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Design

Experiences with HIL Simulator Testing of Power Management Systems

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.

Abstract

The successful operation of DP vessels depends more and more on advanced integrated functionality of software-based control systems. Consequently, software related problems, often in conjunction with hardware and/or human errors, may lead to vessel construction delays, downtime during operation, reduced income for clients, increased cost, and reduced safety. In order to reduce these risks, independent third party Hardware-in-the-loop (HIL) simulator testing has recently been applied for extensive software testing and verification of dynamic positioning systems on more than 40 offshore DP vessels. In this paper we report on experiences from HIL testing of Power Management Systems (PMS) on DP drilling, supply, anchor handling and construction vessels.

The main idea is testing and verification of the PMS software using a vessel specific integrated simulator capable of simulating the dynamic response of the power generation, distribution, main consumers, and other relevant equipment. The simulator is connected via network or bus interfaces to the PMS such that all relevant feedback and command signals are simulated, typically in the range 1000-2000 for a drilling unit and somewhat less for supply and construction vessels. In order to achieve the objective, the simulator is capable of simulating a wide range of realistic scenarios defined by operational modes, operational tasks and single and multiple failure modes in order to verify correct functionality and performance during normal, abnormal and faulty conditions. This includes verification of interfaces and integrated functionality between DP computer system, Power Management System, and Thruster Control Systems.

In the DP vessels considered, the Power Management Systems were parts of Integrated Automation Systems from various makers, and contained the high level power management functionality. In addition to testing the software functionality of the PMS, the interface and integration with associated power control functionality in thruster and drilling drives, protection relays, governors, AVRs and DP load limiting functions were targeted by the testing.

HIL testing of PMS may be conducted in several phases of a new-building or retrofit, where the first phase is usually a factory test. By using HIL simulator technology a virtual sea trial with thorough testing is conducted before the vessel is built. The objective is fully functional and failure testing of the software before the commissioning and integration starts, ensuring that the software will be more finalized and ready for commissioning. Follow-up system and integration testing is normally conducted during commissioning, and a final verification of the integrated functionality is conduced onboard the vessel at the end of commissioning.

INTRODUCTION

HIL Testing

HIL (hardware-in-the-loop) simulator technology has been adopted from the aviation and automotive industries into the offshore and maritime industries. The main idea is testing and verification of control system software using advanced integrated simulators capable of simulating the dynamic response of the vessel with its power plant, thrusters, and other relevant equipment [1, 2]. Such a simulator operates in closed-loop, interfacing with the control system hardware running the control system software being the main test target. The simulations may be performed for a wide range of realistic scenarios defined by weather conditions, operational modes, operational tasks, and single and multiple failure modes in order to verify correct functionality and performance during normal, abnormal, and faulty conditions. This includes verification of interfaces and integrated functionality between DP control system, Power Management System, and Thruster Control Systems. For drilling vessels also the drilling package is considered.

HIL testing contributes to secure the quality and integrity of control system and the vessel, because it detects:

- Erroneous configuration parameters
- Design flaws in the software, including building an operational philosophy
- Sleeping and hidden software errors
- Missing functionality and “gaps” across interfaces and system integration
- Errors in documentation

Some of these software errors could possibly have been detected by other test methods late in the commissioning process, but then at the cost of delays in the vessel delivery. However, many of the software errors found by HIL would normally be hidden bugs, and first be detected or triggered during operation, and thereby possibly lead to severe consequences like incidents, vessel downtime, increased cost, and reduced safety.

HIL Test Scope

According to [3] a DP system is comprised of a positioning control system, a power generation and distribution system, and a thruster system. Further, the DP control system is comprised of the DP computer system, the position reference systems, and sensors. The DP vessel HIL test scope and test activities are typically structured similarly:

- DP control system is the test target for DP-HIL.
- Power Management System is the test target for PMS-HIL.
- SPT-HIL (Steering, Propulsion, and Thruster HIL) focuses on the steering, propulsion and thruster computer control systems.

Third party DP-HIL and PMS-HIL testing were introduced in 2004 and 2006, [1, 2], whereas a first SPT-HIL pilot project was conducted in 2008 [4].

HIL Simulator Technology

The main objective of a PMS is to ensure that stable power supply is continuously available and distributed to the consumers. This means that no single point failure in the power plant shall have consequences beyond the worst case single point failure chosen by design. In order to achieve this, the PMS functionality may be distributed in several control units such as:

- Switchboard mounted centralized PMS control system.
- Distributed load reduction functions in variable speed drives, drilling control system, and others.
- Generator protection systems and protection relays.

- DP and thruster control systems with load limitation functions.

Examples of 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
- Load reduction
- Blackout restoration
- Power plant and diesel engine monitoring
- Detection, identification, and isolation of failure modes

Using a HIL power plant simulator emulating the dynamic response 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 dynamic effects of the following common scenarios can be simulated conveniently with a HIL simulator under any load conditions and in the relevant modes of operation:

- 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

Several of the above mentioned scenarios are usually not tested as part of conventional live testing procedures, simply because of the risk involved. A HIL simulator opens up the possibility for thorough testing of any functions, within the limitations of the modeling accuracy, leading to a significantly increased test coverage compared to conventional testing. The failure conditions marked with * in the list above are considered difficult or risky to test with traditional methods without HIL testing.

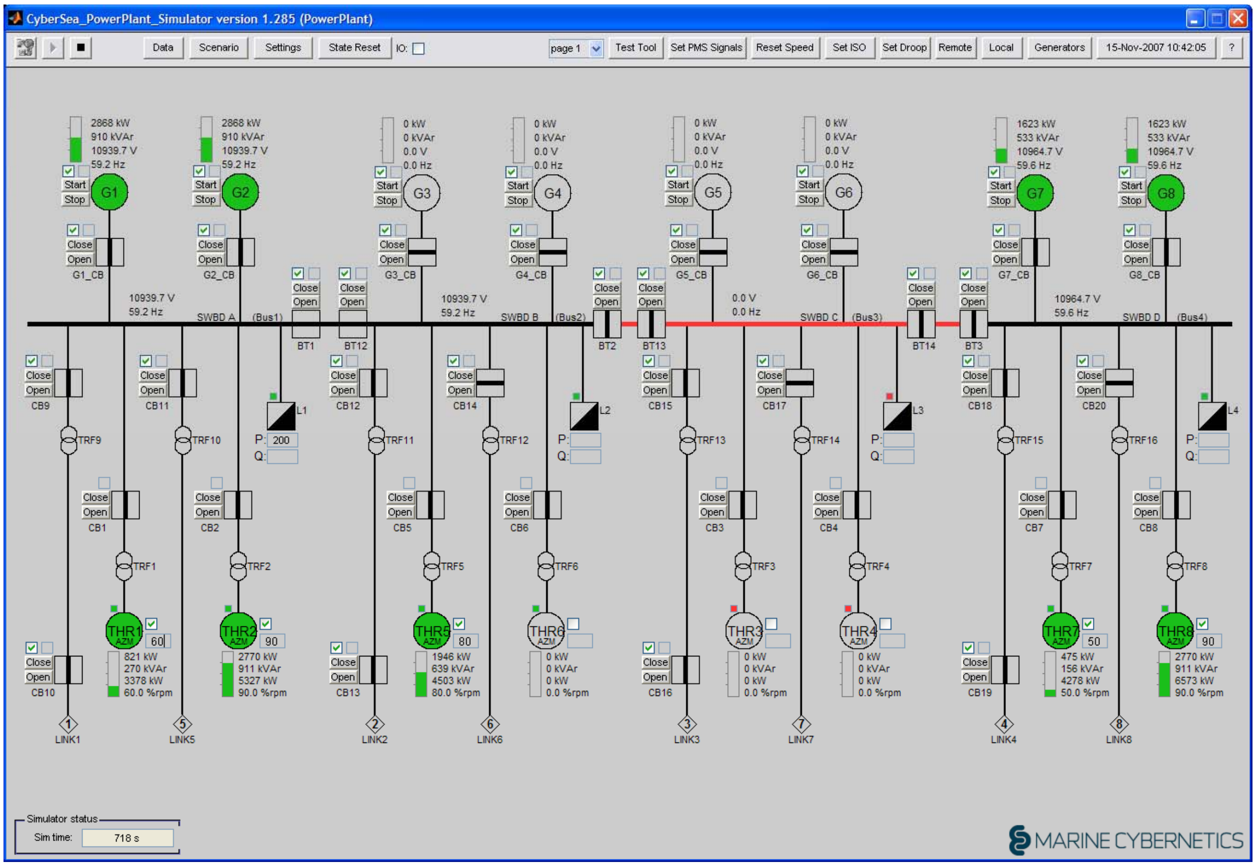

Figure 1: Example of a graphical user interface of a CyberSea Power Plant simulator used to set up scenarios and conduct PMS HIL testing. All key electric parameters such as voltage, frequency, active and reactive power are simulated dynamically in real time at all relevant points of the electric network with resolution of about 100 ms. The dynamic response of electric parameters can be monitored, local control panel functions can be emulated, dynamic loads can be defined and a wide range of failure conditions invoked. The power plant simulator can operate in closed loop taking commands from the PMS and communicating instrument data tags to the PMS.

HIL simulator technology may in principle be applied for testing of all power plant control units, but the focus so far have been to apply it for testing of the switchboard mounted centralized PMS functionality since this is considered the most viable and valuable application.

Typical functionality that is not tested with such a HIL simulator setup may be:

- Wiring in switchboard
- Protection relay functionality, 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.

The interface and integration with some of these functions can still be thoroughly tested since the PMS HIL simulator will simulate the protection relays, governors, AVRs and frequency converters. As an example, a PMS HIL test verifies that correct load reduction signals are sent from PMS, but not that these signals actually are used correctly by the thruster drive. On the other hand, a HIL test can verify how the PMS deals with an abnormal failure situation when the simulated thruster drives **do not** reduce load according to command, or inconsistent command and feedback signals are interfaced between the PMS and thruster drive.

Uncertainty in equipment parameters and lack of documentation will in many cases limit the model fidelity when simulating the functions of governors, AVRs, drives and protection relays. So far our experience has been to simulate the main functionality, dynamics and relevant failure modes of these components rather than very accurate dynamic responses. Still, this has proven to be sufficient to detect flaws, missing functionality and erroneous software implementation in the high level PMS software logic due to unclear functional interface and integration between the PMS and the above mentioned functions.

Test activities

A HIL project for a new-building or retrofit typically consists of at least two phases:

- *Software testing* focuses on the software functions in the computer control systems. It is recommended to be conducted in connection with the vendor's Factory Acceptance Test (FAT), but may also be performed on replica hardware or in a lab setup like a SW FAT (HIL Test at Factory). The objective is to complete a systematic full functional and failure testing of the software before the commissioning and integration starts. This will benefit both the ship yard and equipment suppliers, since the software will be more finalized and ready for commissioning, reducing the risk for delays and undesired "quick fixes". It does, however, require that all parties make early preparations such that fairly complete functional design specifications, operational philosophy and interface lists are available before testing starts. This is recognized as a challenge to the industry for complex vessels.
- *Integration and validation testing* focuses on integration of the software on its actual hardware platform and integration between the various systems. The majority of integration tests are recommended to be conducted in dock or quayside (HIL Test at Dock or Test at Quay).

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

DNV has developed a Standard for Certification of HIL testing [5] that describes generic requirements for HIL testing on marine vessels, and a class notation of Enhanced System Verification based on HIL testing. The class notation is at present applicable to DP Systems (ESV-DP[HIL]) and Thruster Assisted Position Mooring Systems (ESV-TAM[HIL]).

EXPERIENCES: FINDING STATISTICS

By April 2009, 45 DP-HIL and 14 PMS-HIL projects involving several vendors, yards and owners have been fully or partly completed, comprising a total of 1013 DP-HIL and 670 PMS-HIL findings. Table 1 defines the severity grades used in categorization of the findings. Table 2 shows the distribution DP-HIL findings on test activities and severity grades, whereas Table 3 shows the corresponding PMS-HIL data. Numbers of test activities shows that test at doc and test at sea are not yet completed for all vessels. The numbers show that significant amounts of findings are found, with the largest number of findings at Test at Factory, and decreasing numbers for Test at Dock and Test at Sea/Quay. This supports the main philosophy of HIL testing: Reveal software errors earlier by deeper and broader testing when time and cost implications are small.

Table 1: Severity grade definitions

Severity grade	Definition
A	Non-conformity with rules and regulations (IMO, flag state, coastal state, class rules, etc)
B	Non-conformity with requirements (specifications, industry guidelines and standards, documentation such as functional design specifications and user manuals, or intended use)
C	Recommendations to be evaluated for improvement in design, functionality, documentation, or operational procedures

Table 2: DP-HIL findings from 45 projects

	Number of test activities	Total findings	A-findings	B-findings	C-findings
Total DP-HIL projects		1013	21%	49%	30%
Test at Factory	44	706	19%	49%	32%
Test at Dock	30	170	24%	48%	28%
Test at Sea	30	137	26%	51%	23%

Table 3: PMS-HIL findings from 14 projects

	Number of test activities	**Total findings**	**A-findings**	**B-findings**	**C-findings**
Total PMS-HIL projects		670	21%	67%	12%
Test at Factory	14	593	22%	68%	10%
Test at Dock	4	58	14%	60%	26%
Test at Quay	3	19	26%	53%	21%

Out of the 14 PMS-HIL projects, a more thorough analysis has been carried out on the findings from 4 projects. These projects constitute a representative selection of vessel types and different vendors, and yields a total of 211 findings from all test activities (Test at Factory, Test at Dock, Test at Quay).

Each finding has been categorized by the associated functionality in the PMS computer system according to Table 4 in the Appendix. Furthermore, each finding has been assigned a level of potential consequence, where the consequences are defined as follows:

- **Drift-off** - Loss of available power beyond the design criterion “worst case single point failure”, such as full blackout.
- **Operational unavailability (Non Productive Time)** – Consequences that will allow safe abortion of operation and thus not lead to drift-off, but will require downtime and maintenance before safe operation can continue.
- **Deviation from rules and regulations** – Other deviations beyond those causing immediate drift-off or operational unavailability.
- **Degraded system performance** – Consequences that allow continued safe operation, but with reduced DP capability or other performance loss.
- **Deviation from specification** – Deviation from functional design specification (FDS) and intended use, but with no immediate consequences for safety or operational availability.
- **Potential for improvement**.

Figure 2 shows the findings sorted on potential consequence, with the three least serious consequences grouped as “less serious”. Table 4 shows that errors that have the potential of serious consequences are found in several of the essential functions of the PMS.

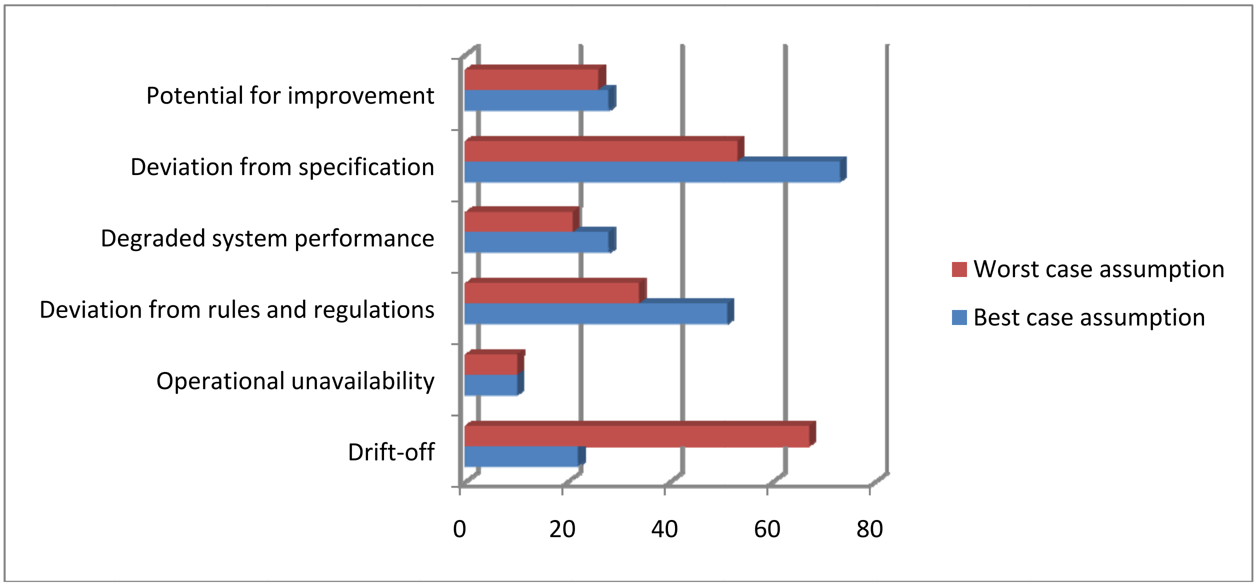

Figure 2. PMS HIL findings sorted on potential consequence. The range between best case (conservative analysis assuming no other hidden failures) and worst case (assumes possibility of other hidden failures) illustrates a level of uncertainty in the analysis due to several protection function being difficult to verify.

PMS HIL testing targets mainly the high level PMS, while functionality such as blackout prevention is often distributed on other systems and components, too, such as drives and protection relays. Often, there will be multiple barriers protecting against blackout with the PMS implementing only one or two of the barriers. One challenge is systematic and non-destructive testing of for example functions in protection relays under a wide range of operational conditions. For this reason, we have separately evaluated the consequences of failures in the high level PMS under two different assumptions:

Best case assumption (conservative estimate, no other hidden error)

- All protection functions in the switchboard work as intended according to the design and operational philosophy of the vessel.
- There are no hidden errors in the protection relays, drives, governors, AVRs, or other relevant components.
- The consequences are evaluated depending on the actual number of online generators, breaker status, bus tie status, and the loads connected during the test.
- Operators respond correctly.

Worst case assumption (possible other hidden errors)

- One or more protection functions in the switchboard fails due to a hidden error, such as:
    - Reverse power to generators.
    - Trip of breakers on over current, over voltage, under voltage, over frequency, under frequency, and similar.
    - Hardwired interlocks in switchboards.
    - Breakers do not open or close on command.
    - Standby generator or its governor, AVR or load sharing line has an error.
    - Incorrect selectivity.

- Possibly hidden errors in online generators' governors or AVRs.
- Operator errors due to missing information or incorrect user interface are considered.
- Closed bus tie operation is assumed if the design and operational philosophy of the vessel permits this mode of operation on DP 2.

The expected practical consequences are likely to be somewhere in between these two cases, depending on the design, tuning and verification of the protection functions and others, as well as the competence of operators and technical staff.

The analysis of the 14 PMS HIL test project has also classified findings according to whether they could have been found without HIL testing or not. The following statistical data illustrate the effect of HIL testing:

Could have been found without HIL:	65.6 %
Could NOT have been found without HIL:	34.3 %

The analysis is based on what are typical test scopes at Factory Acceptance Test, Customer Acceptance Test, FMEA trials and class testing when third party independent HIL testing is not conducted.

EXAMPLES OF FINDINGS

This section presents four examples of software errors that were found by HIL testing. Using traditional test methods, these findings would in the best case have been discovered late in the commissioning process, and probably not at all until an incident occurs.

DP-HIL findings

Example 1: The power calculation in the load limitation function and consequence analysis did not consider loads on the main propellers when the shaft generators were running. If this had not been discovered, the vessel would have been able to operate outside of DP class 2 without consequence analysis alarms. Furthermore, since the load limitation function in the DP would not have worked, PMS load reduction would have been initiated instead, leading to reduced DP capability or in some cases loss of position. The root cause was an erroneous configuration in the DP computer system.

Example 2: A drift-off was caused by an external power reduction of a single thruster by the PMS. The cause was found to be the DP computer system design philosophy, which failed to re-allocate thrust on the remaining thrusters, such that the available thrust capacity was not utilized.

PMS-HIL findings

Example 1: The power system was running with closed bus-tie when a governor or fuel-rack failure leading to full throttle on one diesel generator was simulated. The failure caused full load reduction on all the thrusters and negative power on the other running generators. The PMS did not open the bus-tie. If this had happened during operation, the result would have been a full blackout, since the reverse power protection relays most likely would have tripped the healthy generators. The root cause was found to be a PMS design weakness.

Example 2: Failure on one single bus frequency measurement was simulated, with no failure on the generator frequency measurements. The PMS raised the frequency set-point of all connected generators such that bus frequency was raised from 60Hz to 64.5Hz. If this had happened in operation, the result would possibly have been full (if closed bus-tie) or partial blackout due to over-frequency trip of generator breakers. It would also be difficult to synchronize and connect a new generator due to high frequency. The root cause was found to be the PMS design philosophy. This would probably not have been detected during traditional commissioning and sea trials since such a test would be difficult and potentially dangerous to carry out.

EXPERIENCES: HIL TEST PROJECT PLANNING AND EXECUTION

In order to take full advantage of the HIL technology and successfully close any findings, experience shows that careful planning of the HIL test project is of great importance. Three important topics that will be further elaborated here are:

- Logistics and availability of hardware for the software testing at various phases in the vessel construction process.
- The coordination between HIL and FMEA
- The process and responsibilities involved in closing of findings.

Where and when to test?

The installation, commissioning, and testing of an Integrated Automation System with PMS functionality in an advanced offshore vessel like a drilling or construction vessel involves logistics challenges. The introduction of HIL testing adds to these challenges since one must plan for additional test activities. In an ideal world, HIL testing could be conducted at FAT, and all findings could be fixed, verified and closed before the equipment is shipped to the yard for installation. However, this requires a tight delivery schedules and early freeze of functional design specifications and interface lists. For advanced vessels a good alternative solution has been to conduct HIL testing as part of a Software FAT at a later stage, testing the software functionality of the PMS on replica hardware in the equipment manufacturer's factory. This has the advantage that the HIL testing can be conducted independently of any hardware deliveries. On the other hand, there have been cases when test results depend on the firmware and hardware configuration, so care must be taken to ensure correct setup of the replica hardware, including software versions, firmware and full hardware and software configuration control. For functionality such as dual redundant networks there exists no good replacement for onboard testing of the installed system.

Coordination with FMEA analysis and trials

Independent analysis and testing of a DP system have traditionally been covered by FMEA analysis and FMEA proving trials [6]. The main goal of the FMEA analysis has been to identify the worst case single failure(s), and the main goal of the FMEA proving trial to validate this analysis. The main focus areas of the FMEA analysis and trials are the electrical and mechanical systems and parts of the integration between the computer control systems and the electrical and mechanical systems. However, classic FMEA cannot properly assess possible failures and errors in failure handling inside the computer control systems. We regard FMEA and HIL as complementary tools were both are needed. With both FMEA and HIL as available tools, the questions then become:

- How and when to test a given function or failure mode in the most efficient and relevant way?
- How to coordinate the testing and validation activities to improve efficiency and maximize the test coverage?

A suggested coordination of the FMEA and HIL activities is outlined in Figure 3, which divides a vessel building timeline in two: vessel construction (critical timeline) and analysis and testing (non-critical timeline). Notice that the final test activities in connection with sea trials are on the critical timeline. Data collection and preparations are common activities both for the FMEA analysis and the HIL testing, with significant overlap. This phase of the project should be used to structure the overall test scope for the vessel in the most efficient way. In general, all functions and failure modes should be tested as early as possible, when time and cost implications are lowest, leaving maybe only a minor validation activity to the sea trials. This will maximize the benefits of HIL testing.

To further coordinate the activities, the results from the FMEA analysis should be used as inputs to the HIL Software test (Test at Factory) and Integration test (Test at Dock), and the results from the HIL tests could be used in validation of the FMEA analysis.
Finally, results from the FMEA analysis and HIL tests are used as inputs to the FMEA trials and HIL Validation test (Test at Sea). The results should be both less sea trial time and wider test coverage:

- Some traditional FMEA trial tests may be performed during HIL Software test and HIL Integration test.
- No overlapping tests between HIL Validation test and FMEA trials.
- More efficient testing on sea trials by using HIL test tools.

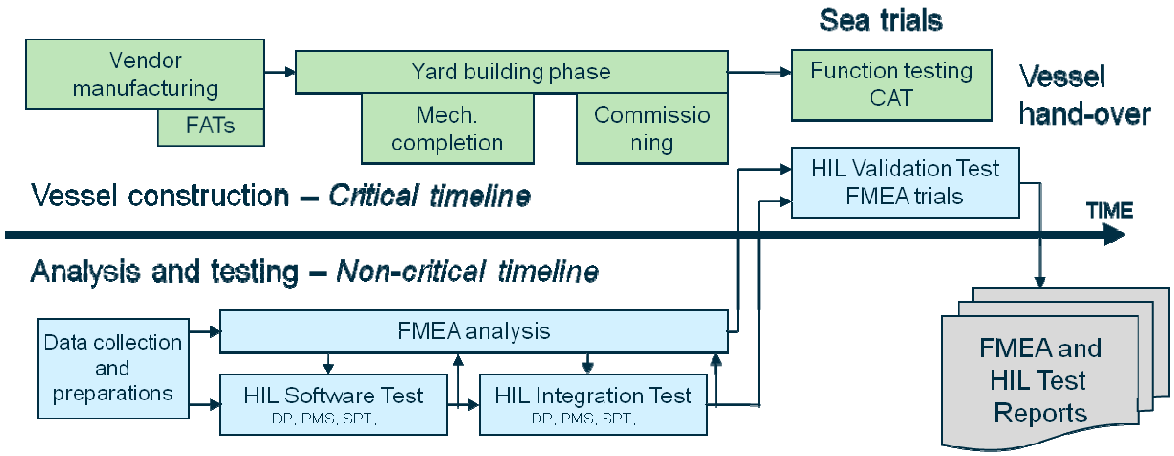

Figure 3: Coordination of HIL and FMEA activities.

When are findings closed?

Figure 4 illustrates the percentage of findings being closed during the different HIL test activities. Note that the different projects differ with respect to number of test activities and the scope at each follow-up test activity. This may be due to various objectives and constraints within the organization of the project.

HIL testing calls for a change in the way the industry works, in a direction where software specifications and the software itself is ready at an earlier stage. This is the way it works in the automotive and aerospace industries, where HIL testing is used as a tool to verify design and implementation at an early stage before full scale trials are conducted. There is no doubt that software issues are being more strongly recognized by the industry, and there appears to be a trend towards change in the right direction.

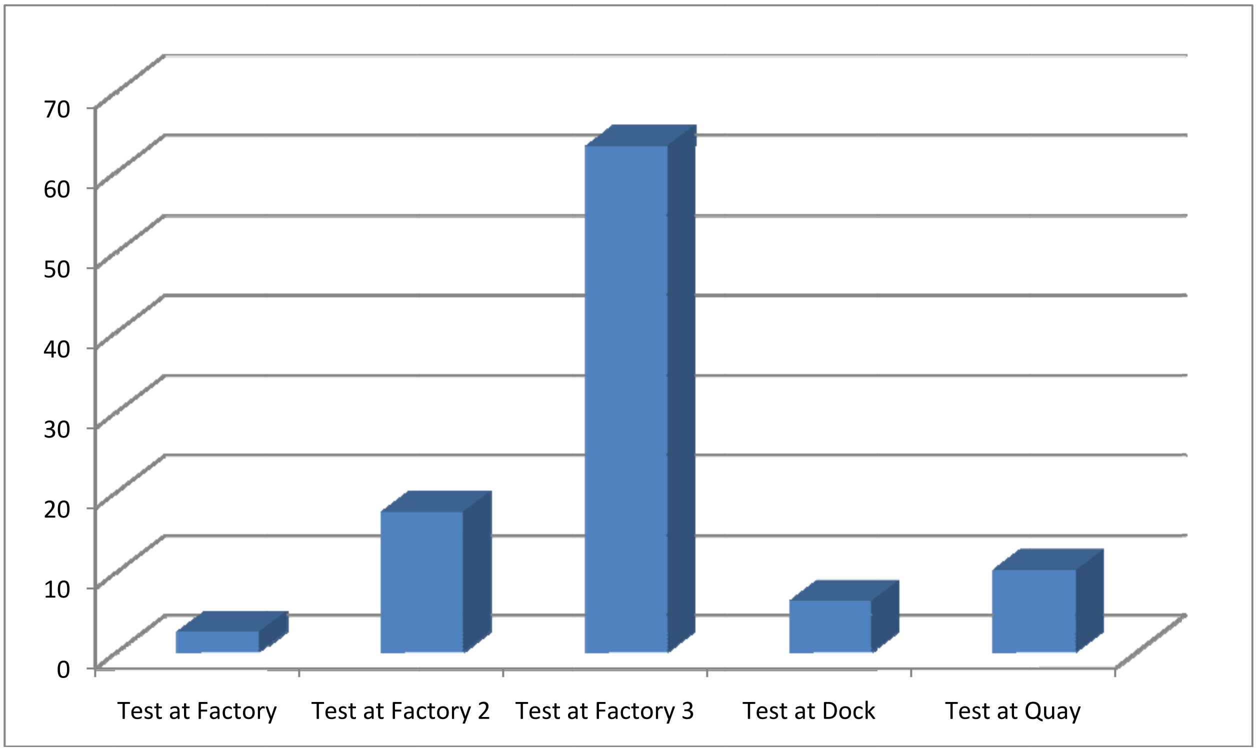

Figure 4. The diagram illustrates the percentage of findings closed at different phases in the 14 HIL test projects analyzed.

CONCLUSIONS

The analysis of project results has shown that findings in the PMS are identified and closed as a result of HIL testing, many of them being critical with potentially serious consequences. About 35% of these findings would most likely not have been found without HIL testing. Furthermore, 88% of the findings were identified already at the first test activity (typically SW FAT).

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APPENDIX

Table 4: Identified findings classified according to PMS functionality categorization and consequences if not found and corrected (best case / conservative analysis).

Function name	Drift-off	Operational unavailability	Deviation from rules and regulations	Degraded system performance	Deviation from specification	Potential for improvement	Total identified
Others	0	0	1	0	8	0	20
Automatic control	0	0	0	0	2	1	3
Semi-automatic control	0	0	0	0	0	0	0
Emergency mode	0	0	1	0	0	0	1
Max. 1/2/3… generators	0	0	1	0	1	0	2
Min. 1/2/3… generators	0	0	0	0	0	0	0
Closed bus mode	0	0	0	0	1	0	1
2/3/…-split mode	0	0	0	0	0	0	0
HMI	1	0	10	6	58	18	95
Communication with IAS	0	0	1	0	0	0	1
Load dependent start of generator sets	0	1	0	0	4	2	7
Load dependent stop of generator sets	0	0	0	2	2	0	5
Active power load sharing	2	3	0	1	1	0	8
Asymmetric active power loading of prime movers	0	0	0	0	2	0	3
Reactive power load sharing	1	0	0	0	0	0	1
Power reservation functions	0	0	0	0	3	0	3
Start interlock of heavy consumers	0	0	0	1	0	0	1
Prime mover and speed governor feedback	1	0	5	4	10	7	31
Generator and automatic voltage controller feedback	0	3	11	2	12	3	31
Circuit breaker feedback	3	1	8	10	22	16	61

Switchboard feedback	0	0	11	2	4	6	24
Synchronization controller feedback	0	0	0	0	1	0	1
VSD feedback	0	0	0	0	3	7	10
Heavy consumers feedback	0	0	0	0	0	0	0
Commands to prime mover and speed governor	1	0	3	0	3	1	8
Commands to generator and automatic voltage controller	0	0	1	0	0	0	1
Commands to circuit breakers	1	1	3	3	6	2	17
Commands to synchronization controllers	0	0	0	0	0	0	0
Commands to VSD	0	0	0	0	0	0	0
Commands to heavy consumers	0	0	0	0	0	0	0
Alarm and messaging functionality	1	0	7	1	7	11	28
Active power unbalance detection and handling	6	5	5	4	2	2	24
Reactive power unbalance detection and handling	3	3	10	0	1	1	18
Under- and overfrequency detection and handling	0	2	5	2	8	1	20
Under- and overvoltage detection and handling	1	0	8	0	3	1	13
Start of standby generator on prewarning (changeover)	0	0	0	1	6	0	7
Start of standby generator on fault	0	0	0	1	0	0	1
Start of standby generator on power distribution overload	0	0	0	0	0	0	0
Load reduction/limitation functions	5	3	1	2	3	3	20
Load shedding	0	0	0	0	0	0	0
Blackout restoration	4	0	2	5	9	4	28
Changeover of functions between controllers	0	0	1	0	0	0	1
Asymmetric load sharing abortion or override	0	0	0	0	0	0	0
Prevention against operator induced blackout	1	0	0	1	0	1	3
Power supply and UPS power to PMS	0	0	3	0	0	0	3
Power supply and UPS power to operator stations	0	0	0	0	0	0	0
Network communication	0	0	2	2	1	1	6
IO unit	0	0	0	0	0	0	0
CPU	0	0	0	0	0	1	1
Overcurrent detection and handling	0	0	1	0	0	0	1
PMS configuration	5	0	2	1	6	2	16