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Experiences from Hardware-in-the-loop (HIL) Testing of Dynamic Positioning and Power Management Systems

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ABSTRACT

The complexity of control systems on offshore ships and rigs is rapidly increasing, and the correct operation of these systems is becoming even more critical for the safe and efficient operation of the vessels. The cost and risk related to incidents and losses due to problems involving control system software, hardware and operators errors are of significant concern for vendors, yards, ship owners, contractors, class societies and oil companies. HIL simulator testing of control systems on ships and rigs has been commercially available since 2004 bringing this technology from aviation and automotive industries into the offshore and maritime industries. The main idea is enhanced system verification using advanced simulators capable of simulating vessel response with its installed systems and equipment for a wide range of operational conditions and single and multiple failure modes in order to verify correct functionality and performance. In particular, redundancy, alarm and failure handling functions of the systems can be tested in detail. The experience from testing of a ten-fold offshore service and construction vessels has proven that Hardware-in-the-loop (HIL) simulator testing provides a significant more in-depth and cost-effective testing compared to conventional test methods. HIL testing contributes to reduced risk for unwanted surprises due to design flaws and errors that eventually lead to delayed delivery of the vessel. In ordinary operations HIL testing contributes to improved safety and reduced number of incidents that lead to expensive down time and vessel off-hire costs. HIL testing is organized such that extensive testing is done early in the design and building process, when the cost implications for finding and correcting errors are small. Later in the building process testing of systems integration is provided.

INTRODUCTION

Hardware-in-the-loop (HIL) simulation is a technology for testing of control system software and hardware that is widely used and well proved in the automotive and aerospace industries. Now, it has been recently introduced and adapted to the maritime and offshore industries for independent testing of safety- and mission-critical control systems on advanced offshore vessels, such as dynamic positioning systems (DP) and power management systems (PMS). The HIL simulator technology must accommodate the requirements for the various vessels with corresponding

Return to Content Page

configuration and customization reflected in the onboard systems, equipment, and control systems.

A HIL simulator test setup involves a real-time dynamic simulator that simulates all signals to, and receives all command signals from, the control system being the test target. For testing of a DP computer control system this means that the HIL simulator will simulate the vessel motion in response to thruster forces commanded by the DP system in addition to wind, wave and current loads. In addition, it must simulate nomal and faulty behaviour of the sensors, position reference systems, power plant, and relevant equipment involved in the marine operations such as hawsers, risers, and mooring lines. The interface between the HIL simulator and the target control system may be the existing signal interface (hardwired analog and digital signal, network protocols, bus protocols etc.) or a dedicated network or bus HIL simulator interface built into the test target in order to facilitate safe and efficient interfacing. Examples of HIL simulator setups for testing of Power Management Systems are given in Figures 1 and 2. Further information can also be found in [2], [3] and [9].

The main motivation for introducing HIL simulator testing to the offshore and maritime industry is due to its potential for increased safety and reduced cost. The objective is to test the control systems earlier, broader and deeper than today’s practice. Earlier testing means that the systems will be more ready when installed on the vessel, leading to faster commissioning time with less risk. Since HIL simulation allows almost any scenario to be realistically simulated well before the vessel is ready for its full scale sea trial program, there will be less surprises during the expensive full scale trials. This means that there will be significant cost savings. Deeper and broader testing means that the control system is tested by simulation for more failure modes, more operational modes, and more environmental and weather conditions. In addition, known failure scenarios or series of events that have been experiences can be simulated. This leads to increased operational availability, less incidents, and less off-hire.

HIL testing of dynamic positioning (DP) systems was first demonstrated on the DP class 2 offshore service vessel Viking Poseidon in 2004. Since then a number of new buildings and upgrades involving HIL testing of DP systems have been completed. In 2006 HIL testing of power management systems (PMS) was developed and implemented on several new building projects.

THE PRESENT MARITIME CONTROL SYSTEM TEST AND APPROVAL REGIME

The present test and approval regime for control systems in the maritime and offshore industry typically consists of the following activities and milestones:

- Factory Acceptance Testing (FAT). The control system is powered up and configured at the site of the manufacturer. In some cases the FAT may involve a degree of integration testing when several systems (possibly from different manufacturers) are interconnected and tested simultaneously. The equipment manufacturer normally develops an FAT program that is approved by the classification society, who is attending and approving the FAT together with the ship yard and ship owner. Conventionally, for most control systems up to today the FAT is focusing on signal interfaces and functional design, but not on testing of functionality.

- Commissioning testing and Customer Acceptance Test (CAT). Throughout the construction of the vessel the different systems and interfaces are tested as they are commissioned. As soon as the commissioning of the different systems are completed, the CAT is the key milestone involving the different parties. It usually involves full scale tests.
- For advanced vessels with redundancy requirements, such as DP equipment class 2 or 3, it is a requirement of IMO and classification societies that a Failure Mode and Effect Analysis (FMEA) is made for the vessel, see ref [5]. The FMEA involves proving trials that for DP class 2 systems shall demonstrate that a single point failure in any active component in the system does not lead to loss of position. For DP class 3 systems there are additional requirements such that failures on passive components, including fire and flooding of a single compartment, shall not lead to loss of position. The DP system FMEA proving trials are normally carried out during sea trials together with the DP system CAT and class approval. This is normally one of the last activities in a new build program since all important systems needs to be fully operational and individually tested and approved before FMEA proving trials commence.

IMO is recommending ship owners to carry out annual DP trials, see reference [5], in order to demonstrate that the FMEA is still valid, i.e. has not been invalidated by degraded or worn equipment, maintenance, or changes in equipment and control system hardware and software. Classification of the vessel is also renewed periodically, e.g. every 5 years.

Additionally, for major equipment or software upgrades or retrofits it may be considered necessary to carry out FAT, commissioning testing, CAT and new FMEA trials.

LIMITATIONS OF THE PRESENT TEST REGIME AND BENEFITS OF HIL TESTING

Although the present test regime involves many test activities and parties, it is clear that there are limitations and possibilities for improvements with respect to depth, test coverage, and efficiency, see reference [1] for a review.

In particular, while FMEA is well suited to analyze equipment and hardware redundancy, it is not a suitable tool for analysis and testing of software and functionality [4]. While equipment and hardware may fail unexpectedly and randomly due to degradation, wear, stress and so on, it is clear that software does not wear or age. On the other hand, software functions may contain hidden errors that cannot be observed or detected until particular conditions arise. Such conditions may be rare, but critical, and may be conditions such as handling of equipment degradation or failure in combination with certain operational modes, conditions or operator input.

An FMEA identifies components and systems that may fail, but does usually not go into depth to analyze all the different ways each component or system may fail. FMEA trials are usually conducted by tripping equipment or disconnecting power or signal cables to simulate a circuit break due to practical reasons. On the other hand, it is widely acknowledged that advanced equipment, such as DGPS receivers, electric thrusters, diesel generators, and computer networks, may fail in much more intricate and less easily identifiable manners.

One area of concern is common mode failures, where two or more apparently independent systems may fail simultaneously or sequentially due to one common cause. Well known examples are satellite failures in the GPS system when using two or more DGPS receivers, certain load sharing systems in electric power plants, and cooling of equipment located together or on the same cooling circuit. Control system software is one particular source of several units failing simultaneously. Even if controller and I/O unit hardware are duplicated or tripled in a redundant control system, it is common practice that the redundant controllers run exactly the same software. Hence, they may fail simultaneously in the same way. Moreover, the correct handling of failures occurring in equipment such as sensors, thrusters, and generators, is usually a software based function. This means that it is not sufficient to have redundant equipment standby unless the control software is able to correctly detect, identify, alarm, and isolate the failure. It is fair to say that in a system with redundant equipment, the weakest links are expected to be the system that integrates them, that is software, computer networks, power distribution and certain auxiliaries such as cooling.

HIL testing makes computer control sofware testing more powerful and efficient due to its ability to excitation of the relevant types of failure modes that exist in a computer-controlled system,

- Realistic operational scenarios can be simulated with a HIL simulator connected to the target control system in order to verify the functionality of the control system under different operational modes and conditions, in order to verify that there are no hidden failure in the control system software that are triggered by changes in operational conditions or operator input.
- Failure scenarios can be simulated in order to verify failure detection, identification, alarm and isolation functionality of the software, again under different operational modes and conditions, to ensure that equipment failures can be detected and isolated, that alarms are presented, and that the system switches to a redundant component or function according to the redundancy requirements of the system. HIL simulation allows complex failures such as signal noise, wild points, sensor signal drift, fail-to-maximum, freeze, increased network load, etc. to be reconstructed.

For ships in operation the HIL technology can be used to verify major software and hardware upgrades before they are installed or the accumulated effect of several smaller updates and modifications in periodic or annual tests.

The human aspects are important for safe and efficient operation of advanced control systems. HIL simulation technology allows testing to be combined with the development and verification of operational procedures and operator training, ensuring that results of the HIL testing and experiences are taken case of in operations and even to use the simulator as a tool in the operational phase of the vessel for further operator training, with new failure scenarios added over time.

HIL TESTING OF POWER MANAGEMENT SYSTEMS

A Power Management System (PMS) is a vital component of a vessel with redundant diesel electric propulsion, such as most DP class 2 or 3 offshore vessels and other vessels such as cruise vessel, passenger ferries, and certain tankers. The main objective of the PMS is to ensure that stable power supply is continuously available, i.e. blackout prevention. This means that no single point failure in the power plant will have consequences beyond the worst case single point failure chosen by design, which may typically be short circuit in a main switchboard when operating in a two-split configuration leading to loss of half of the power generation capacity and half of the thruster capacity. In order to achieve this, the PMS functionality may be distributed in several control units such as:

- Switchboard mounted centralized PMS computer system
- Frequency converters / variable speed drives with load reduction functions
- Generator protection systems and relays
- Marine automation system

Typical functionality found in the centralized PMS software may be

- Load sharing (active and reactive power)
- Load dependent start / stop
- Mode control
- Start of standby generator on fault
- Power reservation
- Heavy consumer control
- Blackout prevention
- Blackout restoration
- Power plant monitoring
- Integration with marine automation system
- Detection, identification, and isolation of failure modes in power generation, distribution, and consumers
- Detection, identification, and isolation of failure modes in sensors, relays, feedback and command signals
- Detection, identification, and isolation of failure modes in computers, operator stations, I/O equipment and network

Using a HIL simulator of the power generation, distribution and consumers, it is straightforward to set up scenarios in order to verify these functions. In more detail for failure mode handling, the following common scenarios can be simulated conveniently with a HIL simulator:

- Pre-warning from diesel engines
- Shutdown of diesel engines
- Short-circuit of one switchboard
- Unavailable diesel engine
- Locked governor – fixed power
- Loss of fuel supply to one diesel engine
- Full throttle to one diesel engine
- Failure in load sharing line of engine governors
- Reduced max power from engine
- Loss of generator excitation
- Full generator excitation
- Deviating generator excitation
- Protection trip of generator
- Protection trip of bus-tie
- Generator synchronization failure
- Generator circuit breaker not following command

- Bus-tie synchronization failure
- Bus-tie circuit breaker not following command
- Partial blackout
- Blackout
- Over / under bus voltage
- Over / under bus frequency
- Protection trip of consumers
- Failure of power reduction function of propulsion/thruster drives

A typical HIL simulator setup is illustrated in Figure 1.

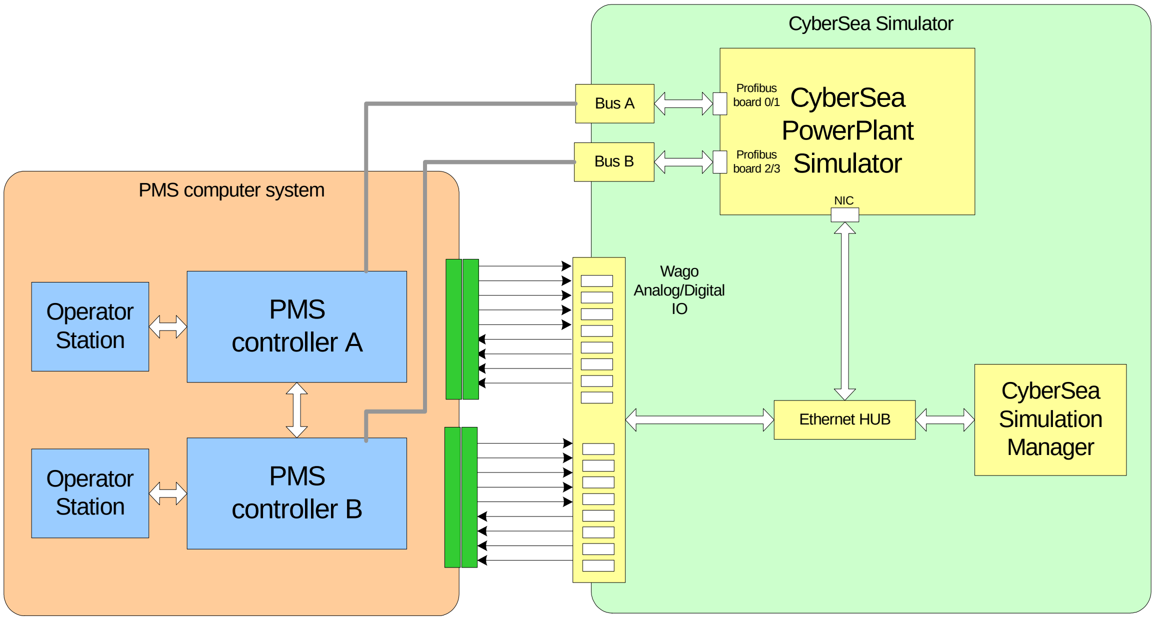

Figure 1: HIL simulator test setup with a CyberSea Power Plant simulator interfaced to a Power Management System.

HIL simulator technology may in principle be applied for testing of all control units, but our focus have been to apply it for testing of the switchboard mounted centralized PMS functionality since this is considered the most apparent and valuable application. Typical functionality that are not tested with such a HIL simulator setup may be:

- Wiring in switchboard
- Protection relay functionality
- Protection relay settings and selectivity
- Power system performance such as voltage stability due to the Automatic Voltage Regulator (AVR) tuning
- Frequency stability due to governor tuning
- Variable speed thruster drive controller stability and performance
- Performance of load reduction function in drives. A HIL test verifies that correct load reduction signals are send from PMS, but not that these signals actually are used correctly by the thruster drive.

Technology for HIL testing of the above mentioned functions is certainly viable, see reference [7] and [8]. These functions may, however, be practically tested with the power plant operational.

In order to support full scale testing with the control system operational, another type of HIL simulator known as an FMEA simulator is available. The objective of the FMEA simulator is to provide a possibility to manipulate control signals flowing between the power plant and the PMS, see Figure 2. Normally this means that the power plant and PMS operates as normal, but it gives us the possibility to simulate the effect of failures by manipulating signals.

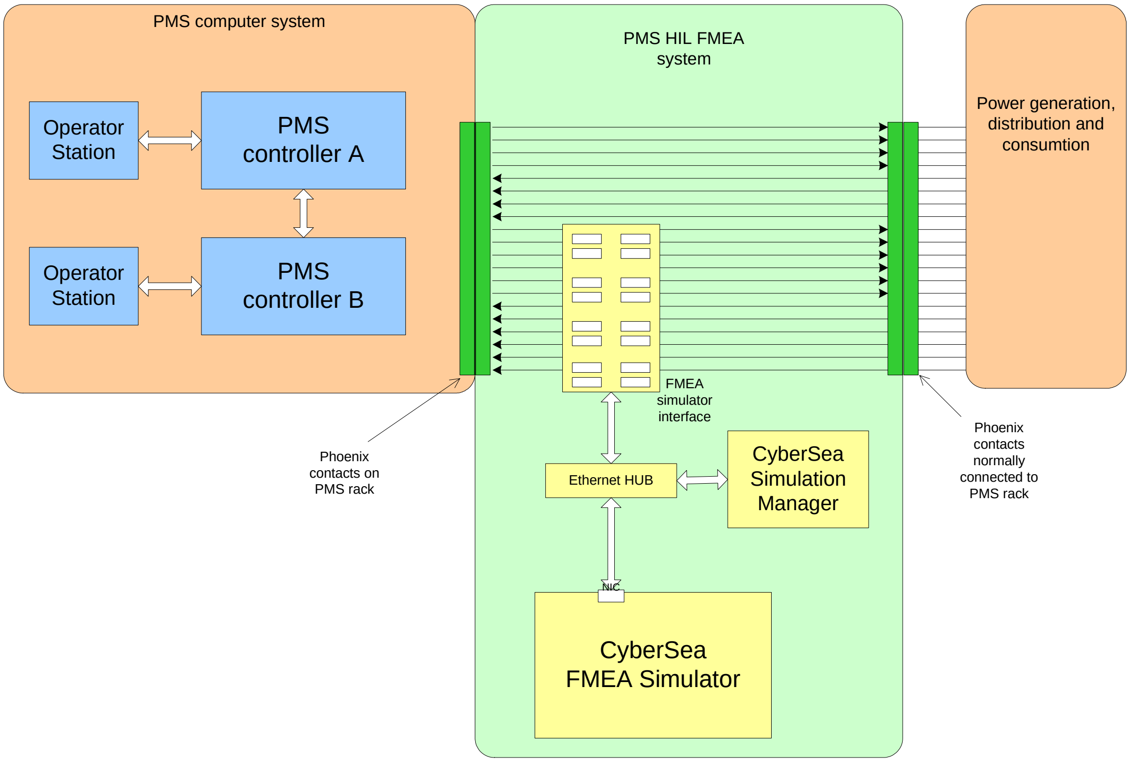

Figure 2: HIL simulator test setup with a CyberSea FMEA Simulator interfaced between the Power Plant and the Power Management System.

One example of a scenario that can be easily simulated with such an FMEA simulator is testing of blackout restoration after bus short circuit by simulating short circuit on one bus by simultaneously:

- Tripping all generator circuit breakers on the bus
- Setting short circuit alarm on the above mentioned circuit breakers
- Tripping bus-tie breaker, if operating with closed bus-tie normally

HIL TESTING OF DYNAMIC POSITIONING SYSTEMS

A DP system consists of a positioning control system (again consisting of a DP computer system, and sensors and position reference systems), a thruster system, and a power system.

At a factory test of the DP, only the DP computer system is operative and is the natural HIL test target. A significant part of the test scope may be completed during the FAT, since there is usually most time available for extensive testing. At FAT the focus is on testing of the following aspects:

- Basic hardware and software configuration testing, including DP computers, and operator stations.
- I/O system hardware and software interface, failure handling, barriers to data transmission buffer and interrupt overload
- DP and joystick basic modes / functions and mode switches, including thrust allocation modes, forbidden sectors, rotation points and thruster configuration
- Special functions related to marine operations such as pipelay, heavy lift, drilling, shuttle tanker offshore offloading, survey etc.
- Power and propulsion system configuration. Verification of the correct devices, their location, ratings, that each device can be selected and deselected without reducing the DP performance. Verification of consequence analysis, power limitation and blackout prevention functions.
- Position reference and sensor system configuration. Verification of the correct devices, their location, that each device can be selected and deselected without reducing the DP performance.
- Alarms and warnings, verification that all simulated single point failures give the expected alarms or warnings, and that correct handling in the DP computer system is made in terms of disabling the faulty device and automatically switching to a correct redundant device if available. A typical test scope may include hundreds of single point failure tests (involving sensors, position reference systems, thrusters, power system etc.).
- DP controller tuning, including gain settings, state estimator performance (model / Kalman filter), feed-forward from wind sensor, dead reckoning performance, wave filtering performance, dynamic capability verification, extreme weather performance. Such extensive testing may give useful indications of performance that should contribute to reducing the time needed for tuning and testing during sea trials.
- Multiple failures testing, and testing of relevant reported incidents.

At dock, quay and sea trials the test scope should be limited to focus more on the items that have been influenced by the installation and commissioning, i.e. re-tuned, upgraded, or re-configured after FAT. In addition, the focus is moved more towards testing of the integrated DP system, rather that the isolated DP computer system. Additional items to be tested include:

- Testing of integrated network functionality and barriers. This may include network storm testing, monitoring of traffic, robustness to partial loss of network and messages etc.
- Testing of mode switch between DP, joystick, manual thruster control, and transfer of command between operator stations.

Further information on HIL testing of dynamic positioning systems can be found in [2].

EXPERIENCES FROM HIL TEST PROJECTS

In order to support independent HIL testing, DNV has launched a Standard for Certification of HIL testing, see reference [6]. This standard describes the process and responsibilities of the parties involved. It defines the following key roles:

- HIL supplier, the independent party that supplies the HIL test program and the HIL simulator tools. In order to secure high integrity and value of the testing, the standard requires that the company involved must be independent of other parties such as the equipment suppliers, ship yard and ship owners with respect to technology and ownership.

- HIL test organization, the party that performs the HIL testing and reports the results. This could be a different company than the HIL supplier. There are no requirements for independence.
- HIL test verification, a third party that witnesses and approves the HIL testing and the HIL test package comprising the tools and documentation. This could be a classification society.

Furthermore, the standard provides information and recommendations for the HIL simulator tools, test coverage, and requirements for verification and validation of the HIL testing.

Marine Cybernetics has completed ten-folds of HIL test activities on DP and PMS. The following experiences are noticed:

- Comprehensive test coverage requires typically one week of testing at FAT.
- In order to be well prepared for the final sea trials, it is very useful with a follow-up testing at dock or quay focusing directly on closing of findings after FAT, new or changed functionality, and integration testing. It is noticeable that by coordinating the HIL testing at dock and quay closely with the commissioning of the vendors and ship yard, the HIL testing is not on the critical path of the project and does not increase commissioning time.
- Due to extensive testing at factory, dock and quay, there are usually few new findings at the sea trials. The findings that have been observed are typically due to hardware problems and integrated functionality that requires full scale testing.
- Typical number of finding at a factory test may range from 5 to 25 critical findings, and up to 25 less critical findings, for each control system on a vessel. Some of these early findings may have been found later also without HIL testing, we expect, but they would have caused higher cost and delay. However, some of the findings made with HIL testing would not have been found without HIL testing, simply because the test scenarios are not commonly done within the traditional test regime for various reasons such as risk or cost, or because it would be impractical.
- Sea trials with DP HIL testing take 16 to 24 hours, and the number of findings at dock, quay and sea trials are in most cases less than at factory test. Typically, we have found from 5 to 20 critical findings for each control system on a vessel during these activities, and up to 20 less critical findings.
- In some cases the findings from HIL testing are easy to classify. Sometimes, they lead to questions regarding design philosophy and operational philosophy, and the solution may be clarification of these rather than changes to the control system. In some cases there are design weaknesses in the vessel that cannot be changed, and one benefit of HIL testing is that these weaknesses are exposed and demonstrated to the operators of the vessel by their participation in the testing, and in the documentation. Recommendations for operational procedures and operator training typically results from HIL testing.
- Many findings are due to configuration of the systems, and integration between equipment of different types. This means that it is necessary to test the control systems on each individual vessel also if the control systems have the same software basis release.
- For series of “sister” vessels with “the same” control system software the preferred test regime is to have a combination of a core test scope with variations due to a rotational test scope. In this way the testing benefits all vessels and efficient use of test time is

made. Since sister vessels are delivered over some time and there may be smaller or larger customizations, or intended or unintended differences in each vessel, the control system software tend to differ to some extent, especially over time.

In conclusion, this leads to the following key benefits of HIL testing:

- Increased safety results from fewer incidents during operation since hidden errors in control system hardware and software can be eliminated. For oil companies, contractors and vessel owners this is a great benefit as incidents is considered a major concern that may have consequences for safety, environment and cost due to delays in offshore marine operations.
- Reduced cost of vessel construction, upgrade and maintenance because at one side HIL testing reduces the need for expensive full scale sea trials, and on the other side it allows to set up simulated scenarios that are too expensive or risky to actually test in full scale. The need for potentially destructive testing is greatly reduced with HIL simulator testing. For the ship yard and ship owner this means that the control systems are tested earlier, deeper and with greater depth.
- Software upgrades and related equipment modifications or changes on vessels in operation are a serious concern of the industry. HIL testing offers a tool for efficient periodic testing or testing before or during upgrades or retrofits, since a large part of the testing can be done while in dock, at quay, or in transit.

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