DEVELOPMENT OF AZIPOD PROPULSION SYSTEM TESTING PROCEDURES

Managing the test portfolio

Lappeenranta–Lahti University of Technology LUT

Master’s Programme in electrical engineering, Master’s Thesis

2023

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Examiner(s): Professor Pasi Peltoniemi, D.Sc, Paula Immonen, D.Sc.

ABSTRACT

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Electrical Engineering

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53 pages, 27 figures, 1 table and 1 appendix.

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Keywords: Azipod, Propulsion, Testing, JIRA,

This thesis is made for ABB Oy Marine & Ports to develop their testing management. ABB has been relying for long time in a conventional way of managing the acceptance testing protocols with word documents. This means that there wasn't actual system to manage the test protocols.

During the research work 2 separate test protocols were introduced, an internal propulsion control system test protocol and test a protocol to do deeper propulsion drive testing in Hardware-In-Loop simulator. These protocols are supposed to be done in two different HIL arrangements.

The test protocols were constructed in JIRA software tool, which is efficient tool for managing project data. JIRA also is effective tool for creating and assigning tasks for the people involved in each project. ABB was utilizing JIRA already for other project related management tasks and after reviewing JIRA and specifying what chosen tool for testing management should be capable of, it was decided to study JIRA possibilities further to expand them to the testing management as well. As a result, a test case template was created with a structure to handle the vast number of tests.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT

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Janne Holla

Azipod propulsiojärjestelmän testaamisen kehittäminen

Testauksen hallinta

Diplomityö

2023

53 sivua, 27 kuvaa, 1 taulukkoa ja 1 liite

Tarkastaja(t): Professori Pasi Peltoniemi (TkT) ja Paula Immonen (TkT).

Avainsanat: Azipod, propulsio, testaaminen, JIRA

Tämä diplomityö on tehty ABB Oy Marine & Ports liiketoimintayksikölle ja sen tarkoitus on kehittää heidän erilaisten testausvaiheiden hallintaa. ABB on luottanut pitkään hyvin perinteiseen tapaan hallita testejä word -dokumenteilla. Tämä tarkoittaa sitä, että ABB: llä ei ole testiohjelmien hallintaan käytössä minkäänlaista todellista järjestelmää.

Diplomityössä luotiin 2 erillistä testiohjelmaa, sisäinen testiohjelma propulsion ohjaus järjestelmän testaamiseen sekä syvempää propulsiokonvertteritestausta varten luotu Hardware-In-Loop testiohjelma. Nämä testiohjelmat on tarkoitus tehdä erillisillä HIL kokoonpanoilla.

Testiohjelmat luotiin käyttäen JIRA ohjelmistoa, mikä on tehokas työkalu projektidatan hallintaan. JIRA on myös tehokas työkalu erilaisten työtehtävien osoittamiseen eri projekteihin osallisille ihmisille. ABB käyttää JIRA ohjelmistoa jo projektien hallintaan, joten tarkastelun ja valittavan alustan ominaisuuksien määrittelyn jälkeen todettiin, että JIRA: n mahdollisuuksia halutaan tutkia enemmän laajentaakseen JIRA: n käyttöä testaushallintaan. Työn tuloksena syntyi test case malli ja lisäksi luotiin rakenne, kuinka testejä hallitaan.

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SYMBOLS AND ABBREVIATIONS

Roman characters

U	Voltage	[V]

Abbreviations

FAT	Factory Acceptance Tests
HAT	Harbour Acceptance Tests
HIL	Hardware-In-Loop
SAT	Sea Acceptance Tests
PCS	Propulsion Control System
RCS	Remote Control System
PCU	Propulsion Control Unit
RCU	Remote Control Unit
AIU	Azipod Interface Unit
AC	Alternating Current
DC	Direct Current
LV	Low Voltage
MV	Medium Voltage
HV	High Voltage
IGCT	Integrated gate-commutated thyristor

Table of contents

Appendices

Appendix 1. JIRA export test case template example.

1 Introduction

This thesis can be seen as an overall development task in many fields of ABB Marine's testing procedures. The whole testing process was evaluated, new phases created and most of all, the made protocols were implemented on a new platform where the protocols can be managed more efficient way all along the project. Focus is on new platform and the two test protocols created using the platform to demonstrate the capabilities. Starting point of the development task was simple, ABB had no proper and modern system to manage the test protocols in each project. Work started by thinking about the wanted features and functionalities and then choosing the platform to implement those.

Azipod electrical propulsion system has gained the leading position in ship building business over the years since its launch. Ever since the system has been introduced to various kinds of vessels from yachts to icebreakers and so on to large cruise ships. Through studies and user experience it has been shown that the system saves fuel up to 20 percent in comparison to conventional shaft line propulsion system (ABB Oy, 2023). Electrical propulsion system with 360 degrees rotating Azipod is a complex system with all its main components and control hardware. Complex systems mean complex testing procedures, and, in this research, focus is on defining tests and how to manage large test protocols better than in the past.

First the configuration of the system is defined and briefly introduced to gain good overall image about the real system onboard a vessel. The main parts like power plant and propulsion power drivetrain including transformers and converters all the way to the propeller is explained. After that the focus moves on to the Hardware in loop simulator or HIL. ABB has HIL in the laboratory to test and verify various properties of the system. This system is introduced to understand the test arrangement and what can be tested with this HIL simulator. The HIL simulator used for the actual drive system will be different than the one used for the internal PCU tests because of the requirements.

After the technical and theoretical part is covered, research concentrates on how the tests for the propulsion system are managed now and how those could be managed. Internal PCU test program is defined for propulsion control unit FAT tests and propulsion HIL program by using the new platform. The new platform is database platform to control lot of information related to the projects etc. Work done for this thesis so forth prepares the abilities and capabilities of ABB for these kinds of tests and introduces the possibility to save efforts and time, when the vast amounts of different types of tests for systems or different component related tests are managed through database.

ABB Marine acts as a system integrator when it comes to propulsion system deliveries. ABB Marine integrates all the ordered subsystems related to Azipod propulsion and power plant together and then integrates that wholeness together with the higher-level automation system and other interfacing systems.

1.1 Power Plant and distribution of electricity

Power plant onboard provides the electrical energy for all the ships electrical systems when ship has diesel-electrical propulsion. After 1990s diesel-electric propulsion has become mainstream solution, leaving diesel mechanic propulsion behind. This means, that all the energy for propulsion, hotel loads etc. is produced with same power plant and not by two separate power plants, one for electricity and one for rotating propeller directly. (Aarnio, 2022. 113). Power plant consists of large diesel engines that rotate the generators to create electricity for the ship’s needs. The number and size of the diesel-generator sets varies in relation to the ships size and redundancy requirements. Each energy producer or large consumer is connected to main switch board. Figure 1 below demonstrates standard medium voltage AC distribution grid on board a vessel for propulsion.

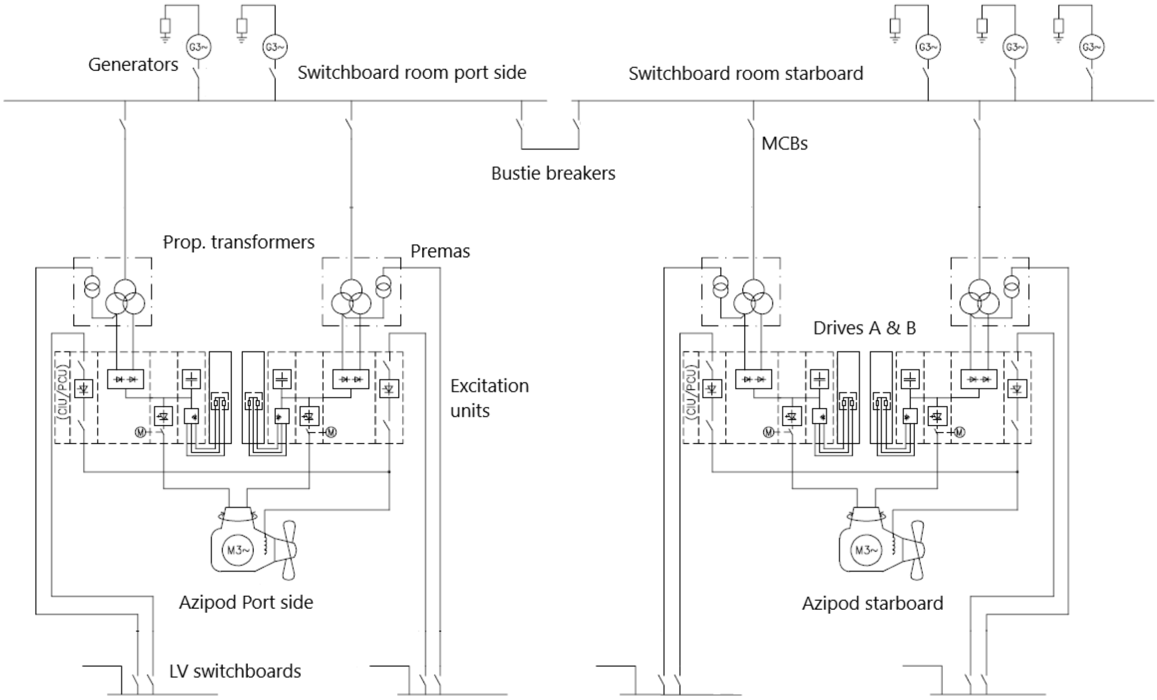

Figure 1. Typical ship power plant configuration for medium voltage distribution for propulsion.

Figure one is demonstrating the propulsion system single line diagram. MCB is short from main circuit breaker. Figure one is missing some main components of the ship like bow thrusters, AC compressors and hotel load distribution. Excitation circuit for propulsion drives can also be supplied directly from HV switchboard via excitation transformer. Box around propulsion transformers indicates that smaller transformer, the pre-magnetization transformer or prema in short, is inside of the propulsion transformer. Prema is used to magnetize propulsion transformer before energizing it to reduce the magnetizing inrush current taken from the power plant when HV main circuit breaker closes.

From main switchboards the electricity is drawn to different loads. Usually, ships have at least 2 main switchboards for redundancy. Meaning the port side main switchboard and starboard side main switchboard. These two are connected to each other via bustie breakers at each side as can be seen in figure one.

In marine sector ships electrical distribution systems are referred in two ways, low voltage system (LV) and high voltage system (HV). Separation is done in a way, that systems < 1000 V (AC) are low voltage systems and systems > 1000 V (AC) are high voltage systems. This means, that on board a ship medium voltage (MV) and high voltage (HV) mean the same thing. This differs from the way how these voltage levels are categorized in land-based applications. (Prenc et all, 2016. 85). In this Thesis the focus is on high voltage AC electrical distribution systems.

1.2 Propulsion drives and transformers

The biggest single consumer in the ship's distribution system is the propulsion. As can be seen in the figure 1, high voltage AC distribution creates the need to install propulsion transformers to bring the distribution voltage to the desired level for the propulsion drives. The drives diode bridge including unit is called a line supply unit or LSU in short. Usually, redundant propulsion drive's LSUs have 12 pulse diode bridge for AC/DC transformation, which means that the propulsion transformer has two secondary windings as is shown in figure 1. These secondary windings need to have some phase shift to provide proper 12 pulse operation. LSU supply voltage typically is around 1700 V_{AC} times 2. Needed DC link voltage level is around 4900 V_{DC} , when drives are charged put not running. DC link voltage is calculated according to equation 1.

$$U_{DC} = \sqrt{2} * 2 * U_{AC} \tag{1}$$

Where U_{AC} is the output voltage of one secondary of the propulsion transformer with two secondaries. DC link voltage drops few hundred volts when drive is running the motor.

Inverter topology is 3 level voltage source inverter using IGCT technology. Voltage source inverter's DC link includes capacitor bank. When system is started, a separate low voltage supplied charging system charges the capacitor bank before the main circuit breaker is closed to avoid charging from HV network side. Propulsion drive controls the main circuit breaker in all situations including normal start and stop and tripping due to a failure. Trip can be made by the drive or propulsion control system. Trip is a protective function of the drive system to prevent further damage or safety risks. Propulsion drive system can be fully redundant, semi redundant, or single drive system. In figure 1 is full redundant system (FRD) with two separate converters rotating one propulsion motor. This is the most common system in cruise vessels for example. It means, that when specific fault situations occur, the system can still be used in full motor operation. For example, if the excitation supply unit in master drive is faulted, the system can simply change the master to other drive and full motor operation is still possible. It could be said in a way, that single auxiliary fault won't disable the full motor operation. Other possibility is to have half motor running with half of the motor power in case of a consistent fault in other drive.

For excitation propulsion drive has excitation cabinet or EXU (excitation unit), that has a low voltage AC/AC converter including thyristor bridge with antiparallel thyristors for each phase to provide and control the excitation current flow to the synchronous motor rotor winding. Drive's main control board controls the reference for the excitation converter according to operation point of propulsion motor and propulsion drive settings.

In marine field the question is often about redundancy which translates to availability of the system and how it can be achieved by economically as possible. The most functional solution is two single drives connected to two galvanically isolated stator windings. These two windings have 30 degrees phase shift. In other words, one synchronous propulsion motor has two separate windings in its iron core and slots. This kind of application is often called master/follower application as well. In this case the upper-level control system is controlling the speed reference for the master drive. Master drive then adapts that and creates a matching torque reference for the follower drive. (Burzanowska et all. 2007). When both stator systems are in use at the same time, it is called full motor operation or full drive operation.

ABB uses their own ACS6000 series medium voltage drives for the propulsion. ACS6000 series uses DTC or direct torque control method to control the motor. This method was developed further by ABB to provide high speed and torque performance in medium voltage drive systems. (ABB prochure). The newest version of 6000 series is ACS6080. This paper is related to ACS6000 when it comes to drive related parts. ABB ACS60x0 medium voltage drives protection scheme is based on fuseless Firing-Through method. Firing through or FT means, that when a short-circuit occurs inside the drive, it will protect itself from further damage by dividing the short-circuit currents symmetrically for all the semiconductors within the high-power circuit. Line supply unit has so called crowbar thyristors for short-circuiting diode legs. Crowbar thyristors simply mean an antiparallel connected thyristor branch for each phase. Inverter unit does the same just by switching on all the IGCTs at the same time. In this way after FT command is given to crowbar and IGCTs, the short-circuit will stress all the semiconductors and not just the ones around broken component(s) a lot. There will be enough time to discharge DC link capacitors energy and the rest of the semiconductors will survive the situation without damage. Firing through situation clears out when the main circuit breaker opens. The situation will be over within millisecond scale time frame.

1.3 Azipod propulsor and steering system

The main electrical motor in Azipod unit is located under the ship inside 360 degrees rotating pod. The main motor of an Azipod can be induction, permanent magnet or synchronous motor depending on the power range. This thesis in concentrating on large Azipod units including synchronous motor with external excitation and excitation system. Power ranges for the pod units start from 1 MW induction/permanent magnet Azipods to 22 MW large synchronous motor Azipods (ABB Oy, 2023). These synchronous motor Azipods are equipped with a rotating exciter machine with rotating rectifier mounted on the shaft, that provides the DC current for excitation for the synchronous motor. In picture 2 is shown two Azipod propulsors under the ship. The hull of the ship is constructed differently in comparison to conventional propulsion systems as can be seen from the figure.

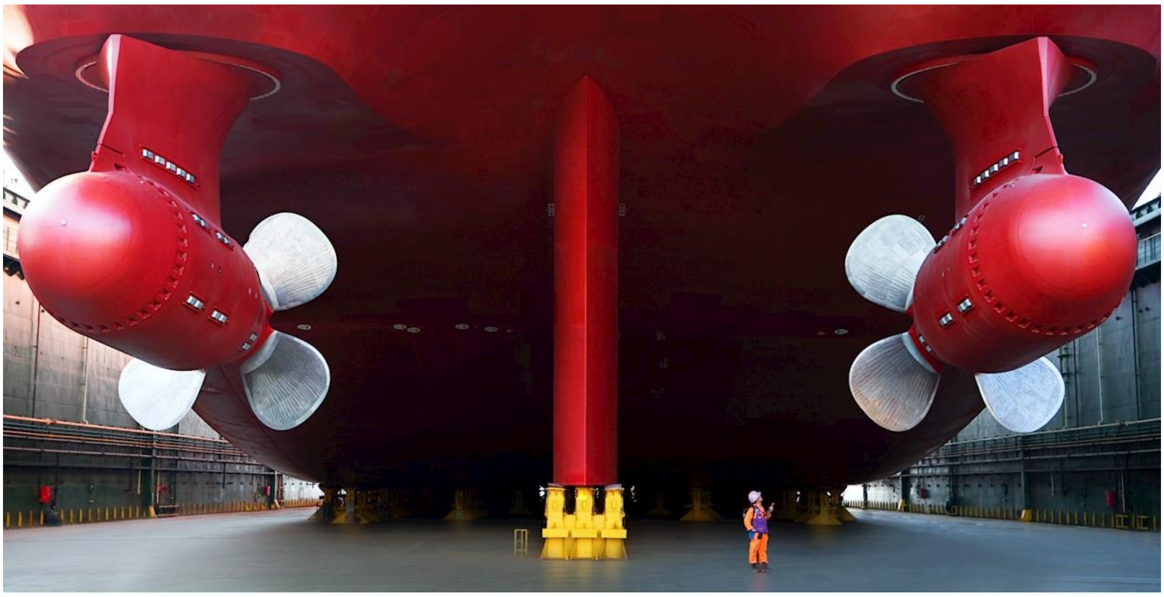

Figure 2. Azipods under the ship. (Vessel finder) 10.5.23

Azipod system works with pulling principle, which means the propellers pull the ship forward. (ABB introduction, 2019). There can be 3 Azipods under one cruise vessel or ice breaker. For example, the Oasis class cruise ships have 3 times 20 MW Azipods concluding 60 MW propulsion power. (Ship technology, 2021). The power plant consists of 6 Wärtsilä engines totalling of 97020 kW available power from the power plant. (Wärtsilä, 2023) This is to bring some perspective; how big the propulsion power can be and how much power the power plant also must provide.

In large Azipod the steering unit has 4 steering motors, which enable the Azipod to turn 360 degrees. Power and data transmission to the pod and out of the pod is done through slipring unit. Main power and excitation supply for the synchronous motor goes through the main sliprings. All the data from the Azipod is transferred through the data slip rings to the control unit above. Auxiliary power for the lubrication is also arranged via sliprings. Lubrication and cooling oil flow for the bearings inside the Azipod go via rotary lubrication join, that is also called swivel, located inside the slipring unit. In figure 3 is demonstrated how the Azipod arrangement looks like on board the ship.

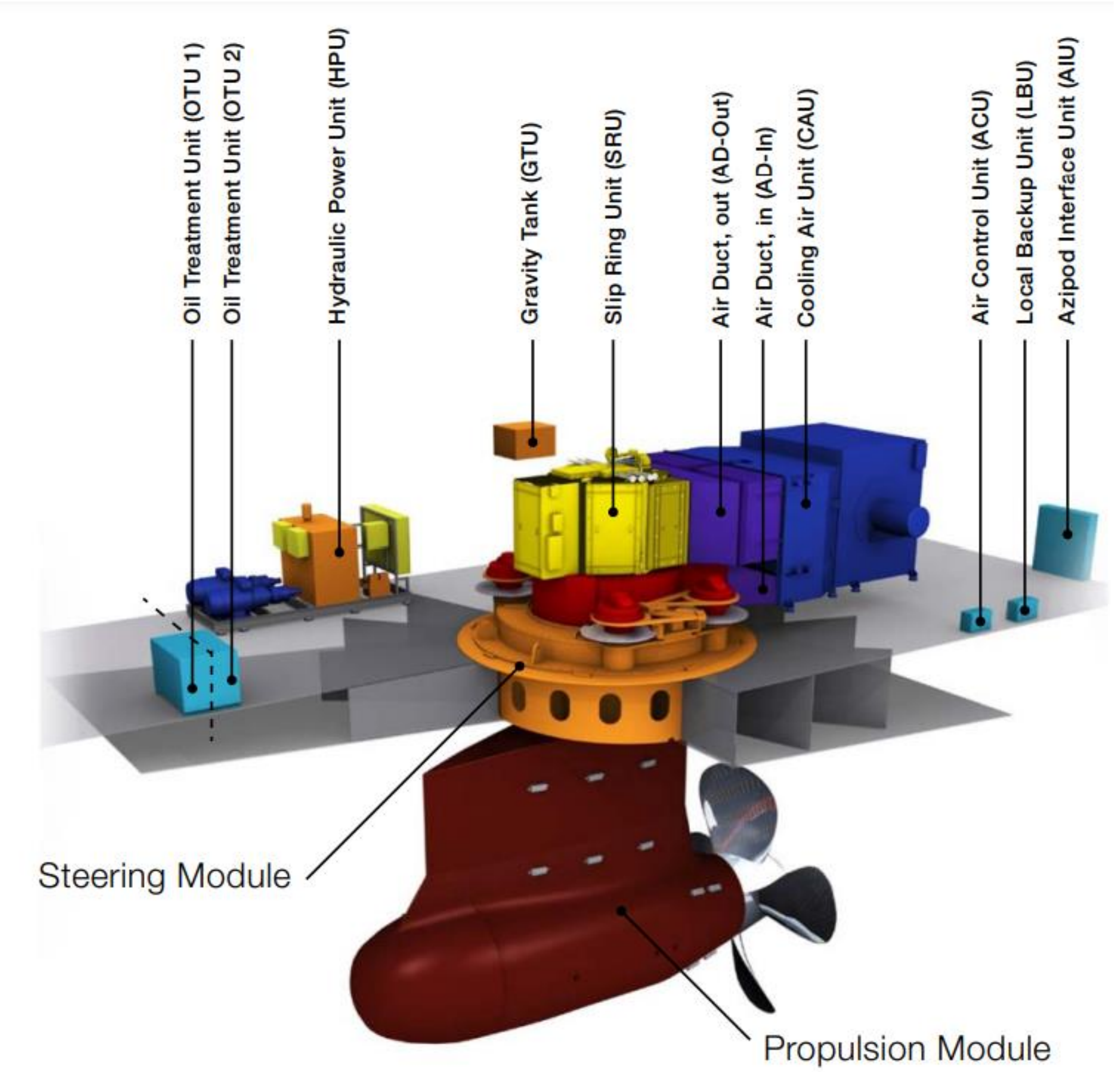

Figure 3. Installed Azipod VI systems on board a ship. (ABB, 2010) 23.8.23.

In figure 3 is hydraulic steering unit with its auxiliary equipment. In ice going vessels the steering is done usually with hydraulic motors. The number of the motors is same as with electrical steering system. Hydraulic power unit (HPU) produces the steering oil flow and utilizes 1 or 2 pumps at the same time to do so. This oil flow then rotates the hydraulic steering motors via the pressure piping, that is done separately to rotate to starboard or port side direction. HPU also includes electric pump motor starters, servo boxes and steering alarm unit (ABB introduction, 2019).

Electrical steering is used in cruise ships, 4 electrical steering motors are connected to the steering module via gearbox. Each motor is controlled by low voltage frequency converter and separate control unit controls the whole steering system.

1.4 Control systems

Typically, the control system for the propulsion system consists of Azipod interface units (AIU), propulsion control units (PCU) and remote-control units (RCU). Typically, one of each for each Azipod. Every unit has controller and I/O cards for control and monitoring. These units are connected to a control network and for that these units include ethernet switches. The control network has servers. Control network is private TCP/IP (Transmission Control Protocol/ Internet Protocol) network for ABB marine devices. Dostalek explains that IP part basically is the network layer and TCP is transferring the data using TCP segments dedicated to individual applications (Dostalek et all, 2006. 35). Each of these units has a communication to higher level automation system on board the ship, that is called MAS (machinery automation system) or IAS (integrated automation system), depending on the case. MAS is the highest-level system that collects the data from all the sub systems and visualizes them and even controls some of them depending on the project.

AIU is specifically monitoring and controlling the Azipod propulsion unit and steering system. It gathers all the data and processes it for the control system's needs. Control system then uses this data for example to create start interlocks and power limits for propulsion system and maintaining the propulsion and steering conditions suitable for operation. AIU also monitors Azipod's auxiliary devices. AIU is in Azipod room at the back of the ship, where all the auxiliary devices related to the Azipod are.

PCU is monitoring the propulsion drives but also the power plant and it controls the propulsion drives according to the information it receives from the power plant, propulsion drives and Azipod systems. Power plant effects naturally a lot to controlling of propulsion due to propulsions large power consumption. PCU creates the start interlocks and power limits related to propulsion drives statuses and power plant. For example, situation when there are not enough generators connected to the network is read by PCU leading to a starting interlock. PCU is typically one more cubicle included in one propulsion drive. Full redundant propulsion has 2 drives for each propulsion line and one PCU handles both. PCU has separate fibre optic communication line to both drives.

RCU is located on command bridge, and it is handling the ABB navigation equipment like Azimuth levers and panels. RCS consists of the remote controls of Azipod system including steering and propulsion control from the bridge and engine control room. In this thesis the focus is more on PCS, PCU and propulsion converters and RCS/RCU is not gone through that specifically.

2 Acceptance testing of Azipod system

To deliver the customer specific propulsion system, it must go through various levels of the acceptance testing. In this chapter it is introduced, what these testing phases generally are and what Azipod propulsion system testing means and how it is done. The focus is on PCU FAT and Drive HIL testing phases but because of the results of the work might be useful for the HAT and SAT as well, are those covered briefly too. In Figure 4 is presented the chronological order of different testing phases.

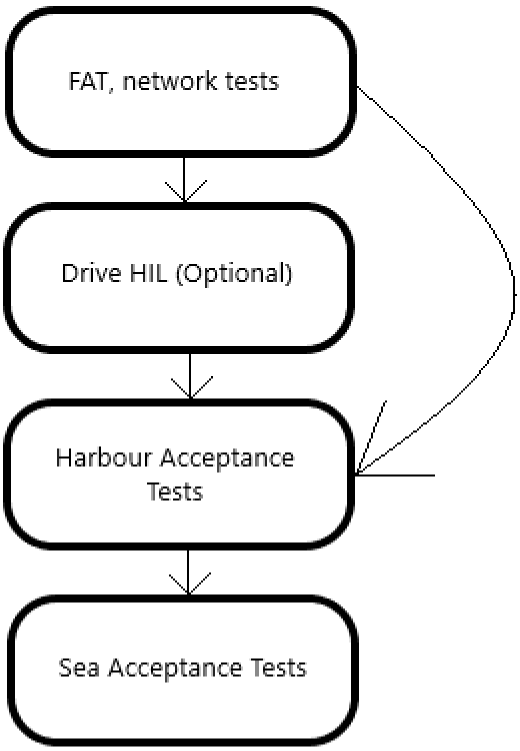

Figure 4. Chronological order of different testing phases.

Usually in every official testing phase there are present persons from the supplier of the tested system, responsible person of the system from the shipyard, classification society representative and end customer representative meaning the ship operator company.

2.1 Factory acceptance testing, FAT

In general, all the main components of the larger system, in this case the propulsion system, must pass the FAT dedicated to each component. Propulsion drives, transformers and Azipod propulsion motors for example go through vast test programs, where components are tested and verified, that they meet the specification. For ABB Marine directly, this means testing of the combined control system including PCU, RCU and AIU and it is called PCS/RCS factory acceptance tests. Azipod propulsor unit is also tested in the factory by ABB Marine. Rest of the main components come from suppliers and the FATs are done by them. Suppliers can be other ABB factories or external suppliers.

FATs are carried out before the final installation of the system to the customer facility or in this case on board the ship. FAT is the final check that the system meets the requirements and customer needs in terms of functionality and safety for example (Farquharson, 2011). FAT gives the valuable information to customer but also to supplier to see, how the system in this stage works and what can be improved when next stage is reached, meaning the harbour acceptance testing or HAT in short. The control system including the control cabinets and bridge consoles are brought to the FAT test place and the whole control system is connected for the first time. During the FAT Azipod side and propulsion side are demonstrated with some low voltage drive and small-scale induction motor or HIL system with motor emulator connected to the drive. This can be done in such a way due to a fact, that propulsion high power hardware is not in the focus during FAT orchestrated by ABB Marine. Networks go through a separate testing protocol that is part of the FAT tests.

2.2 Hardware-In-Loop testing, HIL

Hardware-In-Loop testing for the Azipod propulsion drive system is not used for every delivery project. In an usual project it is enough to go through normal FAT tests for single components and propulsion control hardware/software and then HAT and SAT tests for the whole installed system onboard the ship. Simplified HIL in Marine laboratory can be used for the PCS FAT. The same HIL is also used for verification and testing of new systems or parts of it. Very specific demands from the customer might also lead to a more complex testing of the system. This means that the capability to execute such a set of tests is important.

Hardware-In-Loop testing method is the way to test physical control hardware and the software it uses to operate. In HIL testing the physical control hardware is like it will be on board the ship but the high-power hardware and sensors it operates are modelled in the real time simulator environment. Simulation must be done in real time thus the control hardware, for example the controllers, are physically present and those operate in real time. Interface to simulator transfers the signals to control hardware from the power plant for example and other way around. (Ellis, 2012. 279).

HIL testing has been in use in the industries where same level of testing with actual power hardware would be unnecessarily expensive and time consuming. For example, National Instruments says on their website, that HIL testing can save up to 150000 dollars from testing aircraft arrestor control system when field testing time is cut to half. (Ellis, 2012. 280-281). In the figure 5 is presented basic principle of HIL testing environment.

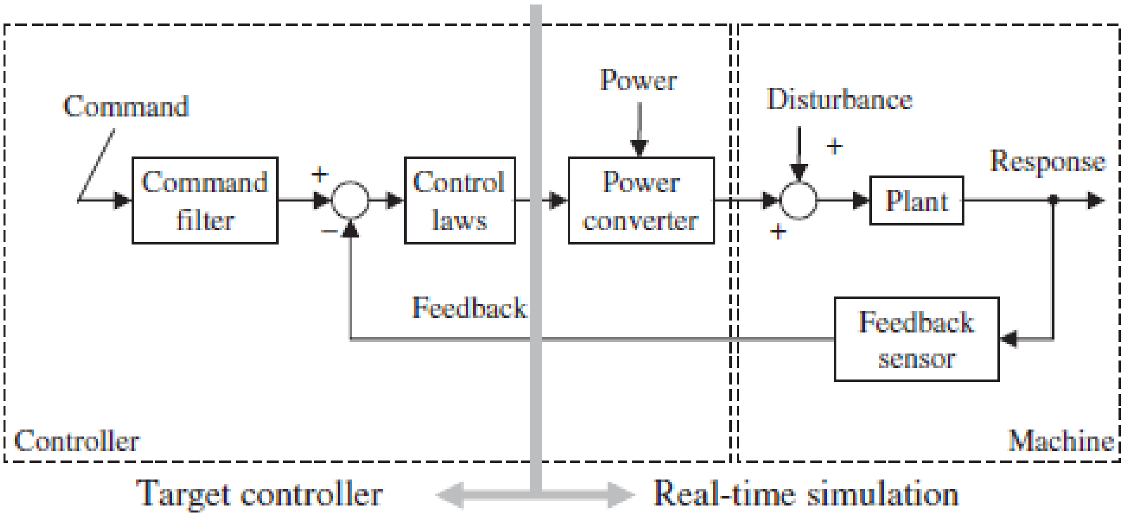

Figure 5. Hardware-In-Loop. (Ellis, 2012. 280)

HIL testing also mitigates the risks when complex systems are tested in a most demanding way. These risks can for example include drivetrain damage or even safety hazards for personnel. The plant hardware is simulated, and it offers safe environment to test the control system. This allows the testing of failure modes in various operation points that cannot be tested otherwise. Also, HIL testing gives valuable feedback how control software works and simulated examples how different failure situations look. Especially for the first implementation of the software version, HIL testing is good way to see, if software works and, in that way, mitigate the amount of software bugs before implementing software to the actual plant. When delivering complex systems, the control hardware is often available before the actual plant hardware is. This means the possibility to start control system testing before the testing with actual system. (Ellis. 2012. 281).

2.3 Harbour acceptance testing, HAT

When ship is under the commissioning at the shipyard, all the systems are brought to live one by one and then adapted as part of the whole ABB system. After all the subsystems are working with the drivetrain, interfaces with other suppliers' systems are established. The harbour acceptance testing or HAT can be commenced. HAT protocol includes testing for entire system divided in the sections like Azipod, propulsion and propulsion control system and remote-control system. In each of these, the related system is tested and accepted to be ready for the seatrial. Fitting out quay has its limitations for the propulsion, limiting the number of rpms which then limits the testing capabilities. This limitation comes from the fact that with Azipod the propeller is installed on the shaft right from the beginning meaning every time the system is tested with rotation, it will create thrust leading to stress to ships mooring ropes. This is the case in most of the shipyards and this limits the testing capabilities a lot, especially when the maximum rpm is limited very low. In other words, the testing of the system is limited, because only small part of the speed range can be used.

2.4 Sea acceptance testing, SAT

Seatrial and sea acceptance tests are the final testing phase when ship is being build. During the seatrial ships systems delivered by various suppliers go through a testing protocol designed for each system. In ABB's case there is one protocol that tests one more time the integration of propulsion system to other supplier's systems and between the systems in ABB's scope of delivery. The propulsion capabilities are put to the limits to verify, that system can deliver the specified numbers like efficiency and ships speed. One major focus for example is the integration with power plant, because during the seatrial it is first time when it is possible to test power plant with full propulsion power. For example, the power plant must survive in extreme conditions like propulsion motor tripping with full load without blackout. All the previous testing phases can be seen as a preparation for the successful seatrial.

2.5 Current testing procedure management

Currently these testing procedures in all the above mentioned testing phases are managed in Microsoft Word format. This means a multiple documents for each project separately managed in project folders. In other words, there is really no system as a such to manage the test procedures. In the conventional word document, the test is simply written step by step with step description and then a check box, if step was successfully done. In this way when the test protocol is under testing, the test protocol needs to be printed and filled by hand. First to mark the completed steps and then the signatures from the participants. Many times, when some test phase is ongoing, there are multiple test protocols printed for each participant to be able to follow through the test steps. After that documents need to be scanned to the electrical form and stored. All that manual work and paper handling could be avoided or at least mitigated. So, it can be concluded, that there is a need to bring the testing procedure management to a modern level using the modern tools.

3 Hardware in loop simulator setups

The Hardware-in-Loop testing for the propulsion drive system is additional part alongside the regulatory factory acceptance testing (FAT) and it demonstrates more specifically the propulsion drive system functionalities. Upper-level control systems from drive’s point of view meaning PCS and RCS are first tested separately including software, hardware, and networks and in those tests ABB Marine laboratory equipment is used. Drive system HIL is performed separately with different equipment in another laboratory to make the system testing more precise.

3.1 Propulsion drive HIL

Propulsion drive system HIL tests will verify the propulsion motor drive and propulsion control system integration and demonstrate the full redundant marine drive operation. During these tests drive related functionalities and responses are tested with drive HIL simulator and propulsion control software.

The testing program for propulsion drive HIL tests was designed for the full redundant drive system so the requirements for the drive HIL hardware are the same, to be able to mimic real life FRD in a sufficient way. HIL arrangement needs to have the control hardware including I/O cards, motor control boards and semiconductor firing command boards for example for two ACS6000 drives. Below in figure 6 is shown the needed HIL arrangement. Red connections mark the drives internal control network and propulsion control and drive’s internal control network. Light blue marks the low voltage 3 phase supply for the synchronous motor rotor winding. Yellow marks the high voltage supply for motor stator windings and brown marks the drives supply side from the main switch board.

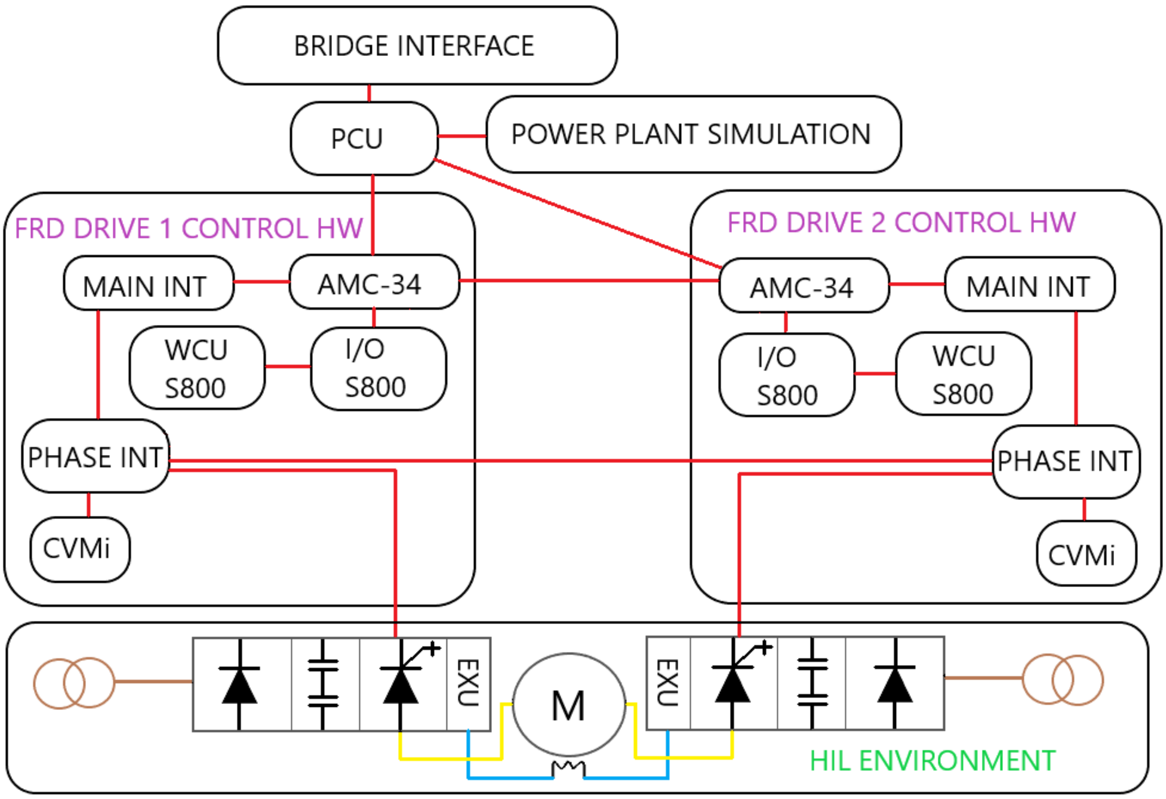

Figure 6. ACS6000 drive HIL arrangement.

The propulsion drivetrain high power hardware is simulated in the real time simulator environment including power plant, propulsion transformers, propulsion drives and propulsion motor. The CVMi in figure 6 is abbreviation from current voltage measuring interface board. Inverter output current measurement and DC link voltage measurement are connected to CVMi, which collects the data and communicates it forward. WCU stands for water cooling unit, and it includes S800 I/O cards for monitoring and control and cluster modem, that connects WCU to rest of the drive's I/O communication. ABB ACS6000 drives are applying DTC control method for motor control. *DTC control is based on a switching table that selects the optimal voltage vector that has to be generated by the inverter to obtain the required increase/decrease of torque and flux variables* (Arnanz et all, 2007, 921). As can be seen in the figure 6, there are phase INT boards, one for each drive, to control the virtual IGCTs or Integrated gate-commutated thyristors in the simulator environment. Phase INT board is responsible for giving the firing commands for the IGCTs according to current operation point and correlating voltage vectors. Main interface board or Main INT is used as a control and communication interface for inverter unit and AMC board (application and motor controller).

3.2 Propulsion control system HIL

HIL simulator to be used in internal PCU FAT is going to be different than the one used in drive HIL. This is due to a fact that in internal PCS FAT the focus is on propulsion control system, not the drives as a such. This means, that drive system does not need to be modelled in detail, but just enough that it reacts in a proper way to propulsion control system commands. For internal PCU tests it is sufficient to use the low voltage drive control board arrangement present in the laboratory and emulator system to model motor side. The propulsion drive simulator environment comprises of ACS880 BCU-12 drive control boards handling the drive side. Each of those BCU-12s is connected to one ACS880 ZCU-12 motor emulator. HIL system feeds the counter torque for the propulsion. For the counter torque modelling laboratory has Typhoon HIL604 real time simulator. According to manufacturer brochure, *Typhoon HIL604 real-time power electronics emulator is an ideal tool for development, testing, optimization, and quality assurance of grid connected converters (i.e. PV, wind, active filter), automotive converters, electric propulsion, drives, micro-grids, and industry automation.* (Typhoon brochure).

The power plant simulation is done in Typhoon as well. Depending on the simulation model size, it is possible to connect several Typhoon simulators in series to form a more powerful computer. (Typhoon brochure). If power plant is modelled together with PEMS and propulsion, one simulator is not enough anymore. In that case all of those are simulated inside Typhoon and the tasks are divided to separate processor cores to even the computational load. Amount of Typhoon's is not related to amount of propulsion drivetrains, but the size of the simulation model in general. In above-described situation the model can have rotating machines like generators, protection relays, main switchboards, low voltage switchboards and counter torque calculation for propulsion, so a lot of calculation power is needed.

4 Testing Development

In this chapter thesis introduces the new platform for the testing management and how the internal PCU test protocol and drive HIL protocol were implemented to this platform.

4.1 Chosen test management platform

The requirements for the platform needed to be defined. The first thing was to bring the testing management properly to the digital age by utilizing some software designed for this kind of usage. There are multiple software or automated test management systems designed for software testing. The chosen software had to have flexible user interface to modify the UI as it is needed and the ability to manage the testing procedure digitally as far as it is possible, meaning from the test procedure planning to execution of the test procedure and even signing tested protocol.

ABB Marine already uses JIRA software to manage the project data as one tool at the moment. JIRA software is created by Australian company called Atlassian in 2002 and it receives regular updates. Springer says in his article at community website, that JIRA was created to support software teams in software development in general but ever since it has gained the status of one of the widely used project management software solutions in the world. JIRA allows the project organization to manage multiple activities like software development, marketing, and bug tracking, just a few to mention. (Springer, 2023)

JIRA does not have just one purpose, but it can be used in a variety of ways. Platform enables the teams to dynamically plan, track and manage the workflows and projects. It allows the teams to organize the project and define, assign, and prioritize tasks within the projects. (Springer, 2023). That is why it was decided to explore the possibilities to further utilise the powerful platform tool ABB personnel is already using and familiar with in some levels.

In ABB Marine JIRA is used for different product software related matters like protection relay software and propulsion control software change logs. These software's are managed in the platform for projects in motion. For example, if in design phase design team finds out that some parameter or software changes need to be done, they will keep change log about those in JIRA.

The structure for test protocol management is very simple. For example, PCU internal test protocol in JIRA is constructed in a way that the actual test cases are done at subtask level. Subtask is like child of an issue and one issue can have multiple subtasks under it. Figure 7 demonstrates the structure.

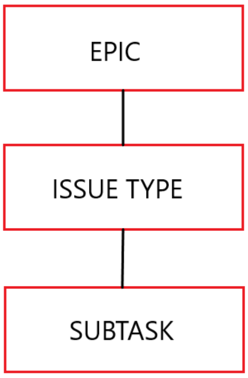

Figure 7. JIRA structure.

Issues could be further arranged under an epic, which acts like parent issue, that can group the different sets of issues together. For example, interlocks can be one epic and under it interlocks from different sources like propulsion drives, Azipod and power plant are grouped together. According to Nelson's article, a task for example is one type of issue and JIRA has some predefined issue types ready to be used, but also allows the users to customize their own issue types. (Nelson, 2020). For testing protocol purposes, issue types of Drive software and PCU software were utilized.

4.2 Testing procedure management development

To manage the test protocols in a better way, JIRA was investigated further. First thing was to understand what is possible with it, because this kind usage of JIRA is something new for ABB Marine. In the conventional word document, the test is simply put step by step with step description and then a check box, if step was successfully done. In this way when the test protocol is under testing, the test protocol is usually printed and filled by hand. In this thesis the intention is to find more efficient way the manage and modify these documents. Many times, these documents have a lot in common, meaning most of the tests are the same for each project. Because of this, it was time to think other ways to manage the test programs and procedures to bring management to the modern age. For example, with database-based management it could be easier to create these documents in a first place but also to add and modify project specific tests for each project or even perform the tests by using the platform.

In the beginning of the process, the same kind of check box layout was created in JIRA for the test case as is in the conventional word document using simple chart tool. Idea was to mark X for example to the table under the “checked” when step was completed. It was easy way but at the end it was the same as with word documents even though it was introduced in JIRA. Because step checked like that doesn’t show in the system, so there was no added value to do it like that. It only shows in that specific test case. JIRA possibilities were further researched and possibility to create actual check list in JIRA was discovered. Actual check list records the actions in JIRA data base and allows better tracking of the progress. Also, the check box created in JIRA allows users to easily modify the test protocol in editor mode. In figure below is shown the created check list.

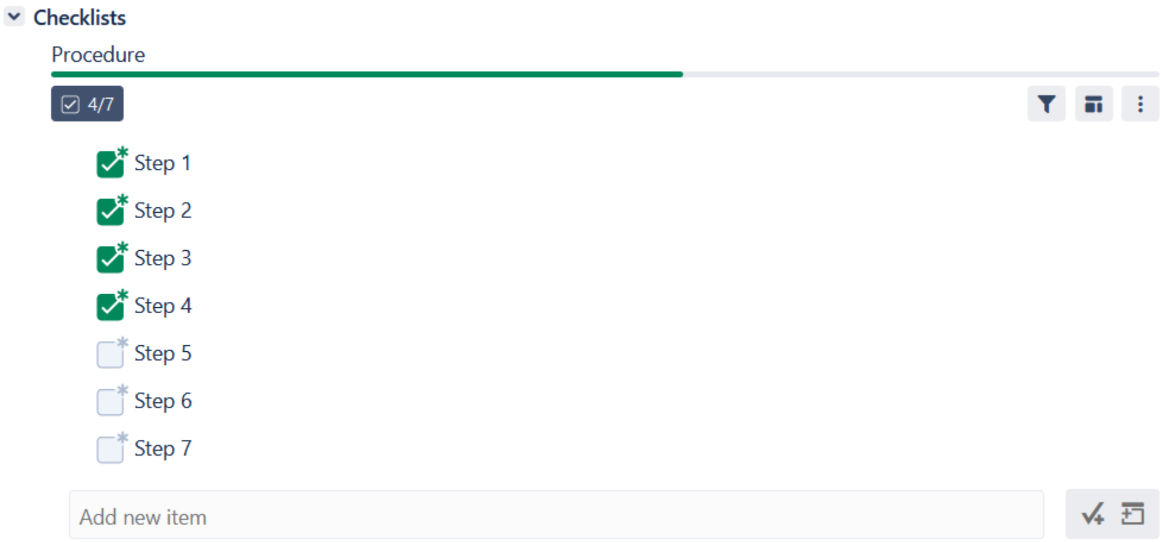

Figure 8. Created checklist in JIRA.

From figure above the user can see the progress and check the steps just by clicking. The editor mode is shown in figure nine.

Figure 9. Editor mode of check list.

User can freely move and modify content in this window. For example, if some test step needs to be added after the rest of the protocol is written, in editor user can simply add it in between steps. In normal check list view user can only add a new step at the end of protocol or delete the last step.

One key point was to define and create a proper referencing system. This became important especially for the PCU internal tests, because at the end there were around 85 test cases under around 57 PCU Software issues. During the creation of these tests, it was concluded that proper referencing is important for the searching of these tests to find them easily. Also, it is possible, that some customers want their own reference number to show in the documents. Reference number field for PCU Software and Drive Software was created to allow the user to give reference number for the issue without any restrictions in usable marks. Meaning special marks like dot or hyphen that some customers might have used when referencing in their own testing desires. That allows the user to find desired test quickly. Reference number is given on the issue level. In figure 10 is shown the reference field of an issue, in this case PCU Software.

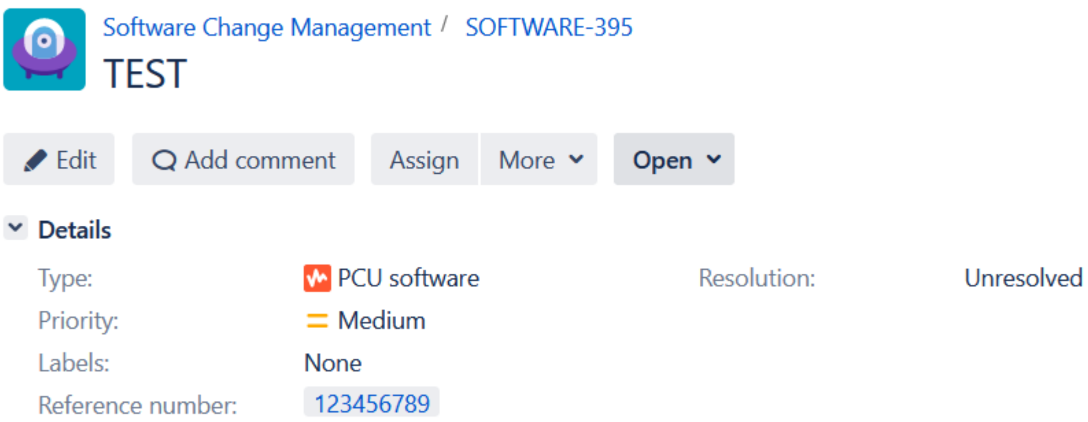

Figure 10. Example of PCU Software issue and reference number.

When reference number is given for the issues, user can create a reference number search and save the user defined search in issue page to find desired references easier. In figure 11 is shown the user created reference search.

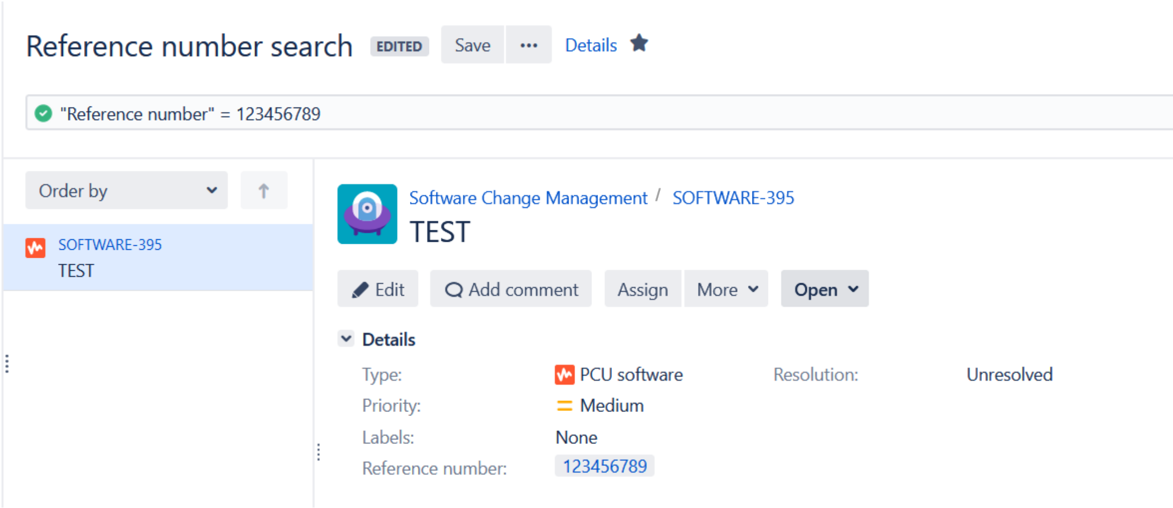

Figure 11. Reference number search example.

User can add multiple search criteria for the search. This becomes useful when specific tests need to be found quickly.

The details that are shown in figure 11 are attributes that can be used as search criteria when using advanced search. Details are not limited to what is seen in figure 11, but there are a lot more of them to specify issues. This in general gives user many options to manage and follow the issues created in JIRA. With these attributes user can also create different kinds of gadgets in dashboard view to demonstrate the filtered data. Dashboard is the main display when user logs in to JIRA. First user needs to create personalized search filter for issues with advanced search and then simply link it to some gadget chosen for the dashboard. Gadgets can be for example pie charts or two-dimensional filter statistic boards. In figure 12 is shown a pie chart demonstrating the status of internal PCU test protocol progress.

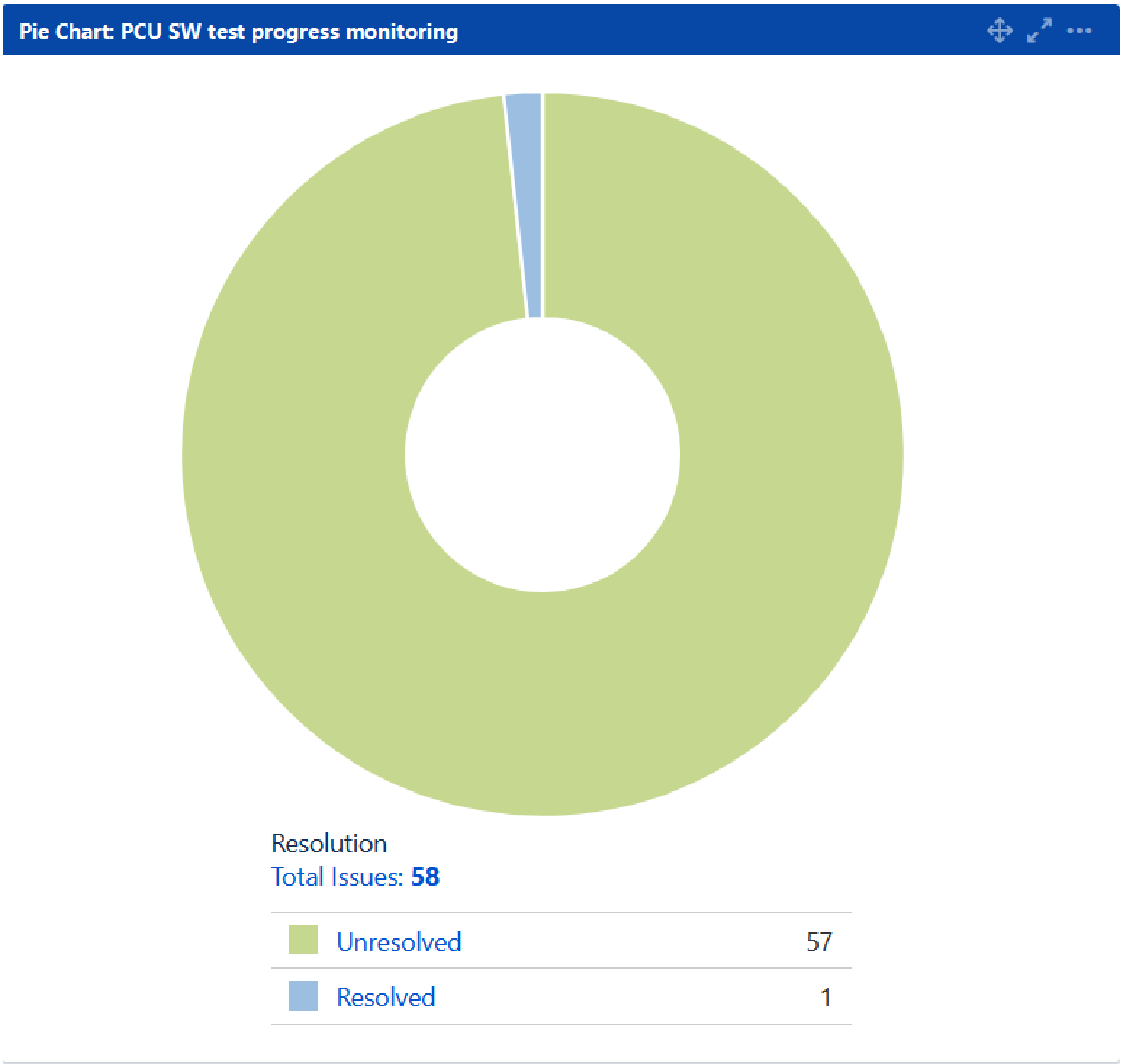

Figure 12. One way to visualize the data in JIRA.

Pie chart is done simply with pie chart gadget and user made filter called “PCU SW test progress monitoring”. The filter is written in advanced search as can be seen in figure 13.

Figure 13. Advanced search filter example.

Advanced search uses JIRA Query Language or JQL in short and it allows user to build structured queries. (Springer, 2023).

Every dashboard can have multiple gadgets demonstrating individually interesting data. Meaning every user can define the dashboards for themselves and then link the data they want to gadgets they prefer to use. This comes handy for lead engineers and project managers for example to create their own filters related to their own projects and then monitor the testing progress. Even though the list of gadgets is long, not all of them are relevant for the test procedure management.

JIRA has also restrictions. During the thesis work it was noticed that very simple operation like making a query to show test cases under specified issue type was not possible. Following simple line of code was made to demonstrate this, project = SOFTWARE AND issuetype = "PCU software" AND type ="Test case", but it didn’t return any results. Line simply tries to specify all type “test case” subtasks under the PCU Software issues. There was no way found how to do it with normal JIRA tools. After some research was done it was found out that with Scriptrunner add-on user can make this kind of query, but it is not that simple as the code above. Needed code would look like the following, project = "Software Change Management" AND issueFunction in subtasksOf("issuetype = 'PCU software'") AND issuetype = "Test case". The code will become a bit more complex but the fact that the desired search is possible is more important. This demonstrates the power of JIRA too, if something is not possible with original tools, it could be done with add-ons. Table 1 summarizes the pros and cons of the word document management and JIRA test management.

Table 1. Pros and cons of the two test management systems.

Test management system	
Word documents	JIRA
Pros	
Works without Internet	Flexible user interface
Old and familiar format	No papers needed
	Progress follow up
	Could be used 100% with laptop or tablet
	With add-ons expandable
Cons	
A lot of papers needed	Needs internet to work at the moment
Printing and scanning	Needed add-ons to fully utilize
	Basics of programming is advantage

Add-ons can be considered as a pro and con, because it would be best that platform supports automatically the wanted features, but it is good that it is expandable.

4.1 Internal PCU testing protocol

Thesis has already described the normal testing procedure for the Azipod propulsion system delivery. These tests are comprehensive already to verify system behaviour. For this thesis the testing is taken couple of steps further to test the system more thorough way. Actual test cases are presented in the next chapter with examples.

First step was to create internal FAT testing protocol for the propulsion control system FAT. Idea of this internal protocol is to test the system further before the official FAT. In this way ABB can be sure that FAT will be successful and when the software is delivered, it is ready as it can be before implementing on site. One main reason is to produce a documented set of test cases that are done to show the customers how thorough additional testing the system has gone through. In the internal protocol features that are not in the official protocol are tested and verified, modified if needed to achieve the correct function. Other point of view of these tests was to evaluate the tests and functionalities and question if something was not right. These matters were then discussed with related people to understand the correct system behaviour.

For the internal testing protocol, flow diagrams were evaluated for each test. These diagrams describe overall flow of the system behaviour to relevant situation. These diagrams were analysed and then the actual test case was created for it. Flow diagrams present a simplified way how the overall flow of the test is going to be, and then the actual test case presents the detailed description of the test steps, what is expected to happen and how the test supposed to be done. In figure 14 is shown an example of these functional flow diagrams.

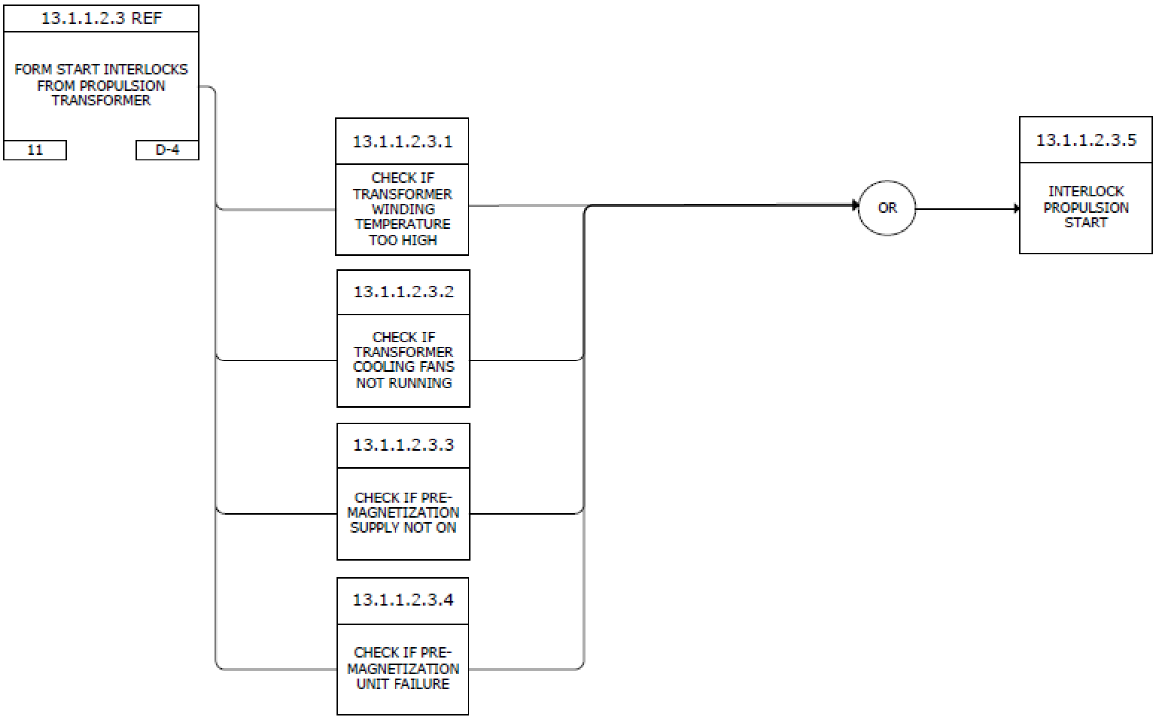

Figure 14. Functional flow diagram for the related test case.

Some of the functionalities are very simple like the propulsion system interlocking reactions for propulsion transformer shown in figure 14. System checks these four conditions for the propulsion transformer and if even one of these is not met, system will create start interlock for the affected propulsion drive. Start interlock is a protective function of the propulsion system that prevents operator damaging the system or further damage for the system. There are multiple different reasons for the system to create one, only one component of the drivetrain like propulsion transformer has 4. Some of these test cases are more straight forward and simple, just with one condition. But also, other way around, there are more complex functions for other system reactions that are affected by multiple inputs creating more than one output. This example was chosen to give clear example what functional flow diagram means in this thesis.

The functional flow diagram in picture 14 can then be divided to more specific one for each start interlock to describe the limits for example to transformer winding temperature. This is demonstrated in picture 15.

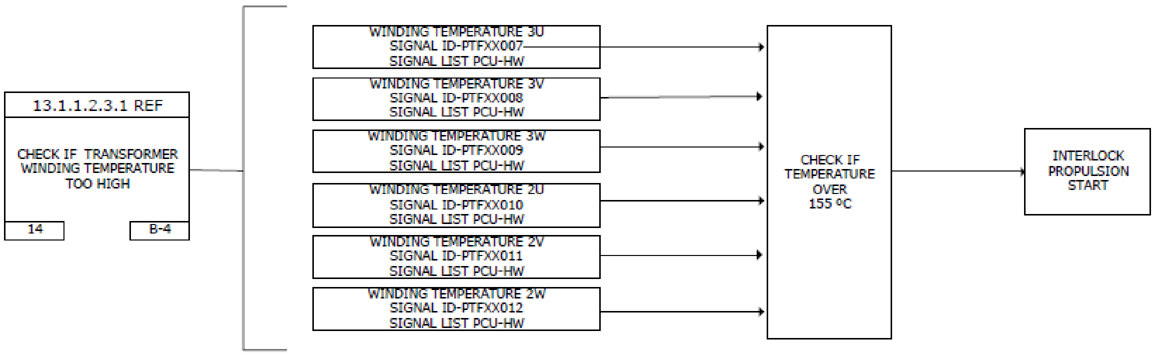

Figure 15. More detailed view of the propulsion transformer winding temperature interlock.

Figure 15 then presents the actual limit for this specific interlock and that it will be activated, if any of the secondary windings of propulsion transformer reaches the high limit of 155 °C. Not all the test cases have this kind of more specific flow diagram, only the ones where applicable.

4.2 Drive HIL test protocol

The drive HIL test protocol is using the same template as internal PCU test protocol. Biggest difference is that in drive protocol the flow diagrams are not added. Otherwise, everything follows the same principles.

Drive HIL protocol is testing specifically the drive system reactions in different situations. For example, some failure modes are not simply possible to test with actual power hardware, like semiconductor short-circuit fault. Like explained before, for the drive HIL the control hardware needs be present. For example, these control boards like AMC boards have the master/follower link between them and phase INT boards have so called block modulation link between each drive. All of those play important role when it comes to drive specific failure modes and reactions. Those are some of the main differences between drive HIL and PCU FAT HIL arrangements.

Drive HIL protocol is designed around the thought that what can be tested and should be tested. This includes more severe tests but also tests that could be done on site but are faster to do with HIL. What are the typical failures for medium voltage full redundant drive system? How to demonstrate full redundant drive operation in realistic situations that can occur on board ship? How drive’s internal short-circuit protection works with load? With HIL it is safe but also faster to investigate all these. The focus in HIL test protocol is in two matters, what interests’ customers but also what could be interesting for ABB to see and verify and learn for the future. In ABB Marine’s interests could also be to learn different fault patterns when it comes to semiconductor failure or other component failures in the drive’s high-power circuit for example. That could help ABB Marine to analyse possible fault situations when there is data available, and personnel has experience of these fault scenarios from the simulator.

5 Test cases

The test cases were created to demonstrate better JIRA and its possibilities. In this chapter are presented some examples of actual test cases that are going be executed. During the process 57 issues were created comprising total of 85 test cases for internal PCU testing protocol and 12 issues and total of 29 test cases for drive HIL testing protocol. A decision was made that the epic level is not needed for the proper management. Epic level becomes handy when handling many large groups. In this case, it would lead to a situation, where there are epics with many issues and then epics with one issue. In chapter 5.1 and 5.2 will be presented 3 cases from both protocols with more detailed explanations.

5.1 Internal PCU tests

To demonstrate the PCU internal test protocol, 3 different kinds of test cases are introduced and explained. Within all 85 test cases there are test related to all the parts and subsystems of the propulsion system but for obvious reasons, all of those can’t be demonstrated in this thesis. The purpose of the sub chapter is to elaborate the test cases for the reader and the level of testing along the way to visualize the look of readymade test case.

First test case demonstrates, how the azimuth lever propulsion control is released. There are couple of conditions, before the propulsion lever reference is released to operation. The detail part of the test looks like the following.

Figure 16. PCU internal release control test JIRA details.

In figure 16 it shows the test case subtask details for actual test case. All the relevant information is there with preconditions and expected results and the person this test case is assigned to. All those details can be used for the search filters. Below the details user can find the description field, and in case of a PCU internal test, function flow diagram. The actual test protocol is presented last. In figure 17 is demonstrated the control release test case.

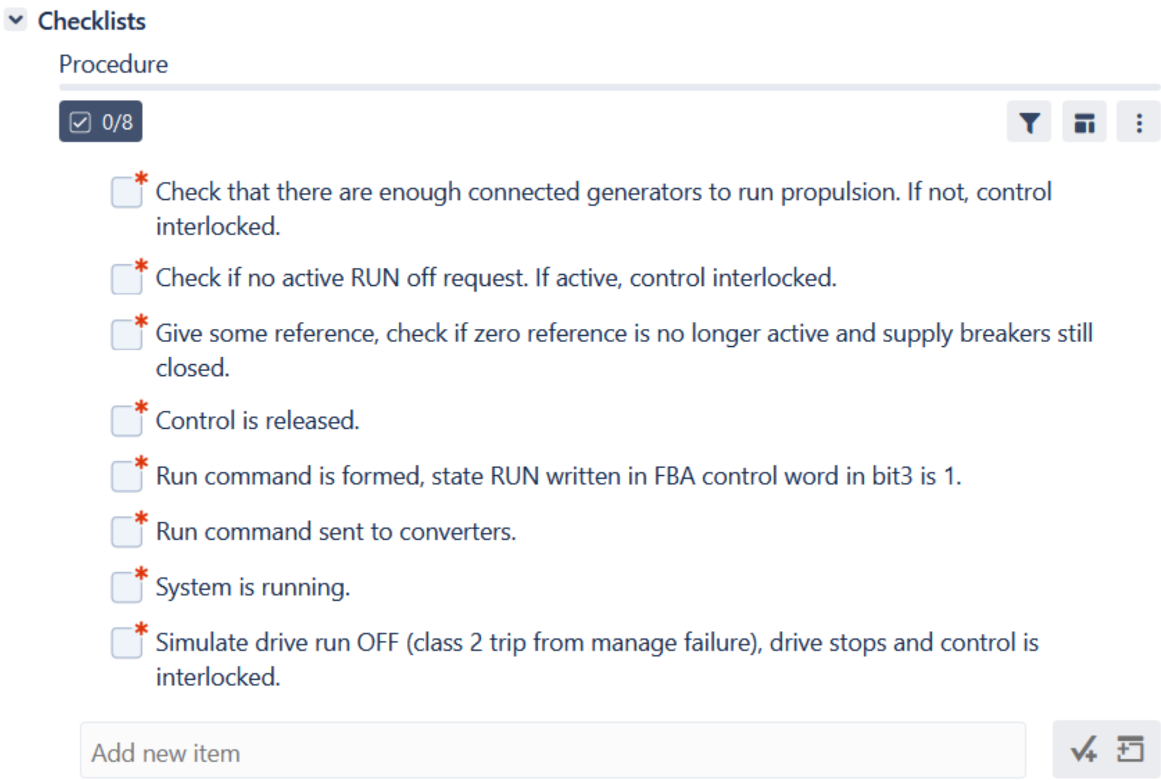

Figure 17. Propulsion control release test case.

First is checked that system have enough connected generators for the running. User can simulate condition “not enough generators” and test the control block. When this step is fulfilled, user checks if no RUN off request is active. RUN off request means fault class 2 trip, which translates to a trip for the propulsion system, that keeps the propulsion converter main circuit breakers still closed and DC link capacitors charged. If either one of these is active, control system is blocking the propulsion reference. When both conditions apply and reference is given, control system releases the control, writes the RUN bit to field bus adapter control word, and sends it to the propulsion converters. Propulsion is running. Test case is finished with fault class 2 trip. STOP command is given, meaning RUN bit is zeroed.

Second test case is related to the steering system and propulsion motor torque limitations. Test case name is “Limit power from Azipod steering angle”. Test demonstrates how Azipod steering angle and active cruising mode effects to the system.

Figure 18. Steering angle test case details.

Test case is straightforward, and it is demonstrated following the figure 19 protocol.

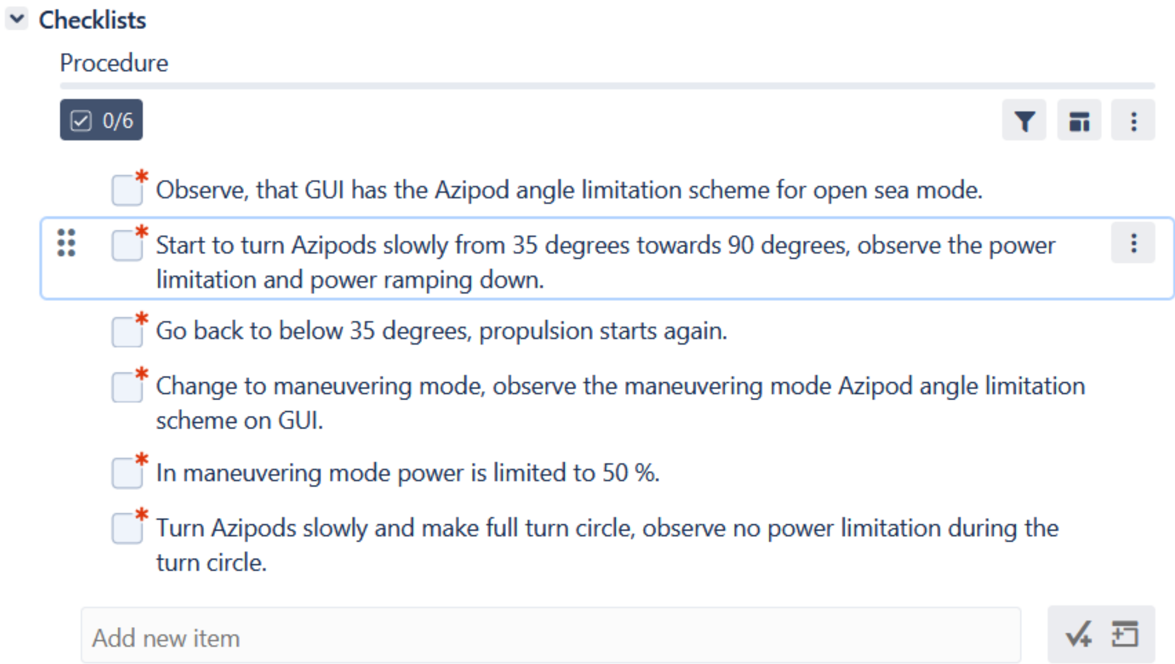

Figure 19. Steering angle test case protocol.

In test protocol term GUI refers to Graphical User Interface, which means the screens located in ship's engine control room displaying the system information for the operators. During the test it is important to verify the GUI showing the steering angle limits graphically in each mode. The idea of the test is, that when operator chooses open sea mode, it releases the full power of the propulsion system to be used. But at the same time, it limits the steering angle of the Azipod to 35 degrees to port side and starboard side. Steering angle exceeding that would lead to too steep turns. If angle goes over 35 degrees while in open sea mode, it limits the propulsion power to 0. When manoeuvring mode is chosen, it limits the propulsion power to 50% of nominal but releases the whole turning circle for operator. Manoeuvring mode is used to manoeuvre the ship to and out of the port, so operator needs to steer the ship with full 360 degrees circle. This way the thruster motors used with conventional propulsion are not needed with Azipod system.

Third example is a test case, where full redundant drive system redundancy is compromised. Both drives have one excitation supply and depending on drive status being master or follower, drive system reacts to it. Test description is shown in figure 20.

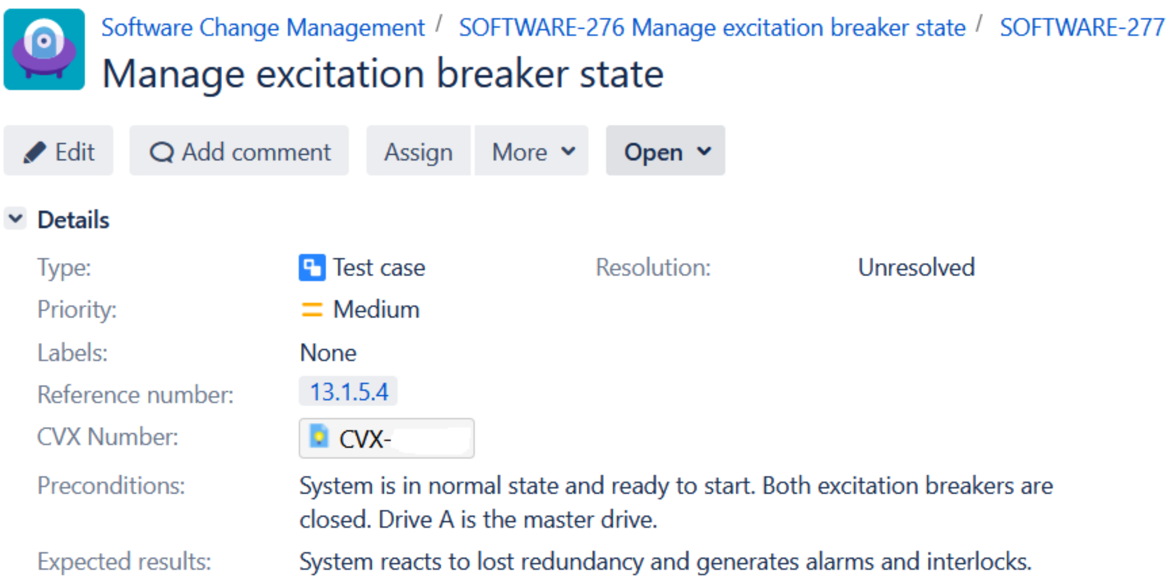

Figure 20. Excitation breaker management test case.

Excitation breaker described in the test means the one that is for example in separate LV switch board and supplies the excitation unit inside the propulsion drive. Breaker could be also in the HV switch board and connected via HV/LV transformer. There is a status signal coming from the supply breaker to indicate the excitation supply status for propulsion control system. Test protocol goes according to figure 21.

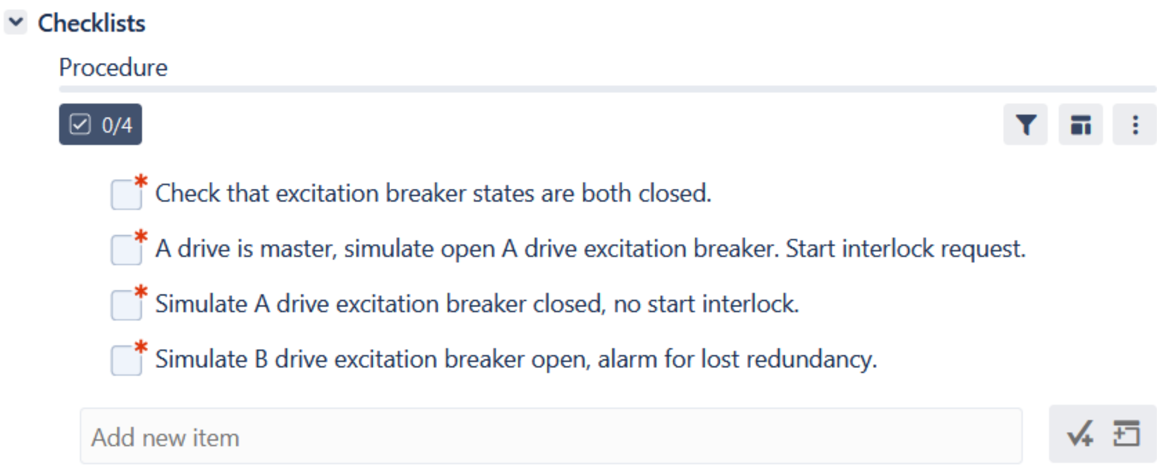

Figure 21. Excitation breaker management test case.

This signal comes from external source from the drive point of view, so no automatic master / follower switchover happens. Operator will witness an alarm and interlock created by propulsion control system. If master drive loses the excitation supply, it is operator’s responsibility to manually change the master drive. In case the follower drive loses the supply, drive system loses the redundancy and alarm about it will be displayed.

5.2 Drive HIL testing

To demonstrate the drive HIL protocol, thesis demonstrates 3 different types of tests to explain the level of drive HIL testing and the created protocol. Short-circuit test is good example of a test, that can’t be done with actual equipment without any risks. Encoder signal break test with full speed is also harsh test with actual equipment. 3rd example test is the stall protection test, that is mainly related to ice breaking vessels, when the ice is thick and propeller can get jammed.

First of the introduced HIL protocol tests shows what happens during the short-circuit in one of the inverter unit’s IGCTs. Creating a short-circuit to actual hardware for testing purposes is not possible, so this kind of test is excellent for HIL environment. In this test case, one IGCT is simulated as short-circuited while system is running at full power and speed.

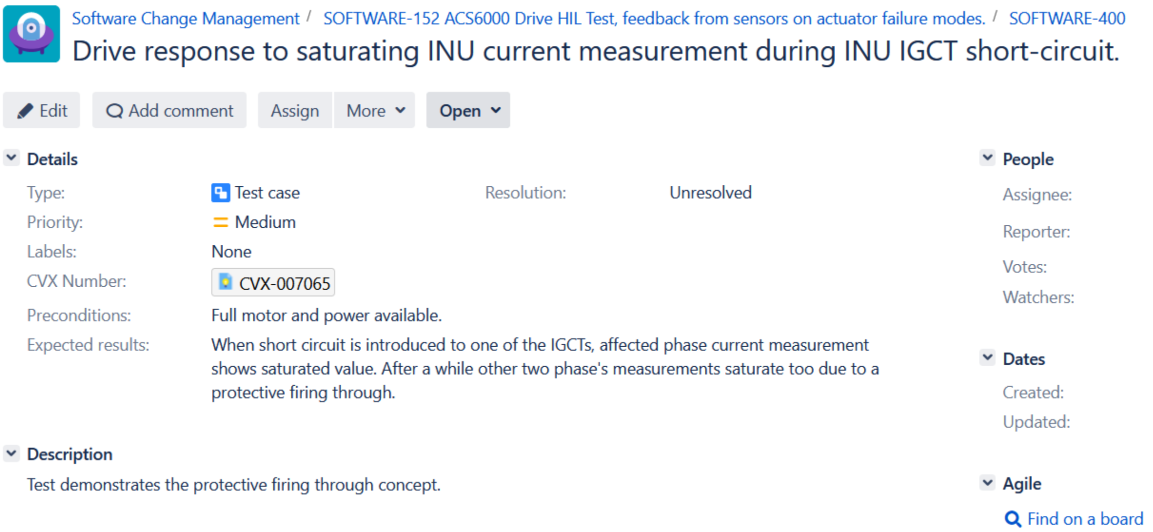

Figure 22. IGCT short-circuit test.

HIL simulator has microsecond level sample rate, so it should be possible to observe the faulted phase current to start rise and show signs of saturating inverter current measurement. After the FT is commenced, the other two phases output current measurements show same behaviour measured by the current transducers.

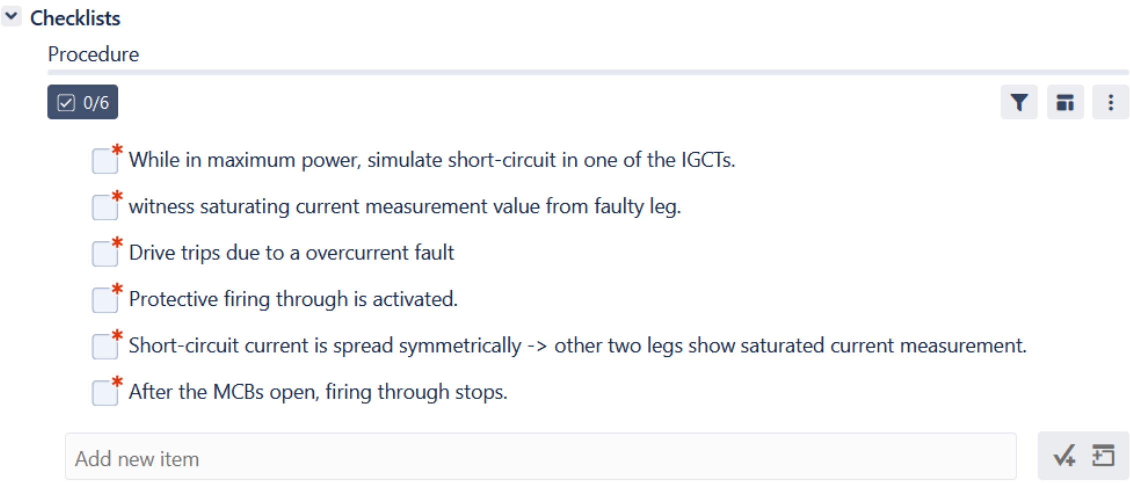

Figure 23. Test steps for IGCT short-circuit test.

Drive notices the over current fault and trips. After the main circuit breaker open, firing through stops and situation calms down. Test case itself is straightforward, but it provides interesting data of how this protection happens.

Propulsion system uses absolute SSI encoders to measure speed and position of the motor. If encoder feedback for master drive is lost, it will lead to immediate tripping of the whole FRD propulsion drivetrain, because follower drive is using the master drive's encoder feedback too. Losing the rotor position and speed can lead assumably to many outcomes, not just one specific. That is why it is interesting to test this phenomenon with full power in HIL.

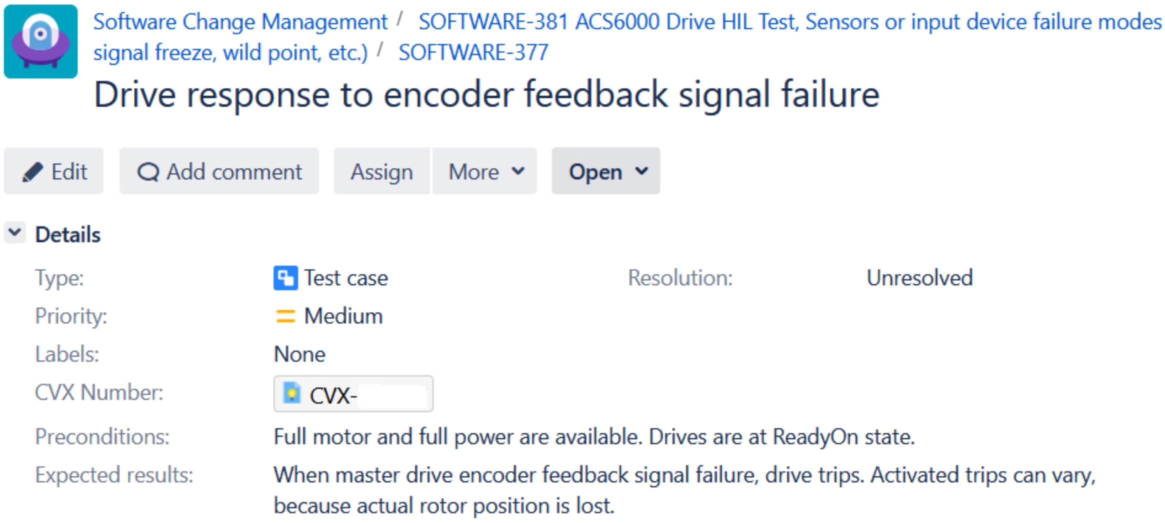

Figure 24. Encoder feedback signal failure test.

In this test also the ReadyOn state is checked. It means how system will react if encoder feedback is lost before starting the drive. Azipod system uses double encoders, one per each drive in FRD propulsion drivetrain. According to machine design website absolute encoder's feature is, it "*Remembers its position after a power outage and offers continuous position monitoring*". (machinedesign.com).

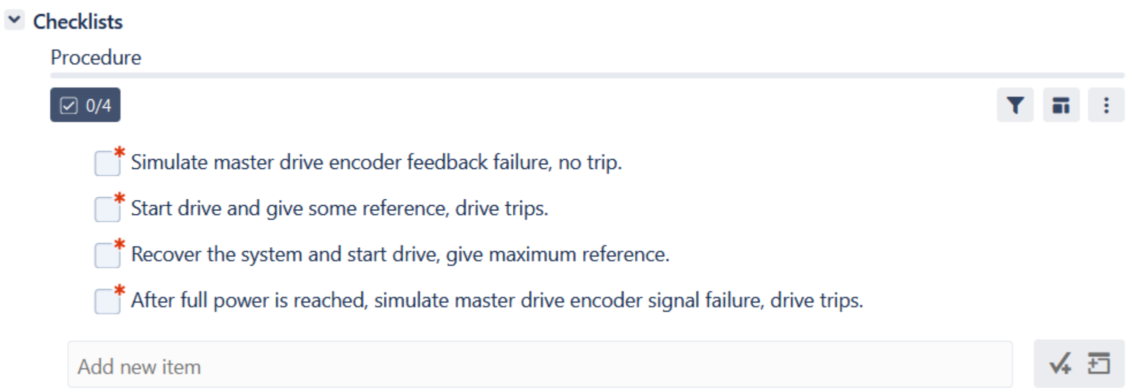

Figure 25. Encoder test case steps.

If encoder signal is disconnected when drive is in standstill and without monitoring functionality, drive doesn't know if the encoder feedback is broken or not. And when absolute encoder doesn’t receive the new position when reference is then given, it will lead to erratic behaviour of the feedback and drive reacts and trips.

Stall protection function is mainly related to ice going vessels. Stall protection have a couple conditions that can initiate the function. First is the motor speed or more precisely the frequency. Other condition is the stator current getting too high. When these two conditions apply, a timer will start and after the delay the system will react. This falls into the category of tests, that cannot be done with actual equipment.

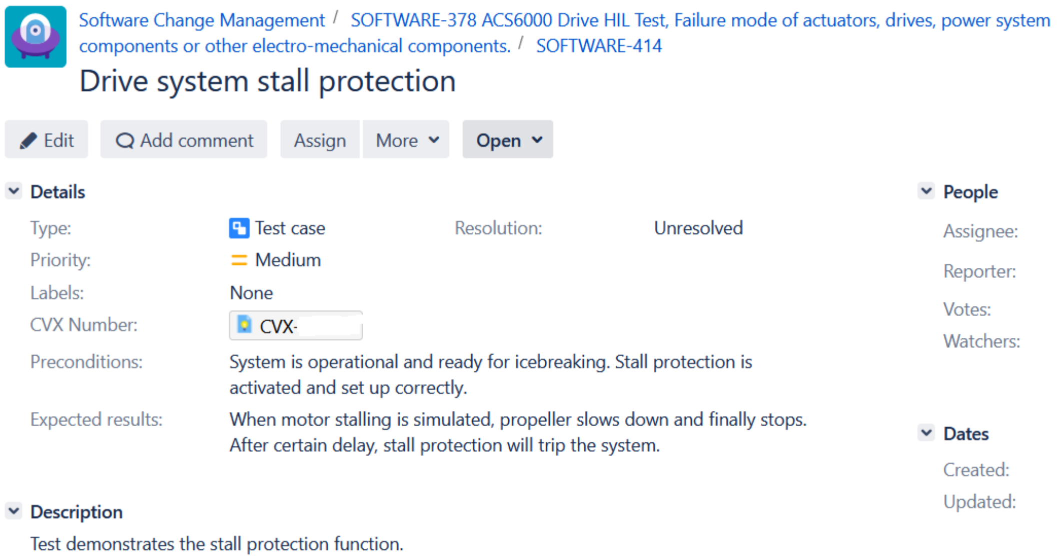

Figure 26. Stall protection test case.

The preset time can be set from 0 seconds to some minutes. But for reasonable reaction time it is set around 30 seconds for ice going vessel and around 5s for cruise ship, giving system time also to recover from the stall without tripping immediately. Normal cruise ships are not considered to be cruising in ice conditions, so the stall protection needs to be faster if propeller gets jammed. Because in that case it is something else and potentially harmful.

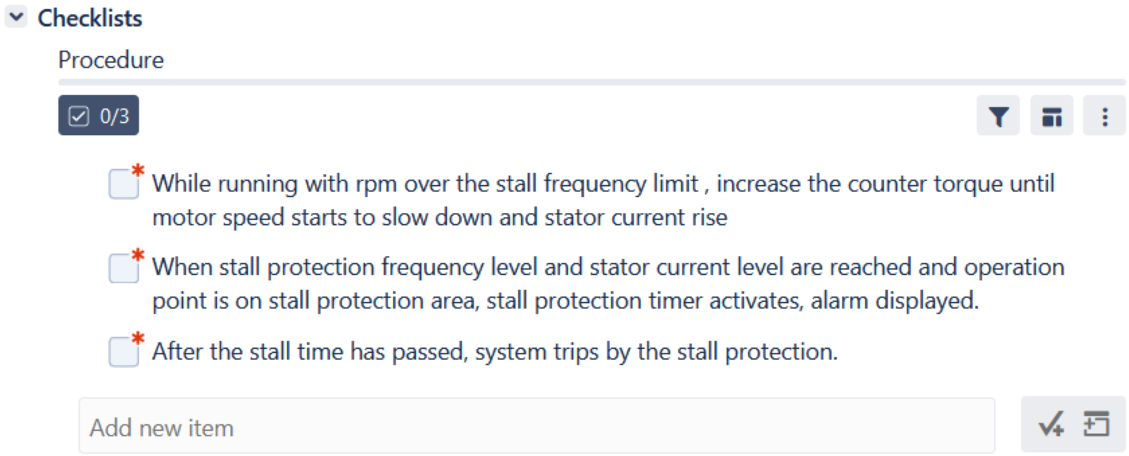

Figure 27. Stall protection test protocol.

In this case, stall protection frequency can be for example 0,5 Hz and the stator current limit can be around 150 % of nominal stator current. Alarm will be displayed when the drive enters to the stall area defined by the frequency and max motor current and when drive stays predefined seconds in it, drive system will trip.

5.3 The export template and other test protocols

The export template was developed to be able to share the protocols for example with customers. The template was specified to include all the test cases within the specified filter search. Every test case would be printed fully to the pdf in an ascending reference number order. Only field that needs to be excluded is the description field at test case level, because for example for PCU internal tests it holds the flow diagram picture and those pictures have different sizes, and that can make the export messy. That is because the picture size needs to be predefined. The description field for issue level is going to be included, because it holds information related to test cases under the issue. Appendix 1 is demonstrating the appearance of the template for the excitation breaker status management test case. Export can be divided by issue level or without any page break, how the user wants. Signature page will be the last page of the document after all the test cases to validate that testing protocol was successfully tested.

During the thesis work FAT, HAT and SAT protocols were not implemented to JIRA. But it was noted that these protocols could be implemented, and it would bring some benefits. The major limitation of using JIRA is the fact that internet access needs to be available to utilize JIRA. This is not a problem while doing FAT testing for example or any testing done in a laboratory where proper connection to internet is available. But especially during HAT it is major issue. Because during commissioning phase usually there is no internet access on board a vessel or it is very faint and not stable. It is because the ships walls block the mobile connection in the areas ABB usually works and the ships Wi-Fi is not available yet. For HAT phase it would be very useful to utilize JIRA, because when tests are done by using the platform, people in the office could also easily follow the progress on site. In normal bases now separate reports are done or meetings held to share the information about the progress. This is because during HAT phase there are multiple separate test protocols to be done meaning there is more testing to be done and because finalizing the HAT protocols marks the mail stone that system is ready for the seatrial from ABB side. Easy follow up could be beneficial for project personnel. During the seatrial and SAT testing ships Wi-Fi is online, and it usually works in a level that could allow the usage and access to JIRA.

During the official testing phases the signing of the documents is a key thing to show, that the system or equipment is accepted. JIRA enables the usage of fully electronic test protocol management. After the protocol is finished, it is possible to export the test protocols from JIRA to pdf document with specified signing fields at the end of it in which the protocol can be signed with some pdf editor tool by the participants. This mitigates the need for big amount of paperwork, when the need to print the documents for the signing and then scanning back to electronic form is not necessary while the whole process could be done with computer. The full export of a whole protocol would then include x amount of appendix 1 like pages, the signature page, official ABB cover with table of content and revision page. Fully handled testing with signing also in JIRA is not possible in a suitable way.

6 Conclusions

At the end this thesis project constructed 2 different types of test protocols in size, and that was good for understanding how the JIRA should be utilized. That way it was possible to analyse how JIRA copes with vast test protocols and with normal size protocols and that the best structure is achieved, when epic level is left out. Using JIRA for creating and managing the test protocols was easy in most of the levels. For new user, only some advanced searching for example can require some coding skills and understanding of JQL language before mastering the platform in a sufficient way.

During the thesis work a question came up, if this platform could be implemented in all the test phases. But JIRA needs the internet and with normal tools JIRA doesn’t support local offline usage, which is one of the major flaws of otherwise good platform. Local offline operation would enable JIRA to be used without internet connection and then when connected to internet again, synchronize the data with JIRA database. This means that JIRA could be used for all the testing phases in the future, but not right now. This kind of offline add-on could be possible, and ABB has already studied the possibility in the past.

Another outcome of the project was, that PCU software was gone through once again a bit more thoroughly than usual. In this way it was evaluated, and some things were discussed and thought again. At the same time. the drive HIL protocol forced writer to think deeper the system behaviour, testing possibilities and limitations. Even when testing is done in simulated environment, it has limitation too. Like in what level the simulated environment is constructed, to understand what signals faults for example can be reasonably tested or tested at all.

Conclusion is that work done in this thesis project was a good start for the journey to the modern age of testing management and propulsion drive system testing in general. For the follow-up and actions to do in the future ABB Marine could evaluate the offline tool possibilities in general for JIRA users and after implementing the tool, get full experience of JIRA based testing management.

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Appendix 1. JIRA export test case template example.

2. Manage excitation breaker state

Reference number	Testing person	Testing date
13.1.5.4	Janne Holla	26/05/2023

2.1. Manage excitation breaker state

2.1.1. Preconditions

System is in normal state and ready to start. Both excitation breakers are closed. Drive A is the master drive.

2.1.2. Expected results

System reacts to lost redundancy and generates alarms and interlocks.

2.1.3. Procedure

☐ Check that excitation breaker states are both closed.
☐ A drive is master, simulate open A drive excitation breaker. Start interlock request.
☐ Simulate A drive excitation breaker closed, no start interlock.
☐ Simulate B drive excitation breaker open, alarm for lost redundancy.