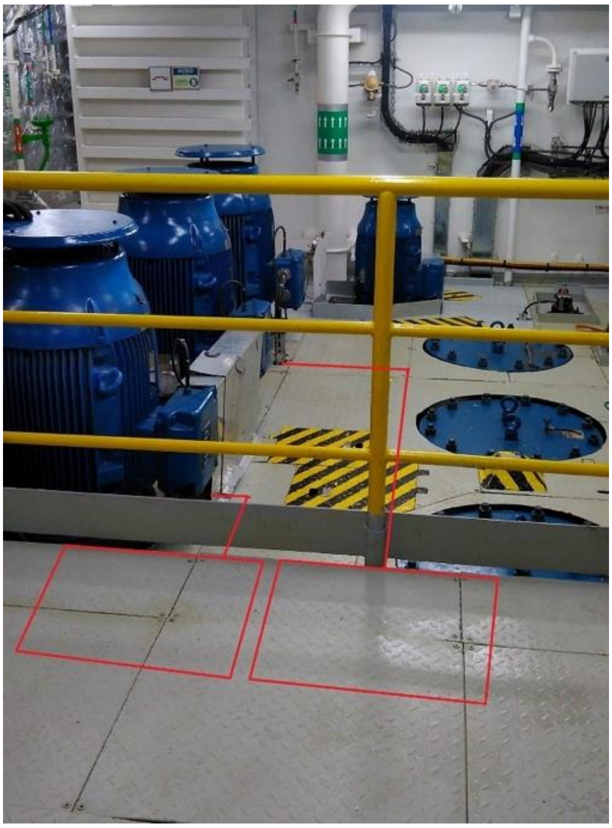

Figure 29 Thruster Room 6 LT HT pump 1 (Port side Pontoon). Source OOS International (2022)

Appendix 3

Figure 30 VFD cabinet with one VFD installed inside cabinet including additional parts (OOS International,2021)

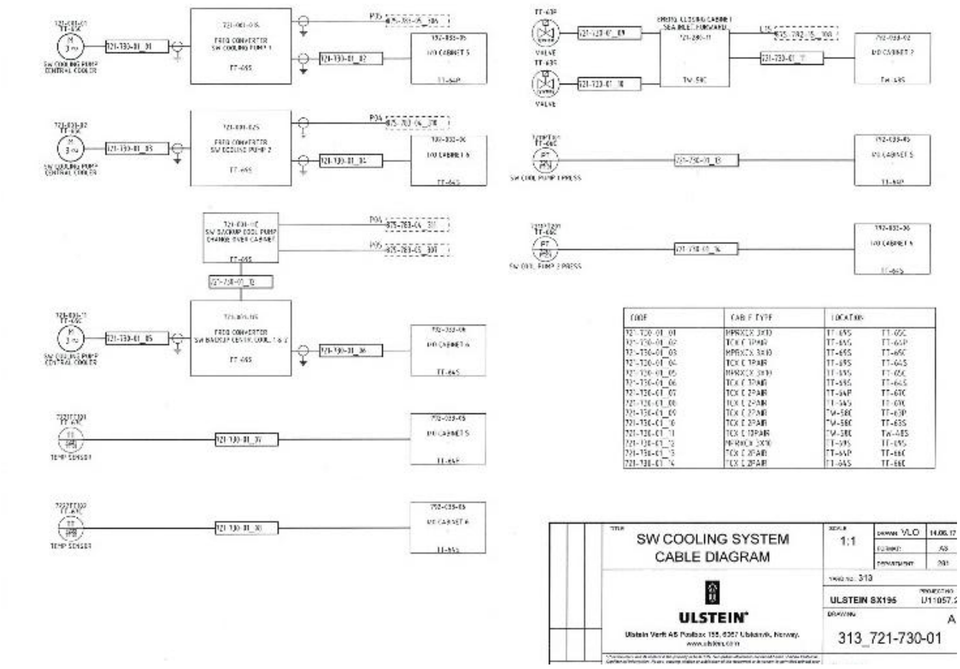

Figure 31 Temp sensor + FC unit connected to I/O cabinet (Acta Centaurus shipyard diagrams, 2019)

Appendix 4

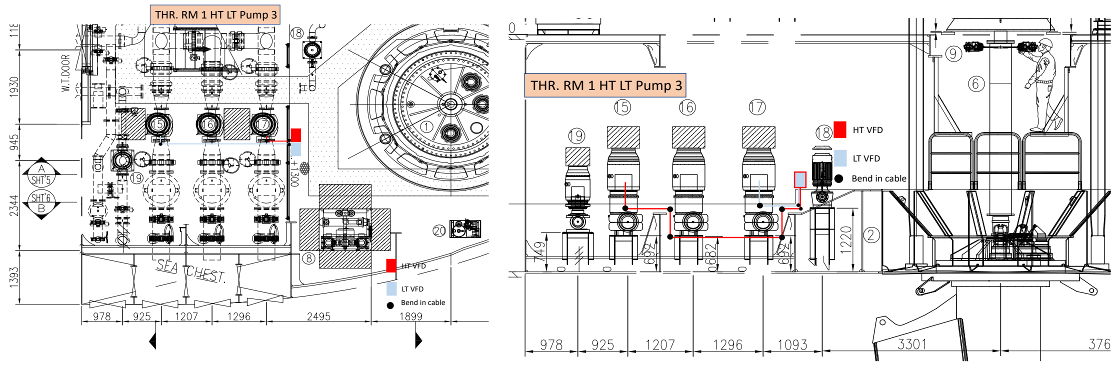

Figure 32 Thruster room 1 wiring plan (L.J.M. Verboven, 2023)

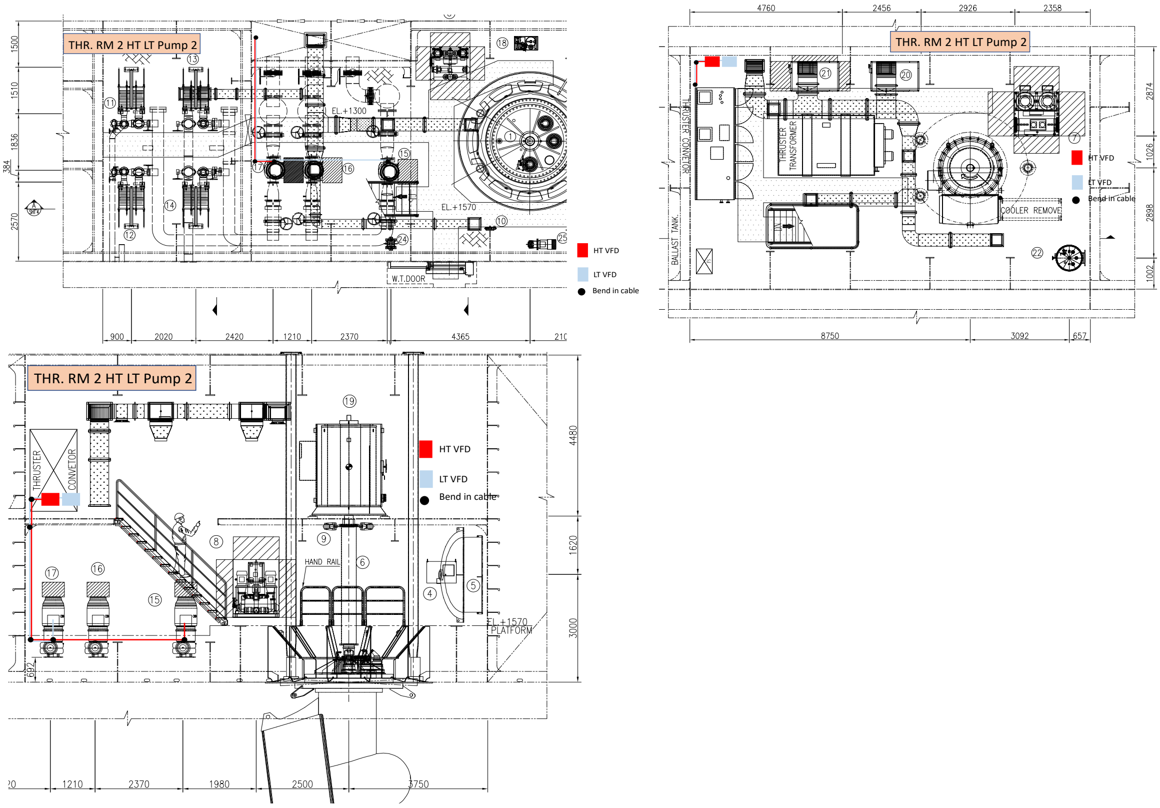

Figure 33 Thruster room 2 wiring plan (L.J.M. Verboven, 2023)

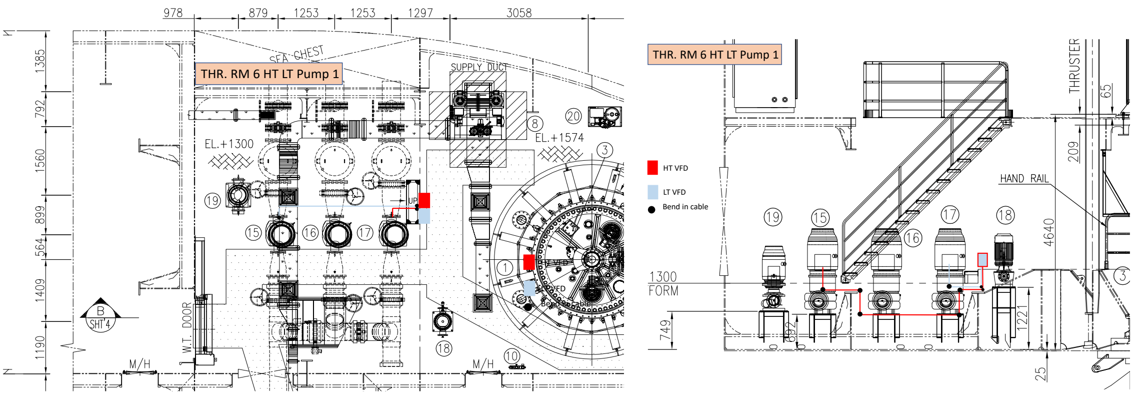

Figure 34 Thruster room 6 wiring plan (L.J.M. Verboven, 2023)