DYNAMIC POSITIONING CONFERENCE
October 14 - 15, 2025

LEVERAGING SINGLE-FAULT TOLERANCE TO SUPPORT BUSINESS OBJECTIVES

MODEL BASED TESTING AND SYSTEM INTEGRATION

Zachary Clark, Savin Viswanathan, Krishna Kumar Nagalingam
Kongsberg Maritime

Contents

Contents 1
1. Abstract 3
2. Executive Summary 4
3. Introduction 5
3.1. The seven pillars of DP operations and DP system integration 5
3.2. System Integration and Adherence To Autonomy, Independence, And Segregation 6
3.3. Benefits of System Integration 7
4. Verification and Validation Of Integrated Systems 8
4.1. Model Based Testing 8
4.2. MBT Literature Review 11
5. MBT workflow 11
5.1. The Roles of The System Integrator and The Simulation Manager 13
5.2. Model Development for MBT 14
6. Key Aspects of A DP Vessel Model Design 15
6.1. Vessel Hydrodynamic Model 15
6.2. DP Control System Model 16
6.3. Power System Model 17
6.4. Thruster Model Simplification/Optimization 19
6.5. Post-Failure Capability 21
7. Model Lifecycle 22
7.1. Phase 1: Concept 22
7.2. Phase 2: Detailed design 22
7.3. Phase 3: In-Service 23
7.4. Model Validation and Refinement 24
8. Case Studies 24
8.1. Case Study 1: SiL Testing on A Drillship 24
8.2. Case Study 2: MBT of Power Plant 27
8.3. Case Study 3: CSOV (Project-in-Flight) 32
8.4. Case Study 4: Tow Assist 33
9. Conclusion 35
Abbreviation / Definition 36
Acknowledgements 37
References 37

Figure 1: The seven pillars of incident free DP Operations. (1) 5
Figure 2: Block diagram of a DP vessel as a SUT. (6) 9
Figure 3: MBT Workflow....12
Figure 4: General steps in the development of a time-domain hydrodynamic model. 15
Figure 5: Virtualized control-system-visualization portal. 25
Figure 6: SiL Topology. 26
Figure 7: Typical AC power-system model in AMESIM.....27
Figure 8: Model of engines, including the efficiency, speed, and voltage-control loop. 28
Figure 9: A trend to show the Active Load Sharing between generators 1 and 3 and bus frequency. 29
Figure 10: Loss of fuel or under-fuel fault on Engine 1. 30
Figure 11: Over-fuel fault on Engine 1. 30
Figure 12 Failure of RPM pick-up on engine-1 resulting in speed-hunting. 31
Figure 13: Failure of Governor-droop control resulting in active load-sharing oscillation. 31
Figure 14: Guidance, requirement and test-documentation dependency workflow. 32
Figure 15: Pilot full-scale test of Tow-Assist (August, 2024). 34
Figure 16: Simulation environment for remote-control testing. 35

1. Abstract

As integrated systems, deliveries, and vessel complexity evolve, ensuring the reliability and efficiency of complex configurations has become paramount. This paper explores the application of model-based testing (MBT) as an integral step for enhancing the verification and validation (V/V) processes of integrated control systems and equipment. By leveraging MBT, we aim to address the challenges posed by isolated testing and configuration-driven development, which can lead to unforeseen issues during later stages such as during Factory Acceptance Testing/ Contract Acceptance Testing (FAT/CAT), Failure Mode Effect Analysis (FMEA), and hidden failures experienced during operation.

The study delves into the principles of MBT, highlighting its ability to create comprehensive test models that simulate real-world scenarios and interactions within integrated systems. These models facilitate early detection and resolution of potential issues and reducing the risk of developmental setbacks. Furthermore, the paper discusses the integration of MBT outcomes with digital survey tools and Condition-Based Monitoring (CBM) to support efficient lifecycle management and enhance vessel longevity.

A key focus of this paper is the critical role of a *System Integrator* in the successful deployment of integrated systems. The system integrator is essential for coordinating and streamlining the integration processes, ensuring that all components work seamlessly together. Through case studies and empirical data, we demonstrate the effectiveness of MBT in streamlining integration processes, improving system reliability, and optimizing performance. The findings underscore the importance of adopting early integration strategies and aligning development plans between control systems and equipment suppliers to achieve efficient implementation and effective V/V.

2. Executive Summary

As vessel systems become increasingly complex, traditional testing and integration methods are limited in their ability to sufficiently ensure reliability, predictability, and operational efficiency. This paper presents a forward-looking approach using **Model-Based Testing (MBT)** and **Dynamic Positioning System Integration (DPSI)** to address these challenges.

Key Takeaways:

- **Strategic value of MBT**
  MBT enables early-stage simulation of vessel systems and uncovering integration issues before deployment. This can reduce reliance on physical testing and lead to faster, more comprehensive development cycles, lower risk, improved system resilience, and effective verification through the lifecycle of a vessel during upgrades and retrofit.
- **System integrator as a critical role to ensure fault tolerance**
  The paper defines the system integrator's role as a strategic coordinator across suppliers and subsystems. Their involvement ensures seamless communication, documentation, and alignment with fault tolerance and redundancy goals.
- **Lifecycle-based modeling aligns engineering with business objectives**:
  Vessel models evolve from concept to in-service phases, supporting design optimization, regulatory compliance, and operational decision-making. This lifecycle approach aligns engineering efforts with business objectives.
- **Integrated subsystem testing to uncover hidden failure paths and improve customer confidence**:
  Combining DP control, power management, thruster models, and mission specific equipment models into a unified test environment improves accuracy and reveals hidden failure paths. This supports more robust verification and validation (V/V) and enhances vessel operability under stress.
- **Case studies to demonstrate Benefits**
  Four real-world case study (drillship retrofit, MBT of power plant, construction support vessel design, and Tow Assist) results are provided to show measurable benefits, reduced time for delivery, and improved stakeholder collaboration.

Business Impacts:

- **Risk Reduction**: Early detection of integration issues prevents costly challenges during sea trials or operations.
- **Customer Confidence**: Virtual testing environments enable transparent collaboration with clients and classification societies.
- **Scalability**: The MBT and SiL framework supports future vessel designs and retrofits, making it a reusable asset across projects.

3. Introduction

3.1. The seven pillars of DP operations and DP system integration

According to the Marine Technology Society's (MTS) guidelines (1), A robust DP vessel design philosophy is founded on seven key principles: autonomy, independence, segregation, differentiation, fault tolerance, fault resistance, and fault ride-through, as shown in Figure 1. These fundamental principles continue to provide effective guidance which shapes modern DP vessel designs.

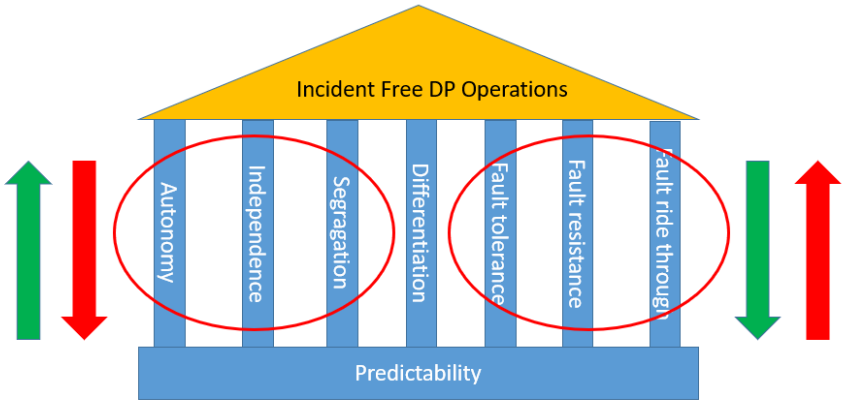

Figure 1: The seven pillars of incident free DP Operations. (1)

The seven pillars, shown in Figure 1, can be viewed as a balanced approach. The left-hand side of this balance consists of design considerations focused on autonomy, independence, and segregation, which collectively define the level of effort required from the right-hand side: fault tolerance, fault resistance, and fault ride-through. By prioritizing high levels of adherence to these initial principles, operators can naturally benefit from reduced risk and increased system resilience The definitions of Autonomy, Independence, and Segregation, topics which are discussed extensively in this paper, are reproduced below for the ease of the reader. For other definitions, refer to (1).

Autonomy: Modern DP vessels are complex systems with several layers of automation. Experience suggests that there are benefits to be derived from making generators and thrusters independent in the provision of auxiliary support services and control functions. Designs should be resistant to internal and external common cause and common mode failures. Designs in which the control function has been decentralized are considered to be more fault tolerant. In such designs, each major item of machinery is responsible for making itself ready for operation and ensuring that all necessary services are online. In addition, control system failure effects are less likely to exceed loss of the associated engine or thruster. In a centralized system, it can be more difficult to prove that the effects of failure do not exceed the worst-case failure design intent. This is an important consideration when choosing a control system topology for fault tolerant systems. There is still a requirement for a remote-control system in decentralized designs, but the functions of this control layer are limited to scheduling and remote manual control. (1)

Independence: Items of main machinery should be provided with all the control systems, services and auxiliary systems they require so that failure effects of support services are limited to the loss of one item of main machinery (typically one generator or one thruster). (1)

Segregation: DP system design should ensure Independence between redundant DP equipment groups. The number of connections between redundant equipment groups should be minimized. (1)

System Integration at an implementation level is the process of connecting and uniting separate hardware, software, and data systems into a single, unified infrastructure that functions as one cohesive unit. The goal is to allow these previously disconnected sub-systems to work together seamlessly, share information, automate processes, and improve overall efficiency However, the process of managing System Integration is a combination of many parallel activities. While integrating systems across redundancy zones can introduce commonality and potentially compromise segregation and independence principles, thoughtful design measures can be implemented to limit and counteract common failure propagation paths. These measures ensure that even with shared functionality, the system maintains fault containment and operationally resilient across zones.

DP System Integration (DPSI) is a process which conforms to the recommended practice DNV RP0684 (2) which was the outcome of a Joint Development Project (JDP), led by MTS, IMCA, OCIMF, DNV, ABS, LR and BV (3), initiated to create a suitable means to address the interaction between software-based controllers within a DP system. The purpose being to identify integration issues between controllers supplied by (the same or different) OEMs that have the potential to defeat the redundancy concept.

Integration Versus Interfacing:
A clear distinction is, with *integration* there is shared authority of control (or) an o*ptimization* which has been designed for parallel systems or components to utilize the same data for proactive response of segregated equipment. If it is only a setpoint feedback loop in an isolated manner, where there is no shared authority, then it is purely *interfacing*. It is important to consider that by integrating equipment and systems, one should not jeopardize the objectives of the 7 pillars, especially Autonomy, Independence, and Segregation.

In short:
Integration= Shared authority or information from equipment for parallel (automated) control response
Interfacing= Point to point isolated control

3.2. System Integration and Adherence To Autonomy, Independence, And Segregation

Reflecting on the objectives of the MTS guidelines, specifically the left-hand side of the seven pillars in Figure 1, autonomy, independence, and segregation, we find potentially conflicting objectives with more integration between control systems. The increase in risk is primarily due to challenges such as common failure points, hidden failure propagation paths, and lack of ability to comprehensively test and validate such designs.

Despite advancements in design, maintaining effective autonomy necessitates strengthening protection systems to prevent unhealthy components from infecting parallel equipment. This is accomplished through automated detection and isolation of malfunction at the component level. A common initial design concept would be to address this with centralized supervisory systems.However, centralized supervisory systems have a limitation that they add complexity and rely on individual health statuses to be communicated from the component or equipment before a mitigating action can be issued by the supervisory system. Ultimately, this results in additional reliance on the component and communication platform for effective mitigations to be taken, which goes against the concept of independence. Moreover, it is essential to consider auxiliary support systems as critical for the reliability of vital components, considering the vessel's redundancy philosophy. This applies as a function for considering component capacity to operate and zonal segregation.

Maintaining Independence is essential to mitigate common mode failures and shared sources of error. At a minimum, design and operational strategies must prevent faults from cascading to similar equipment

within the same zone. Critical equipment must remain operational even when parallel redundant units are lost.

Auxiliary and ancillary systems—such as shared cooling units—can introduce single points of failure that could lead to the total loss of prime movers within an engine room. While shared installations are common, the redundancy strategy for a shared design must consider loss of the zone rather than loss of equipment within the zone.

The most sensitive aspect of control system design lies in segregation. Designs such as centralized control systems require communication to equipment across redundancy zones. However, to achieve fault tolerance, decentralization and redundancy must be maintained. This is typically managed through delegated control functionality to be performed at the equipment level within the automation layer, and using centralized control for scheduling, remote actions, or adjustments in orders (setpoints) to be centralized and communicated over input/output (IO) interfaces.

As technology has evolved, it is increasingly common for multiple control systems to issue commands to the same components or equipment. This may create a situation where control systems act in conflict, and a parallel control system can override another. For example, a DP (Dynamic Positioning) system may determine that the power plant has sufficient energy for a specific setpoint and issue thruster commands to maintain position. However, without an aligned control philosophy, this setpoint may be overridden by the power management system due to a phase-back order, or the need to reserve energy for mission-critical equipment (e.g., cranes). This type of scenario is a potential unknown risk, as it would not normally appear to operational crew that their vessel capability is limited when everything appears to be healthy.

3.3. Benefits of System Integration

Not withstanding the above challenges, system integration offers significant benefits in the form of reduced overall complexity of hardware and/or reduced duplication of ancillary control equipment and cost, optimized control functionality, and comprehensive health monitoring and consequence analysis. Subsystems that are independently *optimized,* generally, are not *optimal* for the overall combined vessel operation of multiple systems.

Reduced Complexity: By integrating multiple systems, designers can minimize duplication of non-essential components such as multiple programmable logic controller (PLCs) which processes a request from a standalone control system with its own local PLC/ field station, which then hands over the command to another PLC.

A typical example is a control system field station, equipped with its own automation capabilities for managing specific equipment. This equipment is also connected to an external controller PLC, which ultimately takes charge of controlling the local equipment's operations. A less complex implementation being an integrated system where these functions are combined into as single controller, reducing the number of components and interfaces required.

By streamlining system architecture and eliminating redundant components, integrated systems can reduce complexity, improve performance, and improve reliability when managed effectively. A common driver for more integration is to decrease costs of procurement, installation, and maintenance for hardware. However, the design considerations must also consider that the system complexity will likely increase at the automation layer by combining more functions within the same controller. Thus, it is

highly important the “de-duplication” is performed in a manner which does not compromise the integrity of equipment and its fault tolerance.

Vessel and System Optimization: By integrating multiple control systems, vessels can optimize their performance by enabling these systems to work in harmony and share critical information. This allows parallel control systems to act proactively to orders, rather than simply responding to the effects of their actions after they have been taken.

For instance, an integrated system can enable real-time data and control targets (e.g., is the intent to turn to port or is there an increase in wind load? By communicating control targets systems reduce the probably of being inefficient in working against each other) sharing between different control systems, such as propulsion, steering, and dynamic positioning (DP) systems. This enables each system to anticipate and respond to changing conditions and control decisions, reducing the risk of errors or conflicts that can arise from segregated parallel control systems.

By working together in harmony, these integrated control systems can optimize vessel performance, reduce energy consumption, and improve overall safety and efficiency.

Health monitoring and consequence analysis: An integrated system enables the ability to aggregate health monitoring data across the entire platform, providing a comprehensive and holistic view of the vessel's overall health and tolerance level. By sharing health status information between systems, parallel control systems can be informed of potential issues and take proactive measures to reduce utilization of components or equipment that are nearing degradation. This shared intelligence allows for a more nuanced understanding of system interactions and enables consequence analysis, where the impact of component failure is considered in real-time. As a result, integrated health monitoring and predictive response capabilities can be leveraged to inform or intervene, by proactive response, to mitigate a worst-case failure or minimize the impact of such.

4. Verification and Validation Of Integrated Systems

While system integration offers numerous benefits, it also presents several challenges that must be carefully managed. One of the primary concerns is the increased risk of failure propagation, where a single failure can have a ripple effect throughout the entire system. This risk is compounded by the potential for loss of autonomy, independence, and segregation, which are essential principles in complex vessel designs. To manage these risks, it is crucial to follow a comprehensive verification and validation process that ensures the integrated system meets the required standards of fault tolerance. While equipment and control systems are tested and verified in isolation, the higher the level of integration the higher the importance to consider the effect these systems and equipment have on each other. Testing is necessary at the component level and subsystem individually, as well as integrating them into a complete system and conducting thorough verification and validation. A rigorous test program in realistic scenarios helps to identify potential vulnerabilities and ensure that the system can operate safely and efficiently.

A key tool of effective system integration is Model Based Testing for documenting protection functionality for standalone systems and integrated vessels.

4.1. Model Based Testing

Model Based Testing (MBT) is the use of a mathematical model to represent part of the system to be verified and validated. It is typically used to minimise the need for the actual vessel to be used as a test bay for subsystem testing. (3) Testers create models that represent the expected behaviour of the system under test (SUT). These models may then serve as blueprints for generating test cases automatically.

A **Digital Twin** is the virtual replica of a SUT, continuously updated with sensor data and operational feedback (4), and when viewed from the viewpoint of model-based testing of a DP vessel, the digital twin is an integrated system model of the DP vessel which includes the interfaced models of the component.

The digital twin may be:

a. **Model-based**: using physics-based or rule-based simulations. These can operate without live data, especially during design or testing phases.
b. **Data-driven**: relying on machine learning, statistical models, or real-time telemetry to adapt and evolve with the physical system.

In practise, **hybrid twins** are common, combining both model-based and data-driven subsystem models in building up the complete system model. For example, the digital twin of a DP vessel may be built by interfacing model-based component models for the vessel hydrodynamics and DP control system with a data-driven model for the power-plant/battery response.

For testing of the control software, three approaches are commonly used (5):

a. **Model-in-the-Loop (MiL)** – an abstract model describes the SUT's basic behaviour. Control algorithms and control strategies can be developed and tested with this model. Both components- the physical system and the control system are represented by a virtual model. MiL does not require any special hardware.
b. **Software-in-the-Loop (SiL) –** in this approach, the physical system is modelled in the simulation environment with the *virtual* control system being modelled in the development environment of the control software. This requires interfaces between the simulation environment and the development environment of the control software (i.e., a co-simulation interface). This scenario does not require any additional hardware.
c. **Hardware-in-the-Loop (HiL) –** in this approach, the actual control unit is tested in real-time with the virtual vessel model. The vessel model provides the control unit with the virtual physical measuring signals and processes the actuator signals provided by the control unit. This requires special hardware for inputs and outputs (I/O) which converts the physical measuring signals to electrical measuring signals, in addition to the co-simulation interface.

In the context of dynamic positioning, the SUT is a DP vessel equipped with multiple thrusters, power sources and distribution systems, sensors (GPS, gyros), and a control system that adjusts thrust to maintain position against wind, waves, and currents. A block diagram representation of the SUT is given in Figure 2 below.

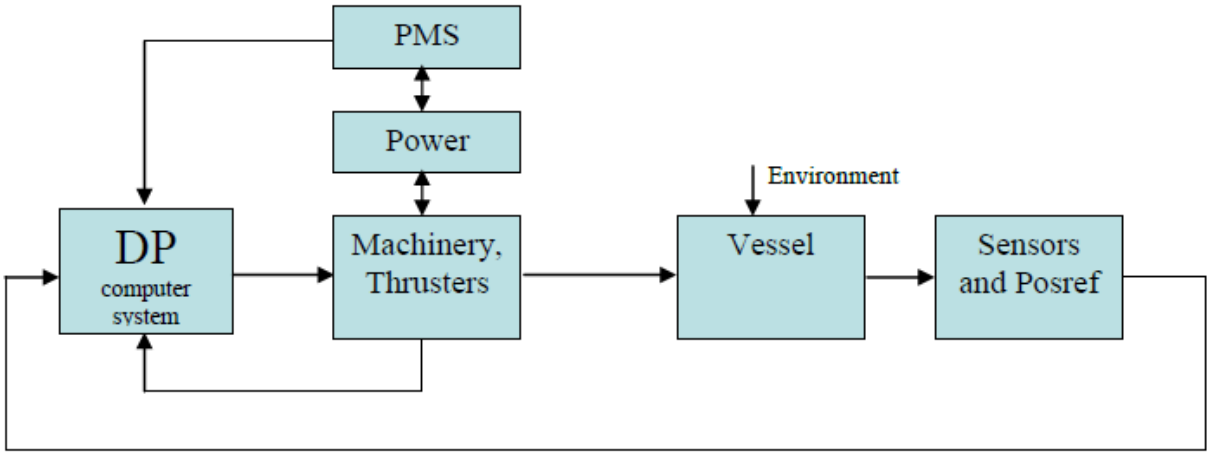

Figure 2: Block diagram of a DP vessel as a SUT. (6)

The conventional approach to testing the performance of a DP vessel during its design/construction phase is mostly limited to functional software and hardware FAT/CAT. In some cases, more comprehensive testing of the DP control system interfaced to a time-domain hydrodynamic model is analysed to assess the performance of specific parameters in a realistic simulation of the industrial mission.

The power management system is often tested semi-independently of the DP vessel model, in the sense that the power consumption time series of the thrusters combined with the time-series of power consumption by other consumers is fed as input into the model of the PMS to test its performance. The power system strategy and load response functionality are verified during the FAT and a various series of ramp up and failure tests by components is tested during the CAT and sea trial onboard.

In a conventional setup, the Power Management System (PMS) is integrated with a simplified thruster-propeller model that estimates power and torque based on speed commands received from the DP system. While an integrated configuration allows direct transmission of speed commands from the DP to the PMS, testing is often conducted independently by replaying time-series thruster speed commands from previous DP scenarios. This approach fails to account for the dynamic influence of the PMS on thruster response.

The PMS typically does not include the behaviour of the drive systems. However, drive control software contains critical parameters (e.g., ramp-up time)_for ensuring compliance with power limits and operational constraints defined by the PMS. However, these parameters are often neglected in simulations, despite their significant impact on DP performance predictions. Proper implementation of drive dynamics and PMS constraints is essential for achieving realistic and reliable thruster behaviour during DP operations.

This effectively means that in many cases, the DP control system and PMS are tested independently.

DP systems are *cyber-physical systems*—they rely on real-time feedback from sensors, control algorithms, and actuators to maintain vessel position. Isolated testing of the DP control system and vessel hydrodynamics might confirm that a thruster responds to commands and that the vessel is able to maintain position, but only integration testing can reveal whether the *entire control loop* functions correctly under stress, failure, or environmental change.

Thus, one may draw the conclusion that the establishment of a digital twin that enables MBT of a SiL/HiL model of the DP vessel is an effective approach to provide an *Engineering Basis* for *Evidence Based Comprehensive Verification and Validation* (3).

Though comprehensive testing of integrated systems is technically feasible, the *fidelity* versus *cost* associated with the development of specialized FMUs must be taken into consideration

If the right factors are considered, individual equipment models can be combined to create a complete system model in a cost-effective manner. This can be accomplished with reduced engineering time, reduced access by specialists to the test environment, and virtualization of equipment. This setup allows for the capturing of the total effect on interdependent systems, within the test environment.

Section 7, presents a novel approach where the objectives of assessments can be considered as part of the model lifecycle, reducing the engineering impact with a graded development based on the needs of a vessel model during the design phase. By following this process, the development is in line with the vessel production and can be utilized in later phases during the lifecycle management of the vessel.

4.2. MBT Literature Review

For an overview of the development of MBT process, in the context of dynamically positioned vessels, and to gain an understanding of the present scenario, readers are directed to the following literature:

- Johansen et al. (6) reports on a pilot study on HiL testing of DP systems. They proposed the setting up of a HiL vessel simulator for use during FAT where the simulator may be configured to simulate the vessel motion and all relevant systems onboard the vessel.
- Skjetne et al. (7) elaborates on the development of vocabulary and set of definitions associated with HiL testing.
- Pivano et al. (8) discusses the automated running of DP software regression testing with HiL technology on platform support vessels.
- Perabo et al. (9) presents the modelling of a shipboard AC power system, and its power management system, which are then exported as FMUs to be connected to the Open Simulation Platform (10) co-simulation environment, and uses this model for HiL testing to validate and verify the correct functioning of the PMS.
- Fonesca et al. (11) proposes an open framework for modelling and organizing ship, sensor and operating context data in digital twins, and presents a case study where a digital model of the research vessel Gunnerus, developed according to the proposed data standards, was used to develop a navigational simulator. Plans of integrating case studies with sensor streams to obtain true digital twins are also outlined in the paper.
- NTNU is currently developing an X-in-the-Loop (XiL) testing platform for marine systems (12), where the X could be a Model, Software or Hardware.
- DNV offers HiL testing as a service (13).

5. MBT workflow

The workflow for the MBT based V/V process is shown in Figure 3.

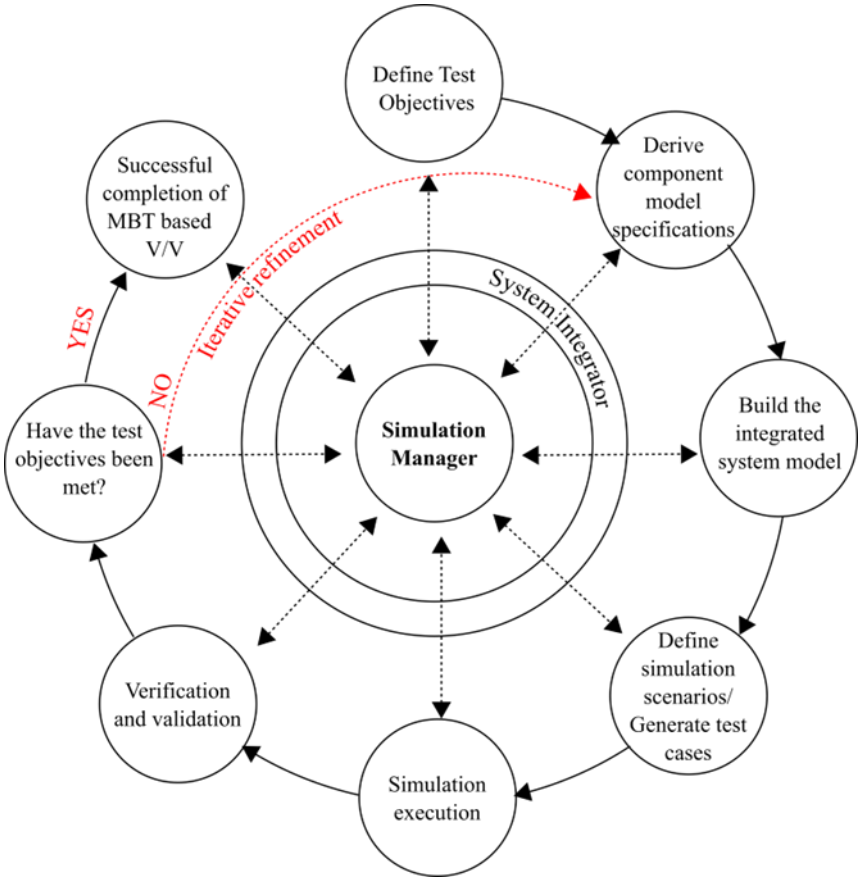

Figure 3: MBT Workflow.

In the context of MBT based V/V of a DP vessel, the workflow items may include:

1. Test objectives
    - Assess fault tolerance and redundancy
    - Evaluate station-keeping performance

2. Component model specifications
    - Level of subsystem modelling required to meet test objectives
    - Type of models to use for the different components – e.g. physics-based models for the vessel, data-driven models for the generators/batteries etc.
    - Interface standards e.g. FMI, HLA, DIS

3. Simulation scenarios/test cases
    - Normal operations
    - Failure modes
    - Harsh conditions

4. Simulation execution
    - Run time-domain simulations
    - Apply disturbances and faults

- Monitor system response and recovery

5. Verification and validation
    - Compare simulated behavior with real-world data

6. Iterative refinement
    - Tune control parameters
    - Update models based on test results
    - Rerun scenarios for robustness

The key testing principles include:

- Modularity- test subsystems independently before full integration
- Repeatability- ensure tests can be consistently reproduced
- Traceability- Link test cases to system requirements
- Automation- Use scripting and batch-runs for efficiency
- Coverage- Test across a wide range of operational and failure conditions
- Scalability- reuse

5.1. The Roles of The System Integrator and The Simulation Manager

The role of the **system integrator** has evolved over time. Driven by advancements in technology, integration of control systems is increasingly more complex.

Historically, the system integrator was often considered synonymous with the shipyard; however, this is not always the case. MTS-RCPD (14), JDP-01, and RP-0684 (2) suggest for a dedicated system integrator. This could be supported by the shipyard, the vessel owner, an FMEA or Assurance provider, or an OEM. In common practice, a system integrator can be defined as an individual or team of specialists responsible for efforts during newbuild and retrofit. Their primary role is to ensure that all systems and equipment are properly installed, implemented, and integrated according to their design specifications and integration strategy. This involves coordinating communication between various system and equipment suppliers to achieve harmony in how these systems work together.

As per DNV RP-0684 (2), a key aspect of the system integrator's responsibility is documenting and coordinating the integration process, including input-output authority, control system interactions on both horizontal and vertical planes, and how individual components affect each other. The goal of this detailed documentation is to enhance transparency and knowledge about integrated systems' impact on vessel capacity, ultimately contributing to improved resilience and resistance to failure.

The role of the **simulation manager**, in the context of MBT, is to oversee the creation and execution of simulations to test, validate, and optimize systems before they are deployed. It is the simulation manager that brings in the real-world operational aspect into the setting up of test scenarios and analysis of simulation results.

Though the responsibilities of the simulation manager and the system integrator can be broadly segregated, both roles have a requirement to have substantial mutual understanding of both the technical aspects of simulation and operational aspect of shipboard equipment with humans-in-the-loop, to ensure that the integration process transitions smoothly from the world of simulations to the actual installation onboard.

Within the context of MBT based V/V, the system integrator role is focused on:

- Model coordination- align models from different subsystems ensuring that the subsystem model meets the specs required to meet the test objectives

- Interface definition- specify and test how subsystems interact (e.g. data formats, timing, protocols)

The focus of the simulation manager role is on:

- Test Case Generation- verify that the test cases generated meet the test objectives
- Coordination of the scenario simulation- run end-to-end simulations that reflect real-world operations and failure modes.
- Verification and Validation- verify that integrated system behaves as expected under all conditions.

The main challenges that are likely to be faced in MBT based V/V include:

- Model inconsistency-subsystems may use incompatible modeling standards (e.g., Simulink versus. Modelica)
- Change management
- Test coverage
- Stakeholder coordination

Best practices to adhere to include:

- Use co-simulation frameworks (e.g. FMI, HLA) to integrate heterogeneous models.
- Maintain a central model repository with version control and traceability.
- Automate test case generation and execution
- Apply coverage analysis to ensure all critical subsystem interactions are tested
- Foster cross-disciplinary collaboration between control engineers, software developers and maritime experts.

Model Based Testing is just one important task to be undertaken while administrating design, testing, and delivery of an integrated system. The Integrator's role extends beyond testing and documentation. By focusing on the coordination of communication between system providers and equipment suppliers, the system integrator plays a critical role in preventing unforeseen risks and potential hidden failures that may arise from unclear system interactions. The refined definition of the system integrator's responsibility emphasizes their duty to coordinate the linking of systems and equipment, document those links, and explain how they affect each other. (2), (14)

In essence, the system integrator acts as a bridge between various stakeholders, ensuring that all parties are aware of the integration process and its implications on vessel performance. This emphasis on higher-level integration aims to achieve better harmony among systems working together, thus minimizing undocumented risks and enhancing overall safety and efficiency.

5.2. Model Development for MBT

The development of a vessel's design and therefore of its satisfactory *model,* is a complex process that requires careful consideration of numerous factors, including fidelity, safety, reliability, and performance. One crucial aspect of this process is the model lifecycle, which spans from the initial concept phase to the final delivery of the vessel and often transitions into application during in-service activities.

The increasing complexity of modern vessels, and availability of tools, has led to the widespread adoption of simulations as a crucial tool in the marine-assurance-and-engineering toolkit. These tools enable designers to assess vessel performance and reliability during the concept and bidding phases of new and

existing vessel design, retrofit, and charter requirements. However, the misuse or limitations of these simulations can have significant implications as a model is extended further from the original objectives it was designed to meet.

6. Key Aspects of A DP Vessel Model Design

6.1. Vessel Hydrodynamic Model

Hydrodynamic modeling is a crucial aspect of vessel design, as it simulates the interaction between the vessel and the oceanic environment. A well-developed hydrodynamic model can satisfactorily predict the behavior of the vessel in various environmental conditions.

Development:
The development of a hydrodynamic model involves several steps, as outlined in Figure 4, and explained in the subsequent text.

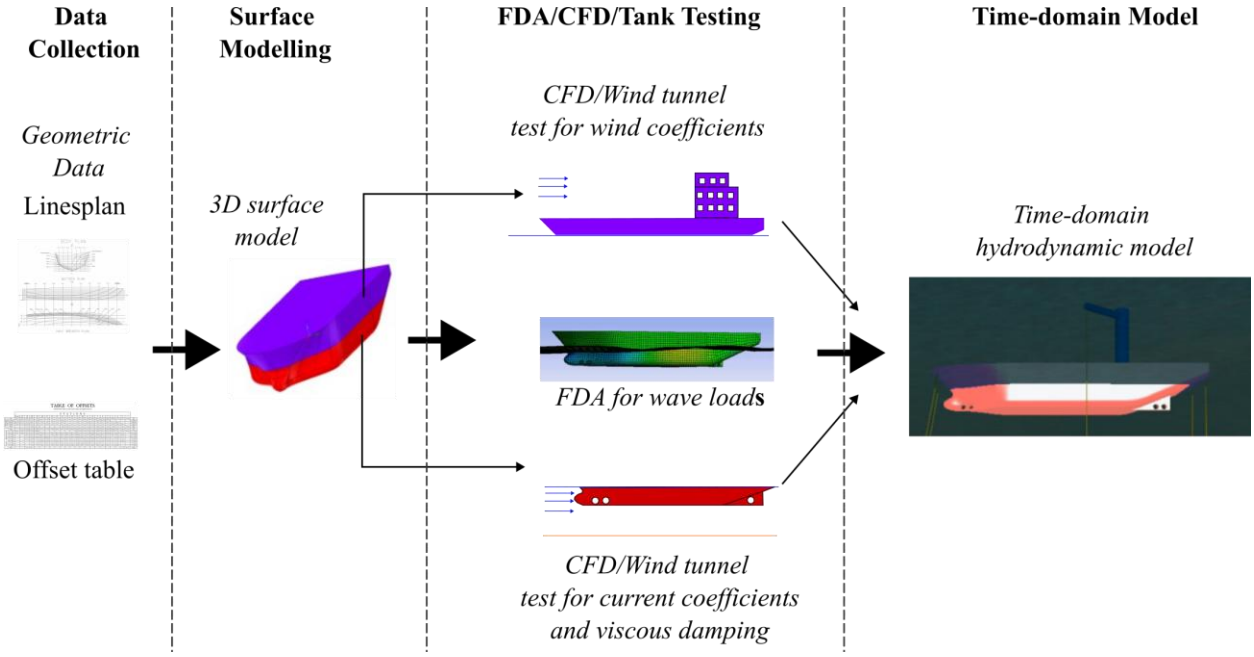

Figure 4: General steps in the development of a time-domain hydrodynamic model.

- **Data collection:** Gather data on the vessel's geometry, mass distribution, and other relevant parameters.
- **Surface modelling:** Develop a 3D model of the hull/super structure.
- **Frequency domain analysis**: Choose a suitable frequency domain analysis software and determine the hydrodynamic parameters. For a DP vessel, this typically includes the frequency dependent added mass and damping loads, the load RAOs, and the wave-drift loads.
- **CFD analysis**: Choose suitable CFD software and determine the current and wind coefficients.
- **Time domain model**: Choose a suitable time-domain analysis software and build the time-domain model of the vessel based on the FDA parameters, wind-and-current coefficients, and other relevant data e.g. viscous damping.
- **Validation:** Validation of the hydrodynamic model is essential to ensure its accuracy and reliability. This involves:

- **Comparison with experimental data:** Compare the simulated results with experimental data from similar vessels or operating conditions.
- **Sensitivity analysis:** Perform sensitivity analysis to evaluate the effect of various parameters on the model's behavior.
- **Model refinement:** Refine the model based on the results of validation and sensitivity analysis.

Considerations:
When developing a hydrodynamic model, consider the following aspects:

- **Loading condition:** VCG/LCG, displacement, draught, radii of gyration etc. used in the time domain simulation to match the values used in the FDA phase.
- **Coordinate systems:** Ensure that the FDA parameters, current coefficients, and wind coefficients are transformed to match the co-ordinate system in the time-domain software.
- **Water depth:** Account for the water depth and its effect on the vessel's performance.

6.2. DP Control System Model

Development
The approach towards including the DP control system or its representation will affect the accuracy and reliability of simulation results. The objective of the simulations or analysis should consider the level of accuracy required. The various approaches are:

- **Simplified DP Model**: uses either an estimator pre-tuned for typical PID functionality, a spring, or moorings representing the restoring functionality of thrusters and DP functionality. This provides relatively quick results. However, accuracy tends to degrade with larger environmental variation.
- **Representative control systems tuned for best results**: This approach involves optimizing the model to achieve specific performance criteria. Often, this approach is similar to the simplified DP model. The caveat is that the tuning can be performed through many varying approaches.
- **Vessel-specific control systems**: These offer a more detailed representation but require significant data and expertise, as well as some assumptions on vessel behavior based on previous experience. Typically, this increases the engineering effort but offers the highest level of accuracy.

Each of these approaches has its advantages and disadvantages:

- **Simplified models**: These models are often used as a starting point for vessel design, providing a quick and rough estimate of system behavior. However, they may not accurately reflect the complexity of the system, leading to inaccurate predictions.
- **Representative control systems tuned for best results**: This approach involves optimizing the model to achieve specific performance criteria, such as maximum accuracy or minimum computational time. However, this approach provides the greatest risk because the measurement filtering, thrust allocation, and control system behavior is often overlooked or not considered. Finally, the control functionality is tuned to provide optimal performance which can limit the impact of filtering and built in protection measures which can affect the performance. This step often can result in exaggerated performance capabilities and less conservative results.
- **Vessel-specific control systems**: These models offer a more detailed representation of the DP system, considering the specific characteristics of the vessel and its operating conditions. However, they require high-level expertise, as well as some assumptions on vessel behavior based on previous experience.

Considerations
When developing the DP system model, several considerations should be taken into account:

- **Level of accuracy required**: The objective of the simulations or analysis should consider the level of accuracy required. If high accuracy is required, a more detailed representation of the DP system may be necessary.
- **Data availability and expertise**: The availability of data and the level of expertise required to develop and use the model should also be considered. Simplified models may be easier to use but may not provide accurate results if the underlying assumptions are not valid.
- **Assumptions and limitations**: Any assumptions or limitations made in the development of the model should be clearly documented and understood by the end user.
- **Use validated and calibrated PID models**: Ensure that the models are based on experimental data and have been validated against real-world scenarios.
- **DP system configurations and operating conditions**: Account for various built-in DP configurations, Kalman filtering, gain, thruster allocation, and operator configuration respective to the industrial mission and operating environment.
- **Account for non-linear relationships between variables**: Use advanced modeling techniques to capture complex interactions between variables such as sensors and reference systems.
  Validate models with real-world data: Conduct experiments or field-trials to evaluate model accuracy.

6.3. Power System Model

Power limitations and configuration
The exclusion of power limitations or mission specific configuration from simulation models can have significant consequences on the accuracy of vessel performance predictions. The power plant configuration is a critical factor that affects a vessel's ability to maintain its position and operate effectively, particularly under varying conditions, post worst-case failure, or at the upper bounds of operability.

Importance of power limitations and mission-specific configuration
Power plant capacity refers to the maximum amount of power available to a vessel, which can be affected by various factors such as:

- Generator capacity
- Efficiency
- Load management and response time
- Power distribution, management systems, configuration
- Energy storage and supply (Battery)
- Advanced Generator Supervision and protection for monitoring and protection of speed and voltage failures
- Additional automated/autonomous protection functionality

Power limitations and restrictions impact the ability of a vessel to maintain position and operate effectively because they determine the vessel's ability to respond to changes in environmental conditions, such as wind, current, and wave forces.

Consequences of excluding power limitations or mission specific configuration
Excluding power limitations and the mission-specific configuration restrictions from simulation models can lead to inaccurate predictions of vessel performance. Inaccuracies include over-estimation of a vessel's capabilities, under-estimation of the required power for certain operations, and inadequate design and planning for power generation and distribution systems. Specifically, without considering power

limitations, a vessel's ability to maintain its position may be over-estimated, leading to reduced positioning accuracy, less speed/maneuverability, and lower efficiency.

Power Limitations/Restrictions
To ensure accurate vessel performance predictions, it is essential to include power limitations and restrictions in simulation models. Best practices for inclusion include:

- Identifying and quantifying power limitations.
- Definition of power plant configuration including the power ramp up/down rate for individual producers, heavy consumers (thrusters, mission equipment).
- Automatic system response such as auto starting/stopping of generators based on load limits and State of Charge (SoC) limits in hybrid mode.
- SoC control of batteries, adjustment of charge and discharge limit of batteries.
- Effects of power losses due to transformers, capacitors, and ac/dc conversion.
- Protection relay response and sensitivity an impact on system performance
- Reduced performance due to configuration such as limited kw due to current limitations across a circuit break on a ring bus

Best practices for inclusion of protection against speed and voltage failure
During Factory Acceptance Testing (FAT), the Power Management System (PMS) setup typically includes functionality to monitor and isolate failures related to speed, voltage, and load sharing. These failures are often introduced using simplified simulation models. However, with advanced and detailed models of engines, generators, batteries, and the electric bus, it becomes possible to simulate more complex failure scenarios—such as faults in governors, Automatic Voltage Regulators (AVRs), fuel racks, and speed sensors—and verify the corresponding protection mechanisms.

This enhanced simulation capability also provides an opportunity to fine-tune system parameters ahead of onboard testing. Furthermore, an integrated setup combining PMS, Dynamic Positioning (DP), and Automatic Generator Start (AGS) systems enables benchmarking of DP performance under various speed and voltage failure conditions, offering valuable insights into system robustness and response.

When considering realistic performance testing the following is necessary::

- Build a FMU of the power system model with possibility to introduce different failures on the governor and AVR
- Establish integration with DP, PMS and protection systems (AGS)
- Run use-cases for DP operation with introduction of speed/voltage failures

Additional Power System MBT considerations
DNV RP 0591 (15) provides substantial guidance for the development and performance of model based testing of power systems and their protective functions. Such testing includes the protection relays within the power plant and their response. Although this paper primarily focuses on the operational impacts of the overall system, it is necessary to consider and investigate the fidelity of the power plant as a whole. While this is not extensively mentioned here the following excerpt from DNV RP-0591 (15) should be considered:

- Short-circuit and earth faults (intermittent and continuous, low/high impedance)
    - Purpose: To verify system stability and protection response under fault conditions.

- Transient performance during faults and recovery (including over-voltages)
    - Purpose: To ensure the system can handle sudden electrical disturbances and recover without damage.

- System synchronism during faults (equal and asymmetric load sharing)
    - Purpose: To confirm that generators remain synchronized, preventing cascading failures.
- Voltage recovery and restart behavior (including over-voltage and re-acceleration)
    - Purpose: To validate safe and reliable voltage restoration after fault clearance.
- Fault ride-through capability of drives, generators, motors, etc.
    - Purpose: To assess whether equipment can continue operating through short disturbances without tripping.
- Crash synchronization of generators and switchboards
    - Purpose: To simulate mechanical and electrical stress during emergency synchronization and ensure safe operation.
- Connection of stopped or under-speed generators
    - Purpose: To test safe integration of generators that are not at nominal speed, avoiding system instability.
- Load acceptance and rejection scenarios
    - Purpose: To verify system response to sudden changes in load, including:
- Trip of single or multiple generators
- Trip of large consumers or switchboards
- Start/connection of large consumers (e.g., motors, capacitors)
- Other relevant failure scenarios (e.g., single pole faults, open breaker faults)
    - Purpose: To explore edge cases that may cause overvoltages or asymmetrical faults.
- Pole slip (if relevant)
    - Purpose: To detect loss of synchronism in generators, which can lead to severe mechanical and electrical damage.

6.4. Thruster Model Simplification/Optimization

Thruster performance modeling is a critical aspect of vessel design, as it directly affects the accuracy of predictions for vessel behavior and performance. Accurate thruster modeling requires careful consideration of various factors, including thruster type, size, and configuration, as well as environmental conditions.

Types of thrusters

There are several types of thrusters commonly used in vessels, each with its own unique characteristics and performance capabilities:

- **Fixed Pitch Propellers (FPPs):** FPPs are the most common type of thrusters and are designed for maximum efficiency at a specific speed.
- **Azimuthing Thrusters (ATs):** ATs are designed to provide high manoeuvrability and are commonly used in vessels that require precise positioning, such as offshore platforms and wind farm service vessels.
- **Pod-Driven Propellers (PDPs):** PDPs are designed for smaller vessels and offer improved efficiency and manoeuvrability compared to traditional FPPs.
- **Conventional Main Propulsors:** These are typically fixed or controllable pitch propellers that serve as the primary means of propulsion. Typically suited for vessels with high bollard pull requirements such as Tugs, Anchor Handlers, and Shuttle Tankers.
- **Tunnel Thrusters:** Tunnel thrusters are transverse thrust units installed at the bow or stern. They provide lateral movement capabilities and are typically limited to use in vessel speeds or currents below 1.5m/s.

Thruster performance modelling

Hydrodynamic forces play a crucial role and encompass various interactions that can influence efficiency and thrust generation. These forces arise from both the design and operational conditions surrounding the thruster (16):

- **Thrust reduction due to thruster wake:** One primary hydrodynamic force is the reduction in thrust caused by the wake generated behind the thruster as it interacts with the hull. This occurs because the flow of water around the thruster's body creates turbulent eddies that can reduce the effective propulsion force.
- **Friction with the hull:** The interaction between the thruster jet and the vessel's hull introduces additional hydrodynamic resistance. This friction contributes to thrust reduction as energy is lost in overcoming this resistance, impacting overall performance.
- **Inline losses:** Another significant factor is the loss of thrust due to variations in inline water velocity. Differences in flow speed can lead to inefficiencies in how the thruster converts power into forward motion.
- **Transverse loss and inlet shape efficiency:** The efficiency of a thruster is also affected by its design, such as the shape of its inlet or whether it has a grid structure (tunnel length being another influencing factor). These structural elements can cause hydrodynamic losses through inefficient water intake.
- **Cross current effects on tunnel force:** Thrusters are often subjected to cross currents which can affect their performance by altering force distribution and requiring adjustments in thrust direction. Decomposing the current vector helps understand these impacts better.
- **Ventilation effects:** If a propeller partially exits the water due to ventilation, it leads to loss of efficiency because only part of its surface is generating propulsion Specification and use of DP capability plots.pdf. This is especially critical during high-speed manoeuvres or rough sea conditions.
- **Thruster-thruster interaction losses:** In systems where multiple thrusters are used, interactions such as one thruster's flush affecting another can lead to performance losses.
- **Power limitations in shallow water:** Operating in shallow waters imposes power limitations due to increased hydrodynamic resistance and potential for damage or inefficiency, requiring careful consideration of manufacturer guidelines.

Thruster model validation

To ensure accurate thruster modelling, it is essential to follow best practices that include using validated and calibrated models based on experimental data and real-world scenarios. Additionally, consider multiple thruster configurations and operating conditions, including various environmental factors such as wind, current, and wave forces. Thrust allocation should also be considered, taking into account control system functionality, roll damping, gain, control limitations, and operator configuration which is especially important during transient conditions. Furthermore, advanced modelling techniques should be used to capture non-linear relationships between thruster hull interaction, thruster-thruster interaction, and ramping/rotation rate. Finally, models must be validated with real-world data through experimental testing, field trials, or comparison with existing models to ensure accuracy and reliability.

Simplifications and optimizations

Simplifications and optimizations are often employed to improve the computational efficiency of thruster models, but these simplifications and optimizations may introduce inaccuracies if not validated against real-world data (17). Simplifying complex non-linear relationships through linearization or making assumptions about thruster performance without experimental validation can result in over- or underestimation of capabilities. This is particularly problematic when considering the complex interactions between vessel motion, external bodies, and environmental forces. Other considerations such as utilization of performance curves for manoeuvring does not guarantee the same effect for station keeping or vice versa. As a result, inaccurate thruster modelling can have significant consequences,

including reduced positioning accuracy, decreased speed and manoeuvrability, and increased energy consumption, ultimately leading to higher operating costs.

6.5. Post-Failure Capability

Post-failure capability refers to the ability of a vessel to safely and effectively suspend or abandon an operation after a failure or malfunction has occurred. Ignoring post-failure capability during model development can lead to underestimated risks and consequences, compromising design safety and continuity ultimately leading to significant potential downtime or retrofit expenses. (1), (16), (18), (17)

Importance of considering post-failure capability
Post-failure capability is essential for ensuring the safe and efficient operation of vessels. In the event of a failure or malfunction, the vessel must be able suspend operations safely and effectively until corrective actions can be taken. A thorough risk assessment should support identification of potential failure modes and assess their likelihood and impact. The basis of this should be the vessel operating configuration and the FMEA.

- **Safety:** Post-failure capability ensures that, in the event of a system failure, the vessel remains safe for personnel and equipment. It also limits environmental impact by enabling a controlled and secure suspension of operations.
- **Continuity**: While post-failure capability does not imply continued operation after a failure, it provides reserve capacity to maintain safety protocols efficiently, thus minimizing potential downtime until normal operations can be resumed safely.
- **Reliability:** Post-failure capability demonstrates the reliability of the vessel's design by showing that even in adverse conditions, there is sufficient capacity to suspend an operation in the event of an unforeseen failure.

Consequences of disregarding post-failure capability in analysis
Disregarding post-failure functionality during model development can have serious consequences, including:

- **Underestimated risks:** Ignoring post-failure capability can lead to an over-estimation of vessel capacity (operational limits) and operability (uptime). This is primarily due to misunderstanding the objective for risk assessment, and insufficient safety margins. In such cases, the capability analysis defaults to the assessment of intact capability only.
- **Increased downtime:** In the event of a failure or malfunction, the vessel may be forced to undergo extended repairs, leading to increased downtime and reduced operational efficiency.
- **Reduced reliability:** Disregarding post-failure capability can demonstrate a lack of attention to detail in the design and construction process, reducing the overall reliability of the vessel. This is largely due to higher expectations for vessel capability or inability to effectively absorb dynamic effects of an operation within the thruster and power plant.

Post-failure capability considerations
When developing models for vessel design, consider the following aspects:

- **Fault tolerance:** Fault-tolerance in a vessel’s design is primarily facilitated through redundancy and segregation. This should be verified when assessing the impact of failures or malfunctions.
- **Redundancy:** Redundancy within the vessel design must be taken into consideration of the model development – such that the critical systems remaining after a single or multiple point-failure are aligned with the vessel redundancy concept and the FMEA.
- **Transient effects:** When running simulations to assess post-failure performance, it is essential to consider the system’s response in the immediate period following a worst-case failure, to accurately capture the system dynamics. In such cases, it might be more relevant to run multiple

shorter simulations covering the time-period around the failure, than to consider fewer, but longer, simulations that account for times far away from the time of failure.

7. Model Lifecycle

The lifecycle of modelling is integral from the initial design stages to final validation. As designs evolve, models must adapt to meet increasing demands for accuracy and specificity. Initially, models address broad questions without needing high precision. (1)

7.1. Phase 1: Concept

In the initial design phase, modelling explores various potential designs and addresses broad questions with minimal accuracy requirements. The focus is on assessing the feasibility of different design choices at a high level. (1), (19)

- **Purpose:** At this stage, the primary goal of modeling is to explore a wide range of possibilities quickly and efficiently without delving into high precision. Post failure capability is considered as a relatively low priority from a performance perspective and is more focused ensuring there is sufficient capacity for maintaining the vessel redundancy philosophy irrespective of dynamic effects.
- **Approach:** Simple or abstract models are employed to answer broad questions such as overall feasibility, preliminary performance estimates, and initial design direction. These models help in setting the foundation for more detailed work later on.

Parametric studies
Parametric studies are integral to the field of engineering, particularly in optimizing the design and performance of marine vessels. They enable engineers to systematically adjust design parameters such as hull shape or power and propulsion configurations. By parameterizing specific critical areas of focus, this process streamlines an engineer's ability to evaluate many solutions against a design basis. Further it provides a foundation for gaining key insights into a potential optimal configuration. This approach not only aids in identifying optimal solutions but also ensures that various design alternatives are evaluated comprehensively while still allowing for flexibility to adjust for design consideration as the final solution becomes clearer.

Exploratory modelling:

- **Purpose:** As potential designs become clearer, modelling focuses on exploring variations within predefined parameters.
- **Approach:** This involves using exploratory techniques such as computational fluid dynamics (CFD) simulations and finite element analysis (FEA) to assess different design alternatives. At this stage, the models are still relatively simple but more detailed than those in the initial phase.

Key techniques in this phase include:

- **Modelling by example:** Utilizing existing validated designs to guide new projects efficiently while maintaining baseline standards. (1)
- **Empirical modelling:** development of a simplified model based on representative experience and previously observed data.
- **Hull form modelling:** Evaluating basic hydrodynamic characteristics and general performance.

7.2. Phase 2: Detailed design

The transition to detailed design in vessel engineering is characterized by an increased focus on precision and accuracy. This phase involves moving from broader exploratory models to more detailed models and simulations that address and refine more critical engineering and performance considerations.

- **Purpose**: Here, the focus shifts to refining designs and finalizing performance criteria of critical equipment. At this stage there is also an increasing focus on post-failure capability.
- **Approach**: Detailed simulation models are developed to address specific technical challenges and validate design choices against precise criteria. This involves integrating various subsystems and ensuring compliance with recommendations and requirements. Models become more complex, incorporating detailed geometrical data, material properties, and operational scenarios.

High-fidelity simulations
High-fidelity simulations play a crucial role during the transition from exploratory modelling to detailed design in vessel engineering. These simulations are essential for achieving accurate and reliable predictions of vessel behaviour under various operating conditions.

Key components of high-fidelity simulations
Four critical components of high-fidelity DP simulations are:

- **Detailed geometric data**: Accurate 3D representations of vessel components are necessary for understanding drag, damping, and environmental loads.
- **Stability analysis**: Loading condition, Added mass and effects on vessel motions.
- **External bodies**: effects due to motion from mission critical equipment or interactive loads due to physical effects from earth bound equipment such as piles, pipes, and jackets.
- **Hydrodynamic accuracy**: The effects of environmental forces on the hull and other relevant sources of hydrodynamic loading.
- **Thruster performance**: Representative losses and expected performance based on layout, forbidden zones, and interactive losses.
- **Control system functionality**: Vessel response in line with process and control functionality and how the systems will handle dynamic fluctuations.
- **Power plant accuracy**: Consideration of power plant response timing, total capacity, power factor losses, spinning reserve, and post failure capability.

The benefit of increasing simulation fidelity raises the accuracy of predicting vessel behaviour under various operating conditions. This potentially increases the *reliability and reduces risk*, by accounting for complex interactions between different parts of the vessel. Which can help identify potential design flaws or operational issues before they become major problems.

7.3. Phase 3: In-Service

As a vessel transitions into activities performing its industrial mission, it becomes increasingly critical to consider higher accuracy in modelling and simulations. During project planning, vessel performance is often a critical concern, in addition to assessing reliability and potential improvements. During operations, continuous monitoring of vessel performance can provide data for updating models, which can then be used to inform maintenance schedules, retrofitting decisions, or future design improvements.

However, as a model is transitioned into its final phase of supporting a vessel design, some challenges arise. Typically, managing increased data volume requires robust computational resources and efficient data management strategies, processes and tools. This requires advanced expertise and specialized software tools. In addition, this also extends computational load and time to perform analysis. Despite these challenges, advancing to this phase with sophisticated simulation techniques offers strong benefits such as comprehensive risk assessments, and optimized vessel utilization.

7.4. Model Validation and Refinement

The end goal is to ensure that the design performs as expected under real-world conditions. In finalizing vessel designs, models serve for verification and validation. The model(s) should be verified through calculations and simulations to ensure no errors in data processing or modelling assumptions. Finally, the model should be validated to ensure the design meets all requirements and criteria through comprehensive testing against real-world scenarios.

Comprehensive validation procedures must be implemented to ensure a high quality and accurate high-fidelity model. Such validation may include full-scale simulations, controlled sensitivity and comparative analysis, wave basin or combination. Final adjustments should be incorporated and documented as well as benchmark comparison to ensure new errors are not integrated.

8. Case Studies

We present the following case studies:

Case Study	Focus Area	Key Outcome
SiL testing on a drillship	Integrated FAT via hydrodynamic and software digital twin	Identified integration vulnerabilities pre-CAT
MBT of power plant	Power system modeling and validation	Enhanced fault detection and protection testing
Project in flight	CSOV design guided by RCPD & DNV-RP-0684	Improved documentation and integration strategy
Tow assist	Multi-vessel coordination system	Validated advisory and remote-control functions

8.1. Case Study 1: SiL Testing on A Drillship

Between 2024 and 2025, an integrated Factory Acceptance Test (iFAT) was carried out in preparation for both a retrofit and the delivery of an enhanced drilling system solution. This mission-specific package was developed to support DP drilling operations by combining advanced control systems with decision-support tools to optimize performance within established risk tolerance limits.

The solution for the 96k Drillship included upgrades to the following systems:

- K-Pos™ Dynamic Positioning System
- K-Chief™ Automation System
- Riser Management System
- EcoAdvisor™ (power plant analyser and advisor)
- K-IMS™: E-WSOG Decision Support Tool

To support delivery, a Software-in-the-Loop (SiL) environment was established. This digital twin mirrored the control systems on the same communication platform used onboard and was linked with machinery, vessel hydrodynamic, and riser models. The iFAT allowed real-world scenarios to be simulated, enabling assessment of operational impacts and system interactions. This process also highlighted potential vulnerabilities at the integration layer, which were resolved prior to Completion Acceptance Testing (CAT) and sea trials. This approach provides a robust means to verify integrated system functionality and address software issues before deploying control system software.

As this delivery would be supported by a diverse set of stakeholders globally, KM has also established and utilized a remote access platform for conducting the iFAT virtually. From a web URL the customer is

enabled to observe all systems incorporated within the set of defined tests. In addition, third-party *marine assurance* and *classification societies* have been allowed to witness the tests alongside the customer, limiting the impact on costs and travel for such complex activities.

Figure 5 is an example of the *observer view* of the integrated systems in a dashboard for visualization. All communication and test logging are conducted through a web meeting where participants and testers can actively review and conduct the test program in real time. This platform additionally provided the ability to *concept test* between the developers and the customer, where it would normally be limited to conducting the test in a hardware lab on site.

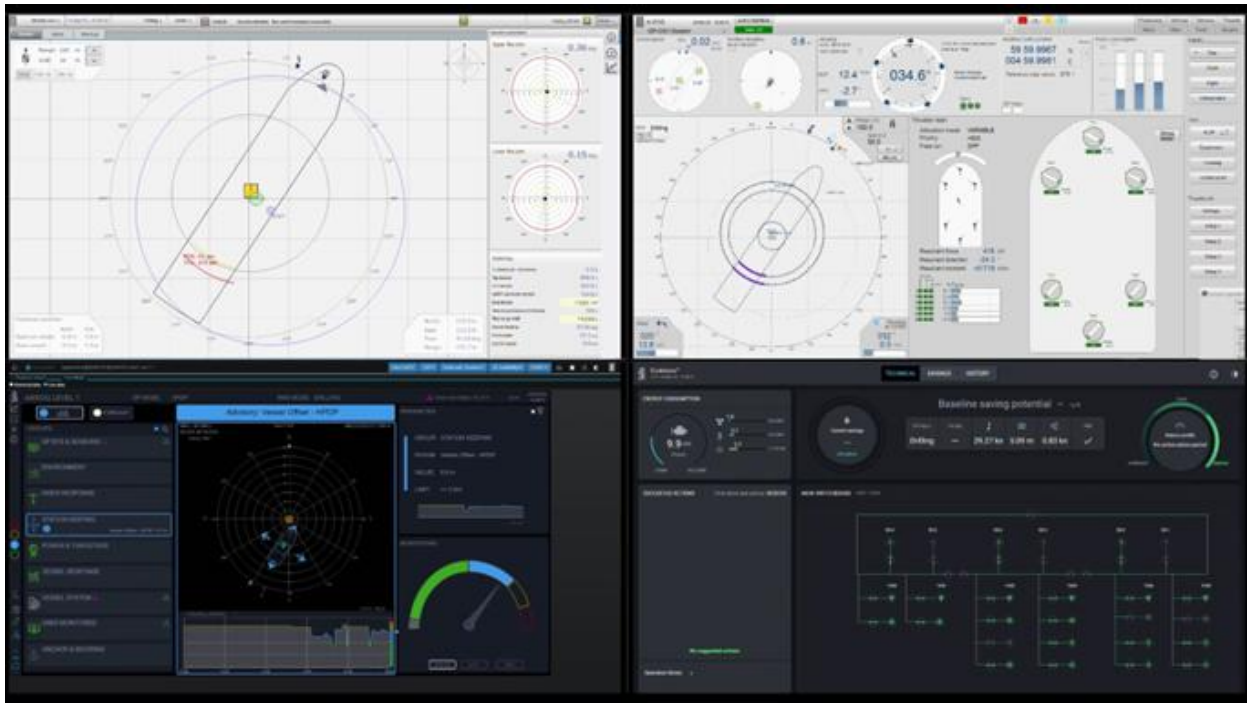

Figure 5: Virtualized control-system-visualization portal.

Test Platform Description

- All control systems are virtualized within a virtual machine, configured to match the operating system version and hardware specifications of the physical system.
- Communication networks replicate the ship's network, including IP configurations for Net A, B, and C.
- The I/O layer is virtualized, with signals exchanged over the network to simulated equipment.
- Signal noise is introduced where variation affects performance, enabling realistic scenario testing.
- A numerical hydrodynamic digital twin is integrated with riser and tensioner models to simulate vessel and riser motion under environmental forces, thruster response, and external loads.
- External loads, such as drilling activities and auxiliary systems, are modelled as consumer loads on the switchboard.

Test Conditions:

As part of the iFAT, the test program is established for two objectives:

a. Comprehensively test cases where control systems have authority or potential impact on a parallel system. *Or*,
b. Conduct scenario-based assessments of real-life dynamic conditions which can affect the vessel, industrial mission or integrated system.

The Following is an example list of conditions which have been investigated:
Note: Heavy and Moderate weather conditions apply for all test cases

- Watch circle and Point of Disconnect (PoD) calculations by RMS informed on K-Pos
- Ramp up environment triggering auto start of standby generators
- Heading change response and trigger of watch circle and POD calculation
- Power plant optimization advice based on configuration and load changes
- Effect of biasing on power plant and optimization calculation
- Effect of loss of equipment triggering advisory, yellow, or red condition
- Effect of relaxed control in DP on power plant, RMS, and *EcoAdvisor* calculations

In Figure 6 is an example of the integrated solution and representation of the models hosted by a simulator for reliable response of vessel and equipment.

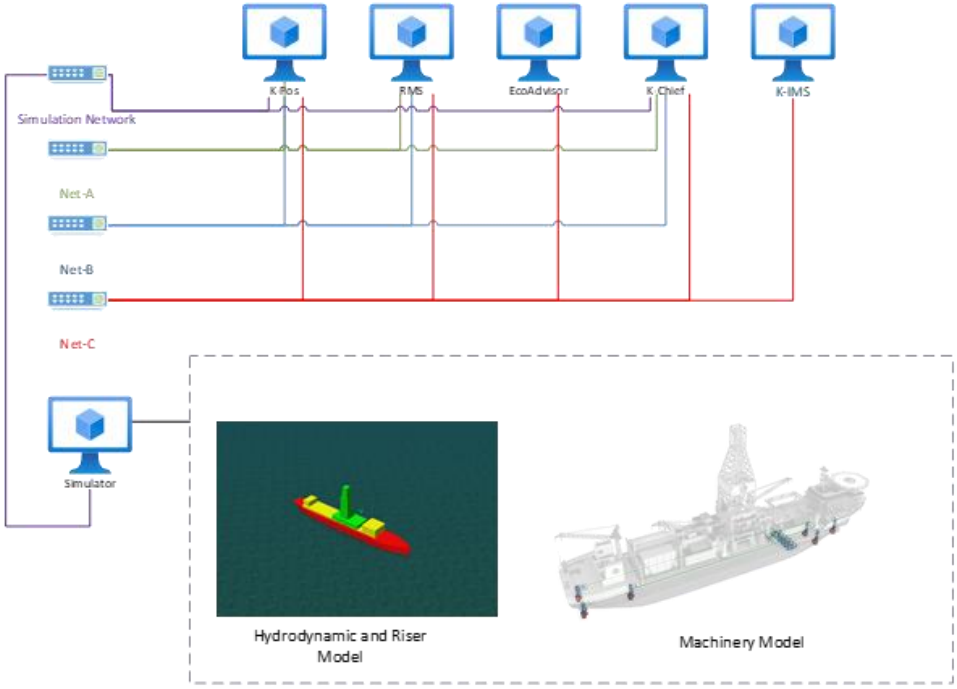

Figure 6: SiL Topology.

iFAT Delivery

As part of the integrated system implementation, an Internal Acceptance Test was conducted in preparation for the Factory Acceptance Test (FAT). Test cases were categorized as passed, failed, non-conforming, or on hold, with each outcome tracked and addressed through defined actions.

Because the system was established virtually and hosted in the cloud, product experts from around the world were able to participate directly in the testbed. This setup eliminated physical constraints and enabled collaborative troubleshooting, system refinement, and action closure in real time.

The project was supported by resources from 4 countries, 7 offices, 5 product areas, and 6 departments, all actively contributing to ensure the solution was fully prepared for deployment.

During Customer Acceptance Testing (CAT), a limited number of conditions requiring further action were identified. These primarily related to scenarios that were not considered for testing within the iFAT environment due to unforeseen vulnerabilities, technical or hardware-specific limitations.

Lessons learned from the test program including the iFAT and the findings of the CAT have been included and shall be incorporated for future cases where iFAT is to be considered.

8.2. Case Study 2: MBT of Power Plant

In this section, we demonstrate how a model-based system can be used to test active and reactive load-sharing failures in an AC power system with generators operating in parallel. A scaled version of the power system elements is created using the Siemens AMESIM simulation platform. The models are parameterized based on vessel-specific configurations. Speed and voltage controllers are modeled according to manufacturer specifications and are thoroughly analyzed based on the power system's response to both static and dynamic load steps.

The schematic below illustrates the power system model of an AC bus system, including the engine, speed and voltage control, electric bus, transformers, and distribution system.

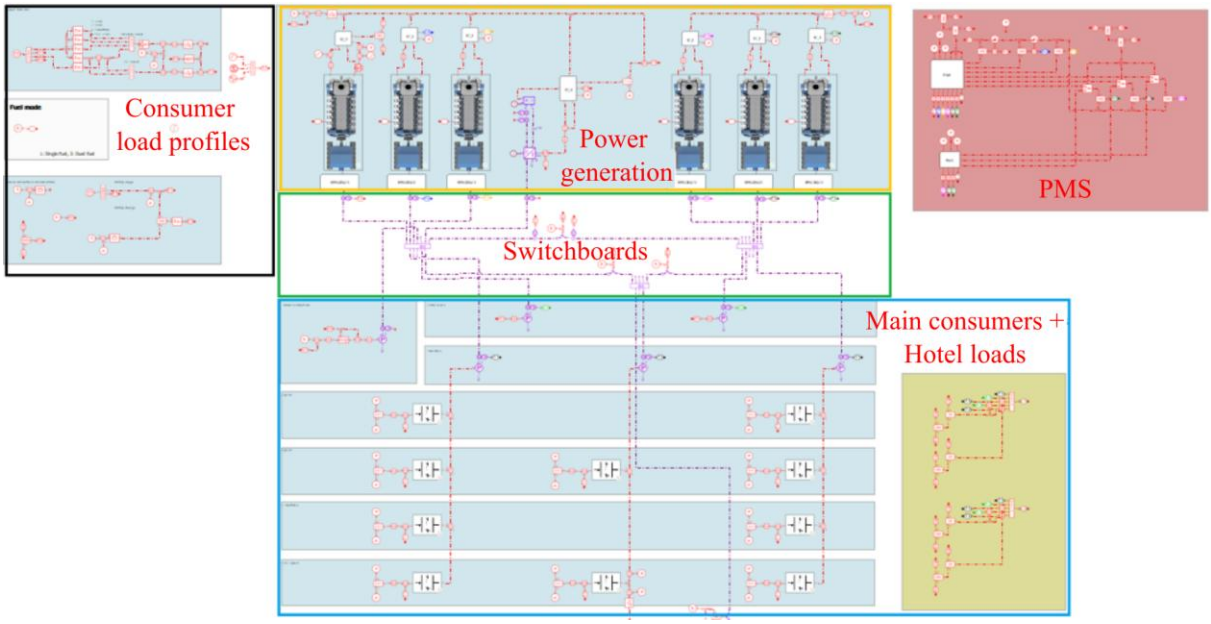

Figure 7: Typical AC power-system model in AMESIM.

In addition to the power system component models, the functionality of the Power Management System (PMS) and a protection system that monitors failures in the governor and Automatic Voltage Regulator (AVR) are also modeled. These models are exported as Functional Mock-up Units (FMUs) and integrated with the Dynamic Positioning (DP) and thruster systems, enabling closed-loop simulation of various DP operations.

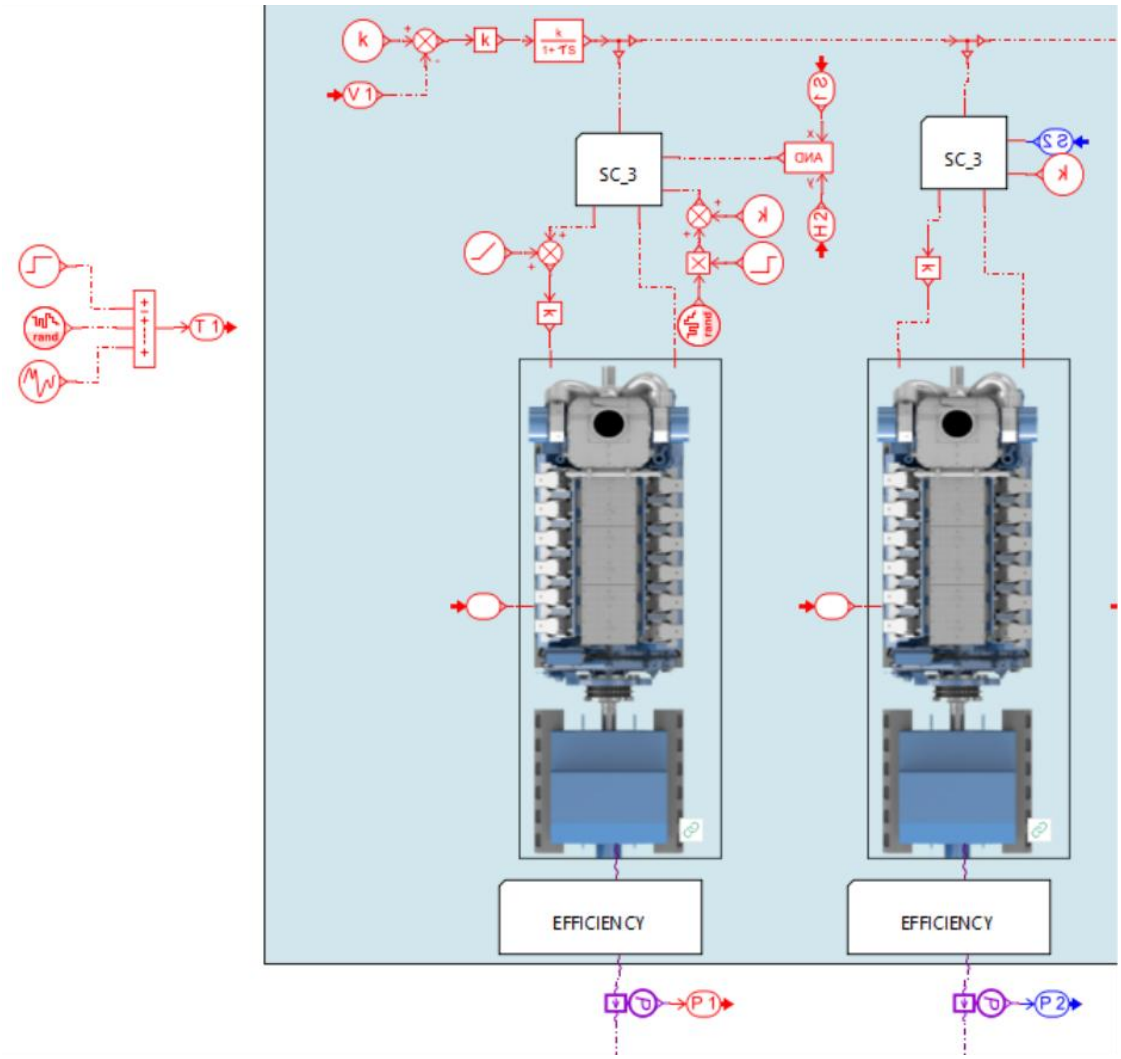

Figure 8: Model of engines, including the efficiency, speed, and voltage-control loop.

The FMUs allow the introduction of failures in the speed and/or voltage controllers during simulation to observe the response of the PMS and protection systems. It is also possible to visualize the post-effect on the DP system, including its position and heading-keeping capabilities.

On the speed controller side, it is possible to simulate conditions such as over/under fuel, speed pickup failures, actuator/sensor failures, and hunting. For the voltage controller, simulations can include over/under voltage, loss of sensing, hunting, field current monitoring, and loss of excitation.

These models enable verification of protection systems under various failure conditions and can also be used to tune the systems prior to onboard installation and commissioning, thereby reducing commissioning hours.

Let us look at a few sample use-cases. The plots in Figure 9 to Figure 13 below indicate the bus frequency (Hz), generator active loads (%), and the total load demand (kW).

Figure 9 shows the results of a simulation where initially only DG1 alone is running, subsequently DG2 is started at ~45 s simulation time. The plots show the dynamics of the bus frequency and the load-sharing between the generators until both generators stabilize at ~40% load. Thereafter, the plots show the

dynamic response of the generators, and the bus frequency to a step increase in load demand at 100 s simulation time.

Figure 10 shows the effect of an under-fuel/loss-of-fuel fault on engine-1 triggered at ~250 s simulation time, and the evolution of the dynamic response of load-sharing and bus frequency. This failure leads to a drop in bus frequency, prompting the healthy generator-3 to take over the load. The protection system identifies this fault condition as *Low Frequency and Low kW* on Generator-1, triggering an alarm followed by a trip command.

Figure 11 shows the effects of an over-fuel fault on engine-1. This failure leads to an increase in bus frequency prompting the healthy generator-3 to drop the load. The protection system identifies this fault condition as *High Frequency and High kW* on generator-1, triggering an alarm followed by a trip command.

Figure 12 shows the hunting behavior of generator-1 following speed pick-up failure. While Figure 13 illustrates, a failure on governor droop-control resulting in slow load and bus frequency oscillations. This failure is identified by the PMS as a load sharing failure resulting in switching the system to another active load sharing mode, if applicable, or the issuance of an alarm.

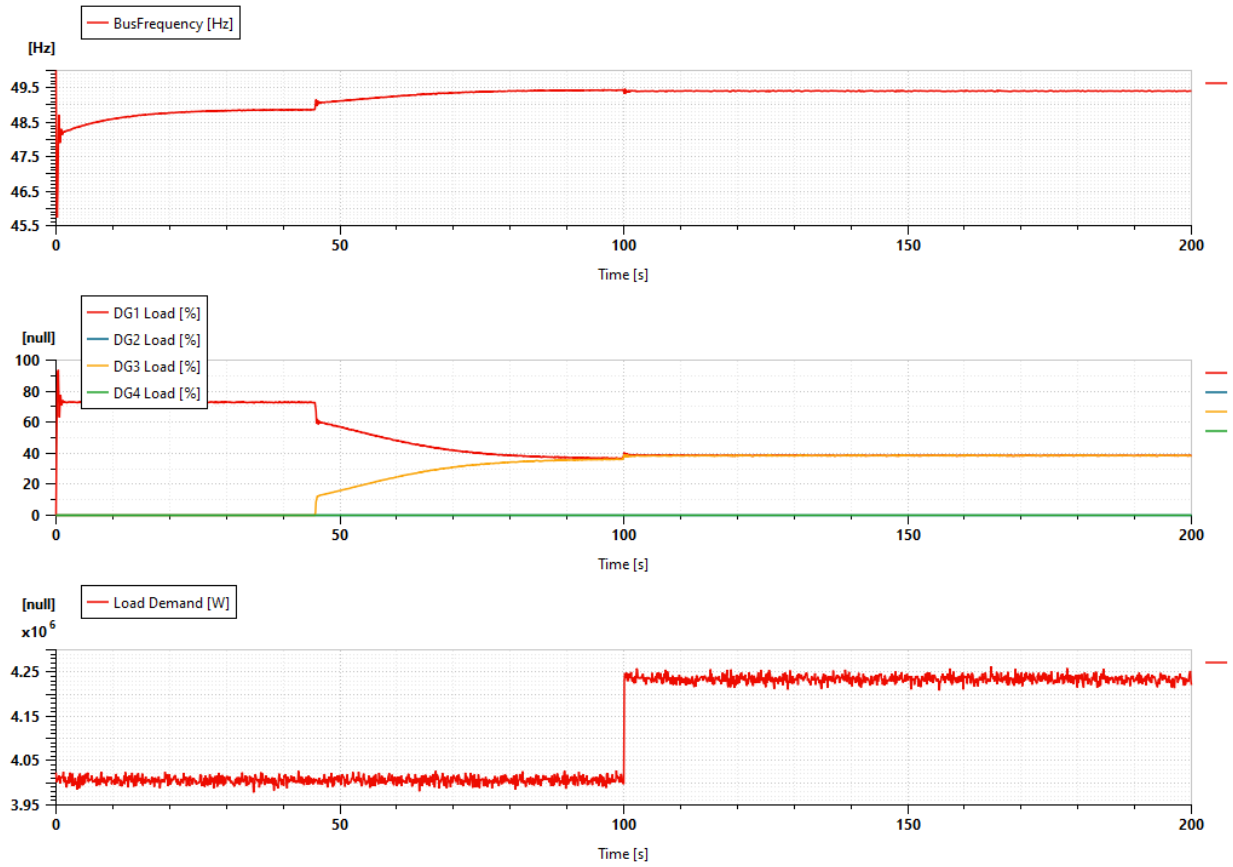

Figure 9: A trend to show the Active Load Sharing between generators 1 and 3 and bus frequency.

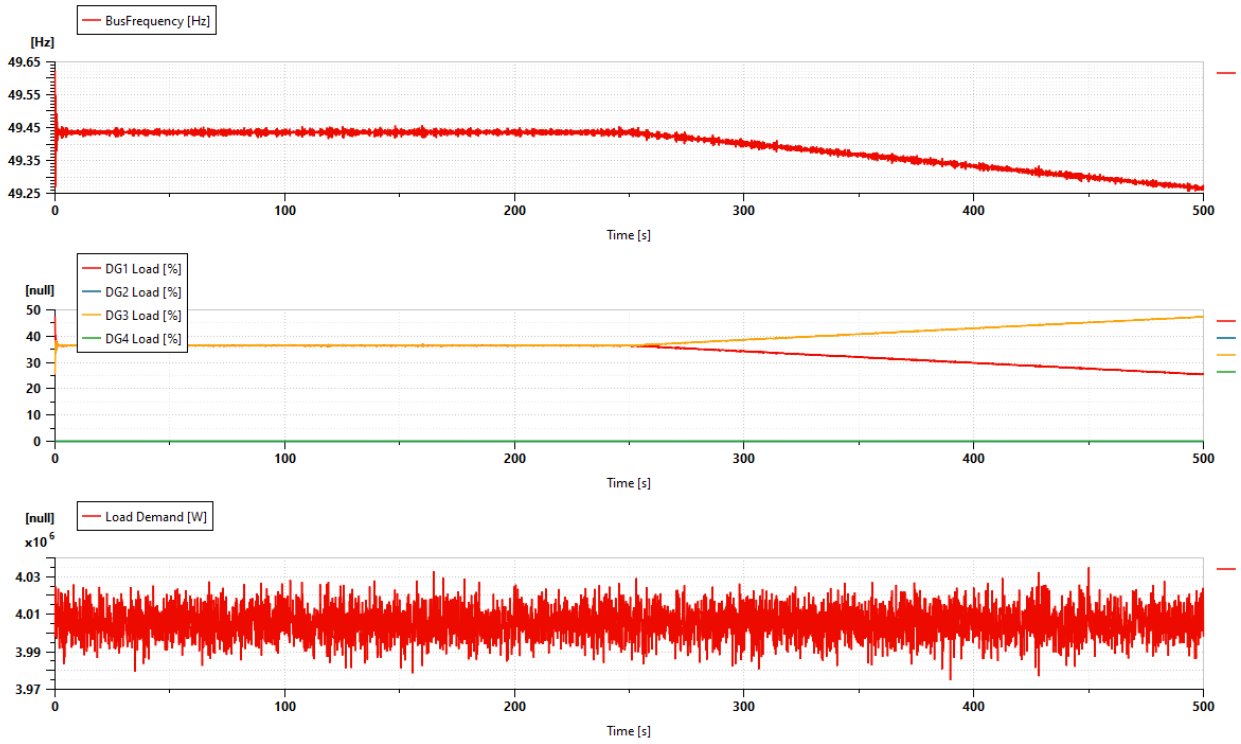

Figure 10: Loss of fuel or under-fuel fault on Engine 1.

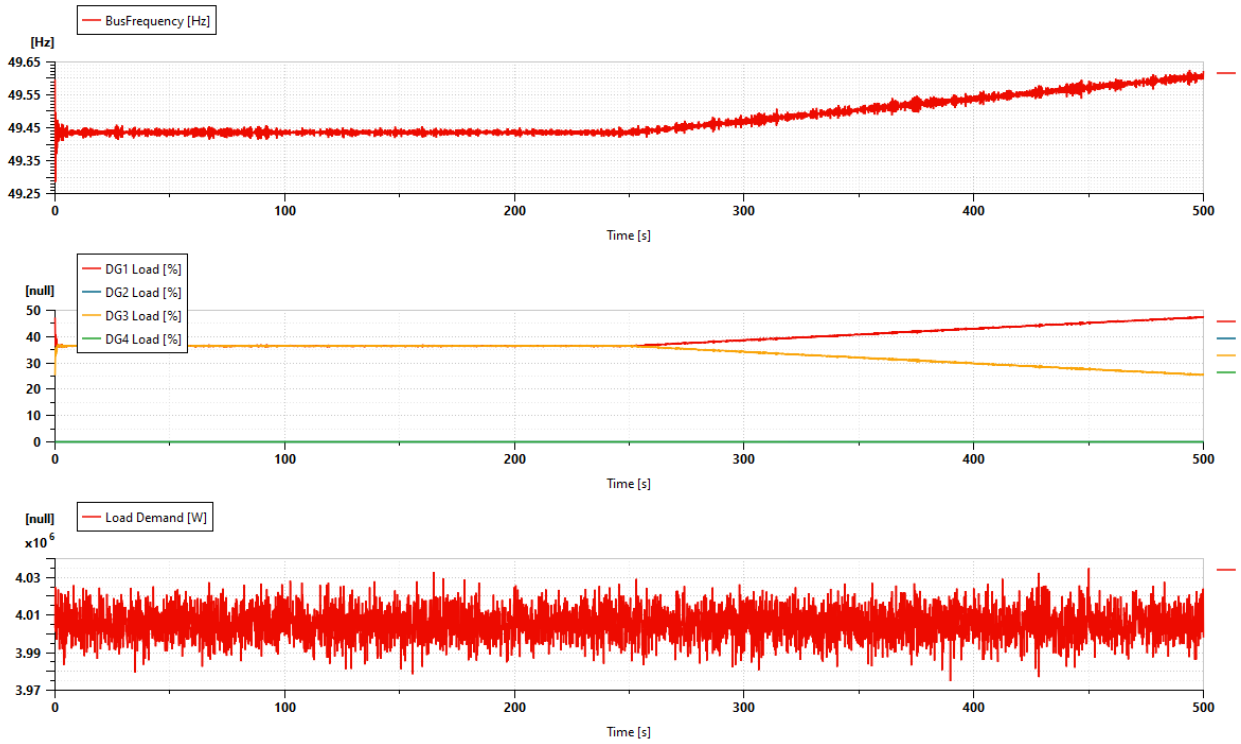

Figure 11: Over-fuel fault on Engine 1.

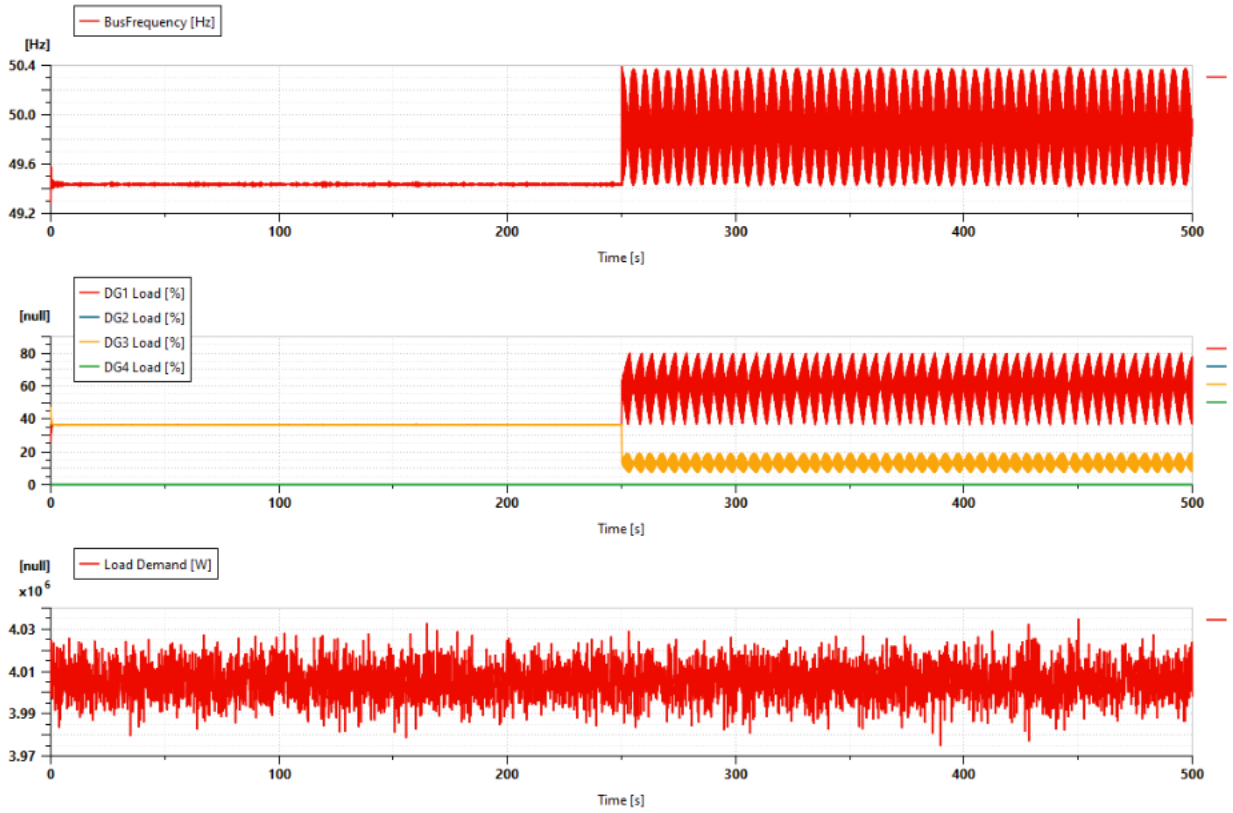

Figure 12 Failure of RPM pick-up on engine-1 resulting in speed-hunting.

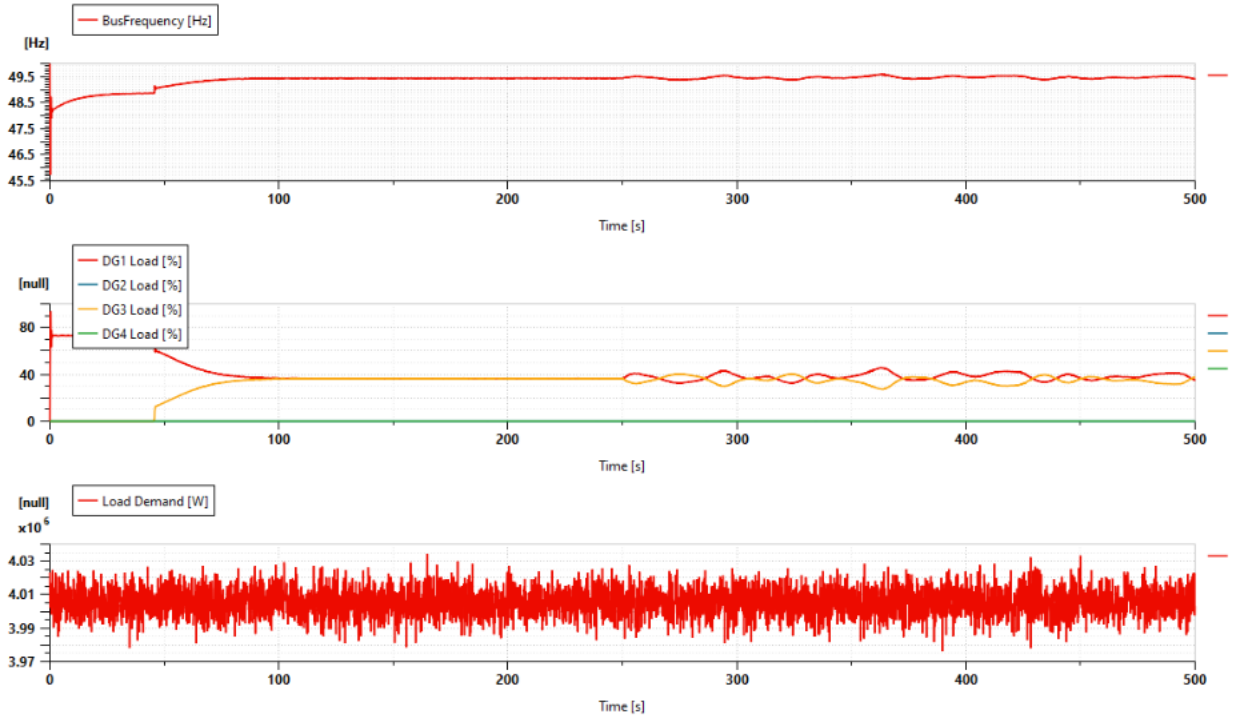

Figure 13: Failure of Governor-droop control resulting in active load-sharing oscillation.

8.3. Case Study 3: CSOV (Project-in-Flight)

KM Ship Design is currently engaged in delivering a Construction Support Vessel (CSOV) that meets the client's functional requirements, guided by recognized industry standards such as JDP01 - Single Fault Tolerance (3), DNV-RP-0684 (2), and MTS Techop RCPD (14). These documents have been instrumental in shaping the preparation and documentation necessary for design, engineering, and pre-delivery phases.

To ensure effective communication among stakeholders, KM has used the RCPD as a reference framework for articulating functional requirements. The delivery involves multiple product areas across various business units, with system integration responsibilities distributed among stakeholders. While KM plays a key role in design integration, this is a collaborative effort involving the yard, class, owner, and 3rd Party.

When clarification is needed, the team refers to the above standards to resolve dilemmas and align decisions with best practices. The principles outlined in the RCPD have been particularly useful for facilitating discussions with internal and external suppliers, ensuring that integration objectives remain clear.

Looking ahead, KM will continue to reference these guidelines when managing design modifications, with a focus on avoiding unintended failure propagation paths during late design stages. DNV-RP-0684 (2) has also been valuable for clarifying control system interactions and supporting documentation requirement related to authority communication and testing requirements.

The illustration below reflects how guidance documents and processes interact during vessel delivery. It is **not a formal KM process**, but rather an overview of how requirements, design development, and verification activities typically align:

Figure 14: Guidance, requirement and test-documentation dependency workflow.

This approach emphasizes collaboration and alignment with industry standards rather than prescribing a KM-owned workflow. The objective for achieving single fault tolerance is guided by JDP01 (3), and DNV- RP-0684 (2). Following the design processes, development the RCPD is established and tested against the "7-pillar comparator", and finally a test and verification plan is developed based on special requirements such as in DNV-RP-0591 (15), RP-0684 (2), statutory and class rules, and additional internal as well as client requirements.

8.4. Case Study 4: Tow Assist

Tow Assist is an advanced solution developed by Kongsberg Maritime for support of towing, positioning, and hook-up of offshore floating structures. Built on K-Pos, the system leverages positioning sensor data, advanced modelling, and interconnected ship systems to enable precise control of towed structures along a track or at a fixed position. Its primary objective is to provide accurate, real-time guidance and coordination for multiple vessels involved in complex offshore operations, ensuring seamless collaboration, improved predictability, and reduced operational risk.

System delivery options
Tow Assist can be delivered through multiple modes to suit operational needs:

- *Distributed Advisory System*
  The system provides real-time situational awareness and graphical guidance via an intuitive interface for the Tow Master. Vessel (Tug) Operators receive recommendations on optimal vessel allocation, propulsion settings, and tow configuration adjustments, enabling informed decision-making without automated intervention.

- *Remote Control*
  In this mode, Tow Assist not only advises operators but also offers semi-automated features to assist with critical adjustments. This hybrid approach enhances efficiency while maintaining operator oversight and control.

  For operations requiring automated and coordinated control, the system can utilize continuous monitoring, and a robust control interface for adjustment of the total *convoy* position and track on-the-fly by a Tow Master. This integrated multi-vessel control allows for global actions to be cascaded as orders towards the localized control system on the tow vessels while still maintaining the ability for manual intervention by the tow vessel operators if necessary.

- *Integrated Support & Training*
  - Pre-Analysis – Simulation and planning for route optimization, risk assessment, and operational criteria validation.
  - Decision Support – Dynamic simulations and predictive analytics to assist in operational planning and execution.
  - Online Advice & Situational Awareness – Real-time monitoring, guidance, and visualization during live operations.
  - Training – Immersive simulator-based training for Tow Masters and towing teams to build confidence and competence.

System validation
As part of the system development, simulation-based testing has been performed at the concept level, verification of software and hardware, and pilot trials of the system used in real operations.

To date, the Tow Assist system has been tested as an advisory system in two full-scale tests:

i. Floating Wind Turbine tow-out, and
ii. FPSO installation. (See

Additional remote control simulation verification tests have been performed for the following scenarios with satisfactory results:

- Loss of connection to one of three towing units
- Tow-sensor failure on one towing unit

- Runaway thruster on one towing unit
  - Bow thruster causing rotation
  - Main thruster causing high tension
- Full thrust ahead by the maneuvering system
- Blackout and partial blackout on one towing unit
- Towline failure
- Heading input failure from the asset (loss of input)
- Heading sensor drift of the asset
- Position Reference System (PRS) failure on the asset (loss of input)
- PRS drift on the asset

These scenarios were validated using K-Sim, K-Pos, and Tow Assist in a co-simulation environment at the KM training center in Trondheim, Norway. The setup included three integrated K-Pos Operator Stations (OS) assigned to three different AHTS vessels and one Tow Assist OS assigned to the FPSO. Each case was documented with video recordings and CRD log files from Tow Assist.

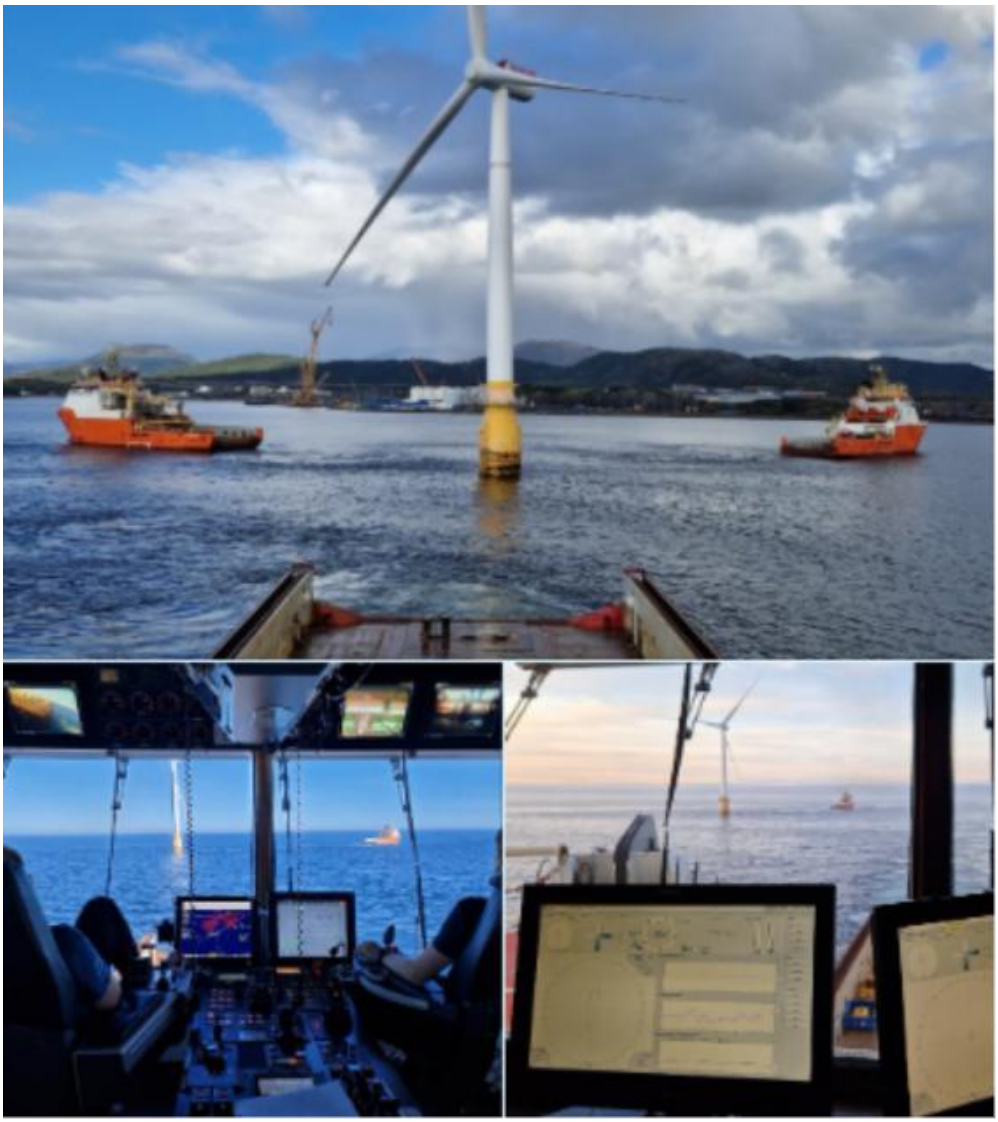

Figure 15: Pilot full-scale test of Tow-Assist (August, 2024).

Figure 16: Simulation environment for remote-control testing.

9. Conclusion

This paper has described how Model-Based Testing (MBT) and Dynamic Positioning System Integration (DPSI) offer a transformative approach to verifying and validating complex marine control systems—well beyond the limitations of traditional FAT/CAT and isolated subsystem testing.

By leveraging MBT, stakeholders can simulate real-world operational scenarios, uncover hidden failures, and validate the integrated system. This can potentially reduce engineering overhead, shorten delivery timelines, and develop a platform to support lifecycle management of a vessel.

The evolving role of the System Integrator is to ensure detailed capture of subsystem integration documentation, and develop a test strategy to ensure that vessel designs meet the redundancy philosophy, technical, and operational objectives. As integration complexity increases, their involvement is critical in bridging gaps between charter and client stakeholders, OEMs, and subcontractors, shipyards.

The case studies presented—from drillship retrofits to validation of novel solutions like Tow Assist—illustrate the tangible benefits of MBT and DPSI in real-world applications. These examples demonstrate the importance of an integration strategy, virtual testing environments, and collaborative verification frameworks to reduce risk and improve vessel performance.

Ultimately, MBT and DPSI are not just engineering tools—they are enablers of predictable outcomes, and future-ready vessel designs. As industry continues to evolve, embracing these methodologies will be essential for delivering safe, efficient, and comprehensively assured marine systems.

Abbreviation / Definition

AGS – Automatic Generator Start
AMESIM – Advanced Modelling Environment for Simulation of Engineering Systems
AT – Azimuthing Thruster
CAT – Contract Acceptance Test
CBM – Condition-Based Monitoring
CFD – Computational Fluid Dynamics
CRD – Case Recording Data (Tow Assist logs)
CSOV – Construction Support Vessel
DIS – Distributed Interactive Simulation
DNV – Det Norske Veritas
DP – Dynamic Positioning
DPSI – Dynamic Positioning System Integration
E-WSOG – Electronic Well-Specific Operating Guidelines
FAT – Factory Acceptance Test
FDA – Frequency Domain Analysis
FMEA – Failure Modes and Effects Analysis
FMI – Functional Mockup Interface
FMU – Functional Mock-up Unit
FPP – Fixed Pitch Propeller
FPSO – Floating Production Storage and Offloading
GPS– Global Positioning System
HiL – Hardware-in-the-Loop
HLA – High Level Architecture
iFAT – Integrated Factory Acceptance Test
IMCA – International Marine Contractors Association
IO – Input/Output
JDP – Joint Development Project
JDP01 – Joint Development Project Objective 1 (Single Fault Tolerance)
KM – Kongsberg Maritime
LCG – Longitudinal Center of Gravity
LNG – Liquified Natural Gas
LR – Lloyd's Register
MBT – Model Based Testing
MiL – Model-in-the-Loop
MTS – Marine Technology Society
OCIMF – Oil Companies International Marine Forum
OEM – Original Equipment Manufacturer
PDP – Pod-Driven Propeller
PID – Proportional-Integral-Derivative (control algorithm)
PLC – Programmable Logic Controller
PMS – Power Management System
PoD – Point of Disconnect
PRS – Position Reference System
RCPD – Recommended Control Philosophy Document
RMS – Riser Management System
ROI – Return on Investment
RP – Recommended Practice
SiL – Software-in-the-Loop
SoC – State of Charge

StatCap – Static Capability Plot
SUT – System Under Test
V/V – Verification and Validation
VCG – Vertical Centre of Gravity
WCF – Worst Case Failure

Acknowledgements

The Authors would like to thank the following Kongsberg Maritime departments for their contribution to this paper:

- Advisory Services: Marine and DP Operations
- Advanced Marine Operations
- Concepts and Advisory
- Digital Ocean: K-IMS and EcoAdvisor
- DP Product Line
- Energy Systems
- Global Customer Support
- Offshore Energy
- Propulsion and Handling
- Ship Design

References

1. MTS. *MTS DP VESSEL DESIGN PHILOSOPHY GUIDELINES (Rev2 - Apr21).*
2. DNV. *RP-0684 Dynamic positioning systems-- system integration.* s.l. : DNV, 2025.
3. OCIMF, IMCA, MTS. *Unified approach to verification, validation and assurance of single fault tolerance in dynamic positioning systems.*
4. Jake Rigby, Prof. Jacqueline Christmas. *Changing definitions of digital twins in ship design.* s.l. : EAAW, 2023.
5. Noack, René. *Developing and testing control unit sofware using virtual models.*
6. *Hardware-in-the-loop testing of DP systems.* Tor A. Johansen, Thor I. Fossen, Bjørnar Vik. s.l. : Dynamic Positioning Committee-MTS, 2005. Dynamic Positioning Conference.
7. *Hardware-in-the-loop testing of marine control systems.* Roger Skjetne, Olav Egeland. 2006, Modeling, Identification and Control, pp. 239-258.
8. *Automated Hardware-in-the-Loop Testing- Experience from Onboard Remote Testing with CyberSea Signature.* Luca Pivano, Nicolai Husteli, Jan Mikalsen, Paal Liset. Houston : Dynamic Positioning Committee, 2015. MTS Dynamic Positioning Conference.
9. *Modelling of a Shipboard Electric Power System for Hardware-in-the-Loop Testing.* Florian Perabo, Mehdi Karbalaye Zadeh. Chicago : s.n., 2020. International Transportation Electrification Conference.
10. OpenSimulationPlatform. [Online] https://opensimulationplatform.com/.
11. *Open framework for digital twin ship data: Case studies on handling of multiple taxonomies and navigation simulation.* í A Fonesca, F F de Oliveira, H M Gaspar. A1, s.l. : Intl. J. Maritime Eng, 2023, Vol. 165.
12. NTNU. [Online] https://www.ntnu.edu/imt/x-in-the-loop-xil-testing-platform-for-a-complex-marine-system-development.
13. DNV. dnv.com. [Online] https://www.dnv.com/services/hil-testing-of-marine-systems-83385/.
14. MTS. *Technical and Operational Guidance, TECHOP(D-11-Rev3), Redundancy Concept Philosophy Document (RCPD).* s.l. : Dynamic Positioning Committee, 2024.
15. DNV. *DNV-RP-0591 Redundant dynamic positioning systems with closed bus-ties.* 2023.

16. IMCA. *Specification and use of DP capability plots Rev. 2.* 2025.
17. DNV. *ST-0111 -- Assessment of station-keeping capability of dynamic positioning vessels.* s.l. : DNV, 2021.
18. *DNV-RP-N103 Modelling and analysis of marine operations.* DNV. s.l. : DNV, 2021.
19. *MSC.1/Circ.1580--Guidelines for vessels and units with dynamic positioning (DP) systems.* Maritime Safety Committee. s.l. : IMO, 2017.