Hardware-in-the-Loop for Naval Platform Power and Energy Test and Evaluation

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ABSTRACT

Traditional test and evaluation of naval platforms utilises a combination of dedicated physical platforms, and modelling and simulation tools. The former provides a high level of assurance, but is expensive, late in the process, and problems can be costly to mitigate. The latter is flexible and economical, but is ultimately constrained by the accuracy of the model.

Hardware-in-the-Loop (HIL) is a hybrid technique that leverages the benefits of both approaches by linking physical equipment to a real-time simulation. One or more real components are replaced with an equivalent model, where the real and the virtual interact as they would in the full system.

Through life management of a platform can be improved by the HIL technique. Key components can be tested as if they were part of the full system earlier in the design cycle, without committing to a full complement of equipment, or a specific system design. Operating conditions can be evaluated in a more repeatable and controlled environment, improving the verification process and support for in-service platforms. New control or equipment technologies can be evaluated with minimal cost, risk, and modification to the test platform, reducing the effort required for technology insertion.

This paper discusses HIL applications to support naval power system test and evaluation, and through life sustainment. Details of a HIL experiment where the main storage battery of a submarine power system is emulated via simulation will be presented to demonstrate the value of including HIL in the repertoire of test and evaluation tools.

INTRODUCTION

Traditional procurement processes for power and energy systems in maritime platforms involve detailed studies which determine the specifications for the various components. Original equipment manufacturers (OEMs) are then selected to supply the equipment based on these specifications. These items are verified via factory acceptance testing before delivery. It is then up to the shipbuilder to integrate the equipment into the platform and perform final integration testing. This method is well suited for mass produced commercial platforms where functionality, configuration, and requirements are generally straight forward, which leads to an established design procedure with known risk mitigation strategies.

Naval platforms differ from commercial platforms in a number of ways. Functional requirements are more complicated as they must satisfy a wide range of design objectives. Advanced bespoke equipment is often necessary to achieve stringent performance requirements, and this creates a number of risks. These technical risks include integration of new equipment that can lead to unforeseeable problems which might not be fully realised until late in the program; as well as certainty in design assurance, since designers are often working with developmental products which they may have little or no prior experience. Ultimately these risks affect the schedule and cost of the program, which can delay or derail successful delivery of a platform. An additional aspect presenting risk for naval platforms is the requirement for upgrading or replacing equipment throughout their service life to maintain a capability edge. This creates a number of challenges for through life design and verification of these platforms.

Effective design testing and evaluation, conducted as early as possible, is a strategy that can alleviate these challenges. This would likely involve a dedicated land based test facility which allows these activities to be conducted well in advance of the final design. The scale of this facility will depend on the risk appetite and budget. The most expensive solution is to replicate the entire power and energy train. This minimises the integration risk for the system prior to installation by allowing the largest range of tests, and should speed up the production process. The alternative is a reduced scale system where only selected equipment is tested. As a reference system for the platform, this test facility also provides a mechanism for live troubleshooting and verification of any changes to the design. Due to the considerable cost in setting up and running such a facility, there is a strong imperative to maximise its utilisation. Furthermore, as the design of the platform evolves throughout its life, the impacts of upgrading and redesigning this facility can be significant.

Hardware-in-the-Loop (HIL) is an experimental technique which enables a real item of equipment to seamlessly interact with a virtual real-time simulation, thus enabling real world testing to occur with a reduced set of equipment. Electric ships and power systems are particular key areas for the utilisation of HIL, as they offer reduced cost and risk for integration testing, and improved flexibility compared to full experimental validation [1] – [7]. This technique can help to mitigate some of the costs and risks of a land based test system, and maximise its utilisation. By providing options for testing that are appropriate for the risk appetite, HIL allows designers and decision makers to trade-off between budget and effort required. It can also be a valuable tool for workshopping faults in a controlled manner, maintaining uptime during maintenance periods, and investigating the integration of new technologies early in the design cycle.

This paper will detail the concept of HIL, and discuss how it can be of benefit to testing and evaluation of a large scale naval system. A number of examples will be presented to support this discussion. The role this technique can play in supporting long term research, development, troubleshooting and upgrade of a naval platform will be outlined. Finally, results from an experimental HIL based battery emulator will be presented to demonstrate the requirements for implementing HIL systems, and the performance they can provide.

HARDWARE-IN-THE-LOOP

The fundamental concept of Hardware-in-the Loop is to break a traditional simulation configuration at the terminals of the system or subsystem that will be replaced (tear point) with its physical counterpart, known as the Item-under-Test (IuT). A hardware interface converts low power signals representing the characteristics at these terminals in the simulation to the appropriate stimulation for the IuT, while sensors measure the response from the IuT to feed back to the simulation and close the loop. This technique has strong similarities with how a player interacts with a virtual-reality game, where the user (IuT) interacts with the game (real-time simulation) through a head-set (interface), and the user's response is measured and fed back through controllers (sensors).

The nature of the signals exchanged with the IuT defines the type of HIL, which can be divided into Control Hardware-in-the-Loop (CHIL) and Power Hardware-in-the-Loop (PHIL). Diagrams outlining these two types of HIL are shown Figure 1 below.

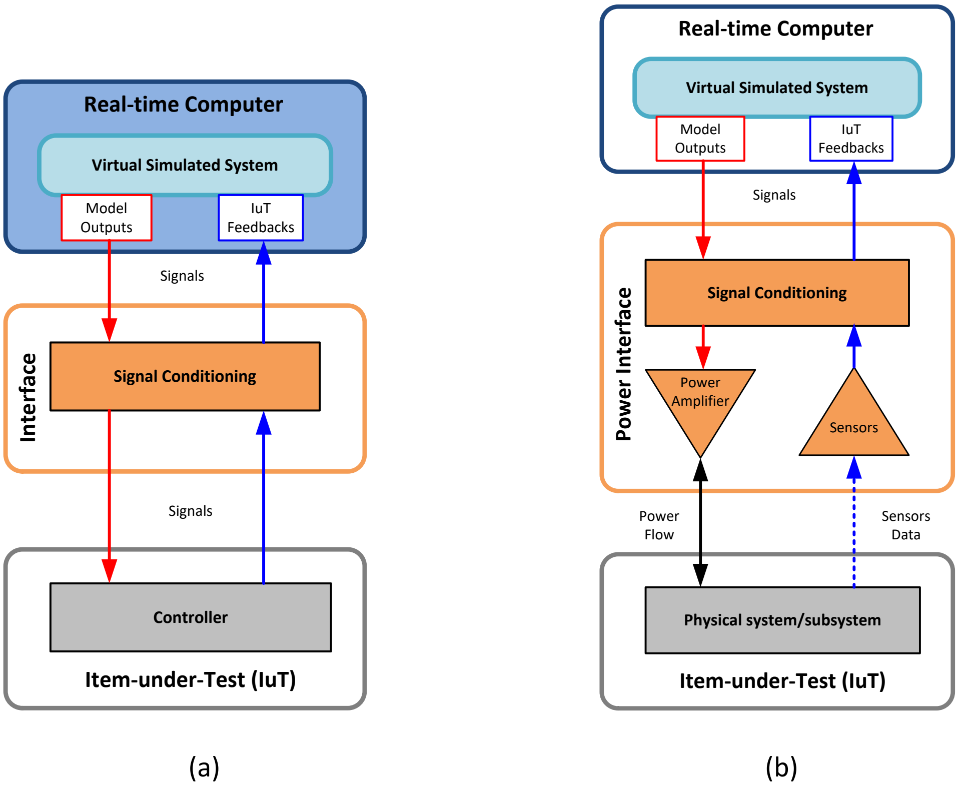

Figure 1: Conceptual forms of Hardware-in-the-Loop (HIL) – (a) Control Hardware-in-the-Loop (CHIL) and (b) Power Hardware-in-the-Loop (PHIL).

Control Hardware-in-the-Loop as shown in Figure 1(a) is focused on the testing of controllers, where a physical controller is the IuT. This controller interacts with simulated versions of the equipment it is intended to control. No real power is exchanged between the interface and the IuT. The interface merely acts as a conduit for control and sensor signals that are exchanged between the IuT and the simulation. CHIL can be used to test items such as software and control algorithms in an environment that is easily controlled, with no risk to physical hardware.

In a Power Hardware-in-the-Loop system as shown in Figure 1(b), the IuT is a physical system or subsystem such as a motor, engine or power distribution system of a ship. The roles of the power interface are to amplify the control signal from the virtual simulation to the power level required to stimulate the IuT, and to condition measurements from the IuT for feedback to the simulation. For electrical systems, the power amplifier facilitates the bi-directional exchange of electrical power by controlling the voltage or current at the interface, and is generally some type of power electronic converter. For mechanical systems, assertion of speed or torque is required, which can be achieved with an electrical motor controlled via a power electronic converter.

For design assurance and prototype testing, both PHIL and CHIL provide a means to emulate the behaviour of a system at both sides of the interface. This enables the system and the integrated platform to be tested in a more realistic environment which can help to expose faults that are difficult to discover via traditional testing.

Some key application examples of HIL, and a discussion of the benefits it can provide as an additional tool for test and evaluation are presented in the following section.

EXAMPLE HARDWARE-IN-THE-LOOP APPLICATIONS FOR TEST AND EVALUATION OF MARITIME PLATFORMS

Hardware-in-the-Loop can be utilised to replace any desired system or subsystem with its physical counterpart. In this section, examples based on a simplified submarine power and energy system, as shown in Figure 2, will be used to illustrate and discuss how HIL can support test and evaluation of maritime platforms, in conjunction with or in place of a full test system.

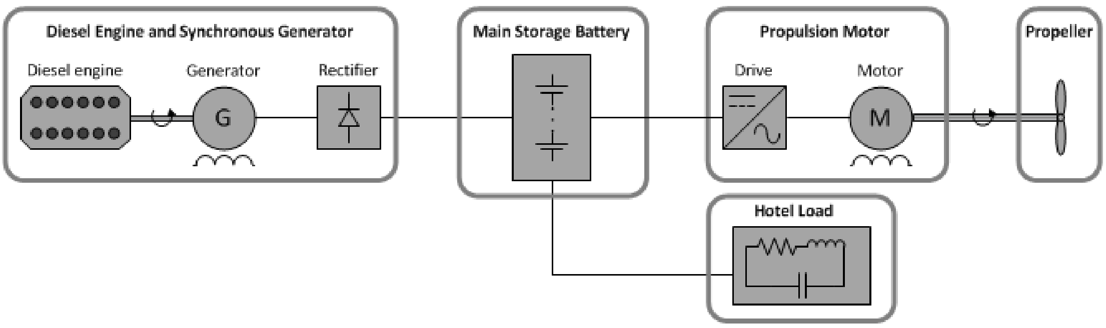

Figure 2: A simplified submarine power and energy system.

Hardware-in-the-Loop Emulation of a Propeller Load

An excellent candidate for PHIL is the emulation of the propeller with an electrical machine controlled by a power electronics converter as shown in Figure 3. While more expensive and complicated compared to a traditional water brake or other dynamometer load, this system should provide better replication of the propeller load dynamics. This allows the propulsion motor to be easily and repeatedly loaded according to any desired operational profile for the propeller.

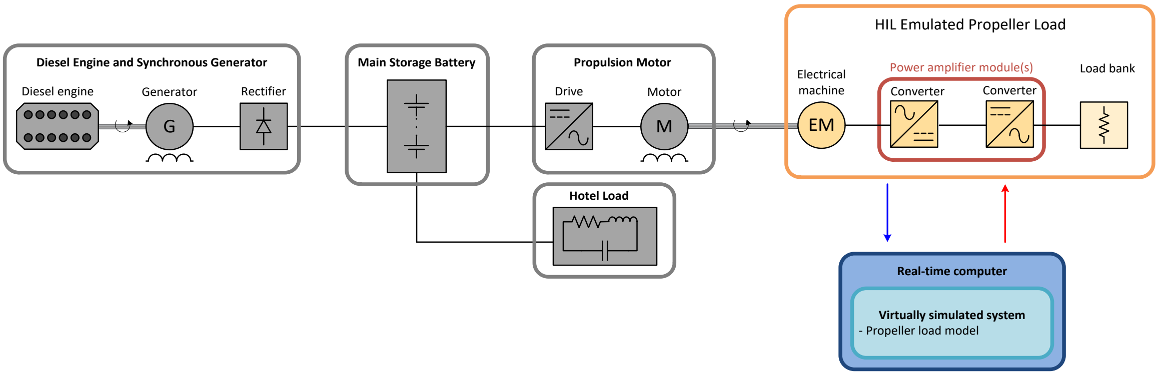

Figure 3: A simplified submarine power and energy system with emulated propeller load.

This HIL topology allows the test system to leverage the benefits of having a high quality propeller model into realistic stimulation of the propulsion system. Changes to the propeller model over time are also easily incorporated. An additional benefit of emulating the propeller via this topology is realised when used in conjunction with the following example.

Hardware-in-the-Loop for Mechanical Systems

Two key examples of how individual mechanical items can be tested with a HIL implementation are shown in Figure 4 and Figure 5. Figure 4 shows a HIL configuration which uses an electrical machine to draw power from a diesel engine. The mechanical load profile applied to the engine is controlled by the virtual simulation of the rest of the power system. The configuration in Figure 5 takes the concept one step further by interfacing a main propulsion motor to a virtual simulation at both its input and output. The simulation is configured to apply realistic supply and load stimuli such that the motor is tested as if it were connected to the actual power system. As shown in Figure 5, this topology also has the ability to recirculate the electrical power to minimise the overall power consumption.

Both topologies are useful for tests that do not require full fidelity, or when it is not desirable to operate the rest of the physical system if it exists. For example, an endurance test of an item of equipment over a long period of time would be expensive for a full test system in terms of fuel costs and maintenance overheads. Furthermore, it would prevent a full test system from being used to perform other tests. Subject to availability of hardware, the configurations outlined in Figure 4 and Figure 5 can be operated in parallel to reduce costs and maximise the utilisation of a test facility.

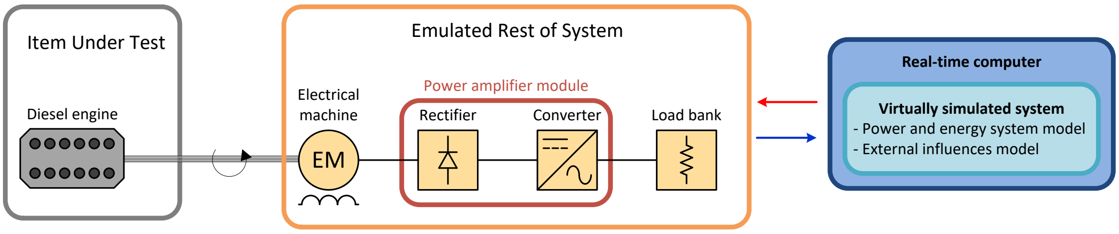

Figure 4: Hardware-in-the-Loop configuration for testing a diesel engine.

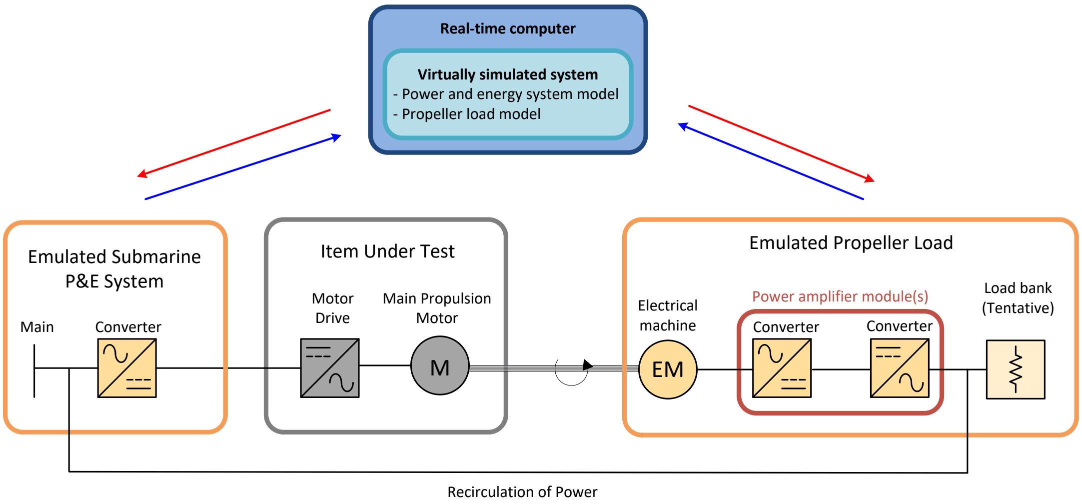

Figure 5: Hardware-in-the-Loop configuration for testing a main propulsion motor.

Hardware-in-the-Loop Emulation of a Main Storage Battery

A main storage battery strongly affects the performance, stability, and characteristics of the power and energy system of a maritime platform. Tests that involve the main storage battery can often be difficult to coordinate and time consuming, as significant efforts are required to condition the system to the required state.

Emulation of a battery using PHIL can be implemented as shown in Figure 6. The battery model is simulated and interfaced with the rest of the system via a power electronic converter. This topology has a number of advantages compared to a real battery. First, unlike a real battery, an emulated battery does not deteriorate with age. Second, the emulated battery does not require pre-conditioning prior to a test. This can eliminate or minimise significant long term running costs of such a system. Key parameters including age, state of charge, and state of health can be easily adjusted within the virtually simulated system and hence the emulated system, significantly reducing the preparation required for an experiment. An experimental proof of concept for emulating a battery via PHIL will be presented in the following section.

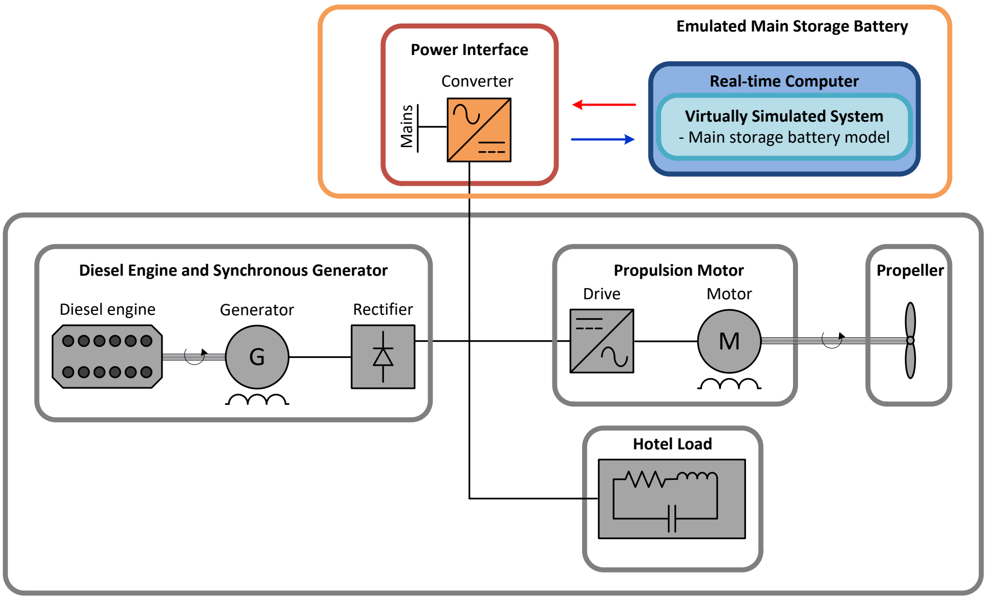

Figure 6: A simplified submarine power and energy system with an emulated main storage battery.

Discussion

Replicating the behaviour of a simulated system at various tear points using HIL provides an interesting means to scale hardware testing to satisfy the appetite for cost and risk in verifying a design. While it is expected that testing conducted in a large scale facility which fully replicates a platform should have the highest level of fidelity, it is also a very expensive solution. Examples in this section have demonstrated how HIL can be used to enable testing from a single component to the entire system. While subject to the accuracy of simulation models and the interface, a HIL system will not be able to fully replicate the exact behaviour of the original system. However, for most applications HIL based systems should provide sufficient fidelity to deliver the necessary level of assurance. Hardware-in-the-Loop ultimately gives the designer an extra tool for achieving the objectives of the test and evaluation program.

Broadening the range of tools available for testing provides options for test designers to satisfy various considerations such as: reducing overall program costs, improving scheduling and utilisation of test facilities, investigating faults, and early assessment of the impact of new technologies.

For the maritime platform considered in this paper, emulation of the main storage battery demonstrates an opportunity for a PHIL system to replace expensive consumables to achieve savings, while increasing overall flexibility. The implementation of this example will be further explored in a case study in the next section. Replacement of diesel generators with a power electronics based emulator powered by the main supply can further reduce fuel and maintenance costs. An emulated system can also work in parallel to partially replace a real system, providing trade-offs between cost and fidelity.

Schedule risk is a common consideration, as inevitably unforeseeable events such as damage to key components can cause delays in the test program. The impact of delays can be lessened by replacing unavailable components with an emulated system, enabling critical tests to continue with well understood penalties in overall fidelity. HIL implementations also enable a large test system to be broken into smaller test benches that can be operated in parallel, such as the mechanical system testing example. This provides additional scheduling options and maximises system utilisation.

By modifying models in the virtually simulated system, HIL implementations can be manipulated to replicate faults in a controlled and safe manner. This provides a valuable tool for troubleshooting and fault mitigation. For example, testing a main storage battery short circuit could cause significant damage to the battery and surrounding systems. A battery emulation based on a sufficiently rated power electronic interface allows the test to be conducted repeatedly in a controlled manner. As the understanding of a platform improves and the virtually simulated system is enhanced to more accurately reflect the behaviour of a real system, selected high risk tests can be conducted in the virtual system. Additionally, CHIL provides the option for testing software without risk to the real equipment, and can be conducted in parallel with other testing activities.

The ability to emulate behaviour of virtually simulated models using HIL also provides an interesting tool for research, development and testing of upgrades for a platform. The traditional process for upgrading a component is: simulation development, manufacture of a prototype, and verification in a complete system. HIL can provide an intermediate step between simulation and prototyping, by emulating the developmental component in a full test system. This enhances confidence in the design by allowing problems to be identified early, and potentially reduces the number of design cycles required. Initial integration testing can also be performed alongside the design verification. Both measures should reduce problems encountered with the eventual prototype. In the long term, emulated components with verified performance provide alternatives for testing upgraded components in a reference system for the platform. This reduces the need to maintain a full inventory of all versions of key components over the life of the platform. Additionally, the stress placed on the test system due to configuration changes, and requirements to work on parallel versions of the same platform are eased.

In summary, HIL provides a tool for designers and decision makers to scale their test regime according to the risk appetite throughout the life of a platform. Obviously the fidelity of a test is affected by how much of the real system is emulated, which directly affects the level of assurance a test can offer. However, the HIL implementation offers reduced setup effort, running cost, and risk, which can be an acceptable compromise.

The following section presents an experimental case study of PHIL emulation of a main storage battery to demonstrate the practical implementation and performance of the technique.

POWER HARDWARE-IN-THE-LOOP EMULATION OF A MAIN STORAGE BATTERY CASE STUDY

A low power, proof of concept PHIL experiment where a main storage battery is emulated in a physical test system has been performed at DST. The purpose of the experiment was to demonstrate the technique itself, as well as the performance.

A simplified equivalent electrical circuit for the submarine power train is shown at the top of Figure 7. It consists of the battery and the current flow to or from the rest of the system. To demonstrate this PHIL implementation, the experimental system needs to simulate the battery model and provide a power interface to the physical rest of system (ROS) as in Figure 6. However, in a low power system such as that at DST, the rest of the physical system does not exist. Therefore, the experimental proof of concept system also needs to emulate the ROS. The physical ROS was implemented as a current exchange with the emulated battery terminal as shown at the bottom of Figure 7. The exchange was configured to be representative of the power that the actual submarine systems would draw from or supply to the battery.

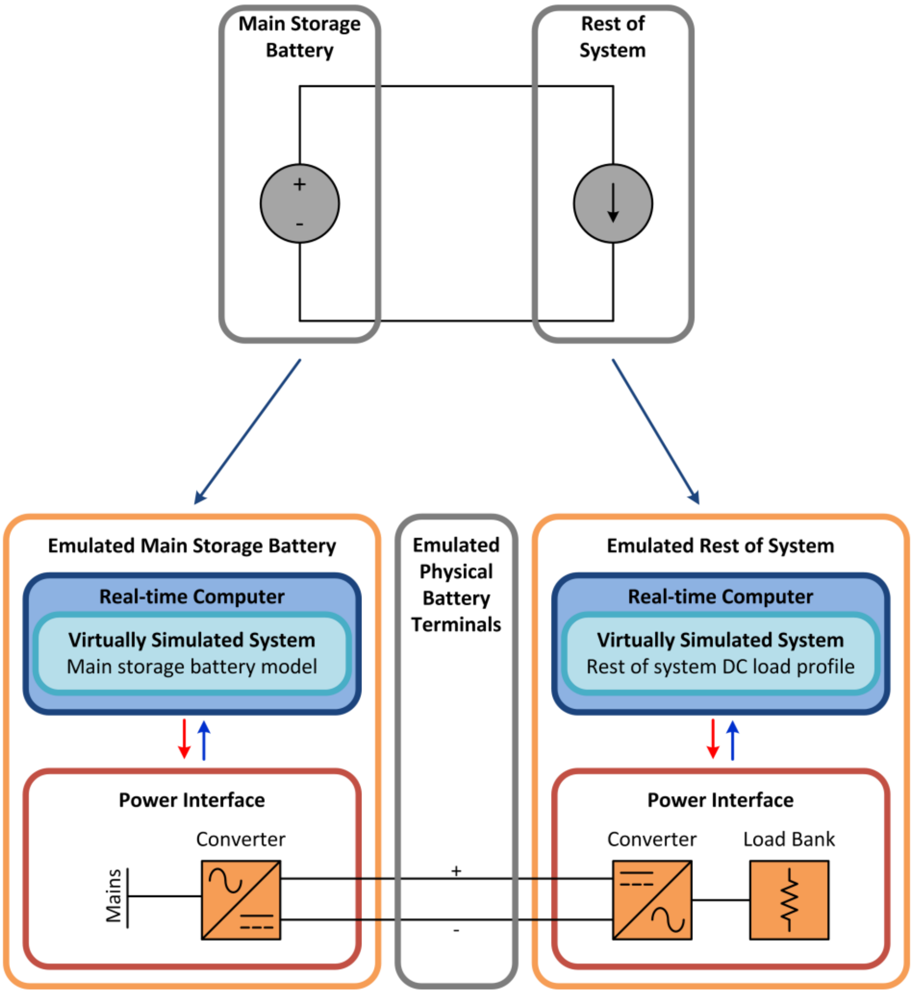

Figure 7: Reduced scale Power Hardware-in-the-Loop emulation of a main storage battery – simplified equivalent electrical circuit of a submarine power train (top); Power Hardware-in-the-Loop implementation (bottom).

Battery Simulation Model

A generic lead-acid battery model has been constructed from experimental data collected by DST from a single lead acid battery cell. The experimental data captured the response of the terminal voltage of the battery cell to a stimulation current profile. The model was built from the Ceraolo flooded lead-acid model [8], which is a network of electrical components tuned to represent the dynamics of a battery as shown in Figure 8. The experimental data was used to determine the parameters of the model via a parameter optimisation process. The resulting model provides good reproduction of the original experimental terminal voltages when stimulated with the same current profile. A larger battery string is obtained by simply scaling the output of the single cell model to the desired number of series cells.

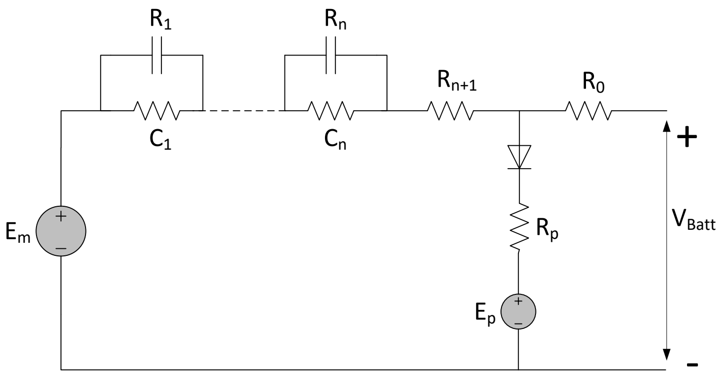

Figure 8: Ceraolo flooded lead-acid battery model.

Experimental Configuration

The configuration for the PHIL experiment is shown in Figure 9. It consists of three power amplifier modules (PAMs), two load banks, and the Real Time Digital Simulator (RTDS) Technologies' real-time computer. The PAMs are a power electronic building block approach to enable virtually any interface topology to be constructed, including the DC terminals necessary for emulation of a battery as shown in Figure 9. The PAMs were designed to maximise bandwidth for their power level to facilitate interfaces with as much transparency as possible while maintaining stable operation [9].

The control objectives of the interface for this configuration are the DC voltage and the DC power draw. The DC voltage is controlled by PAM2 which regulates the power exchange with PAM1 to obtain the target voltage provided by the terminal voltage of the simulated battery model. The DC power is regulated by PAM3 and the measured current is fed back to the simulated battery model. This creates the closed loop system where the battery simulation model is stimulated by the experimental current, i.e. Power Hardware-in-the-Loop.

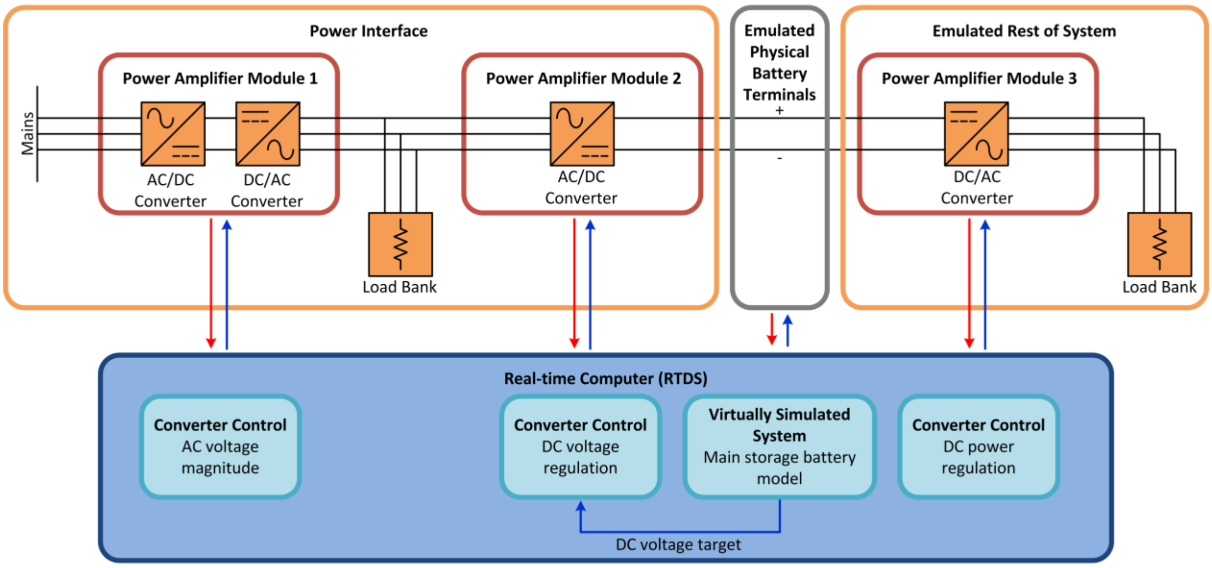

Figure 9: Experimental system configuration.

Power Hardware-in-the-Loop Results

The PHIL experiment was performed for 20 minutes, with 5 minute alternating cycles of charge and discharge. A constant current at the emulated battery terminal was used for both cycles as shown in Figure 10, and the transition between the modes was instantaneous.

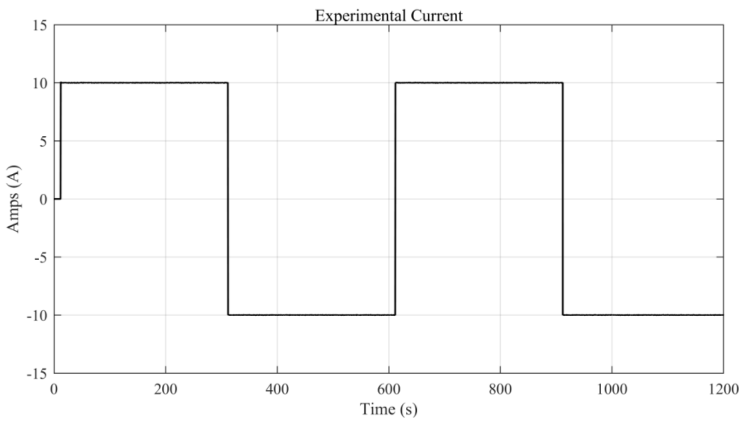

Figure 10: Experimental battery current during 20 minute PHIL experiment.

The simulated and experimental battery voltage waveforms obtained from the PHIL experiment are shown in Figure 11. A closer view of the charging cycle is shown in Figure 12. Both plots show good agreement between the simulated and experimentally emulated battery terminal voltages.

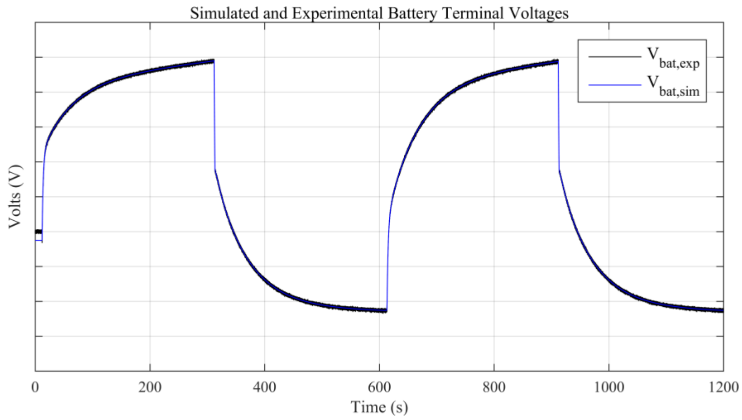

Figure 11: Simulated and experimental battery terminal voltages during 20 minute PHIL experiment.

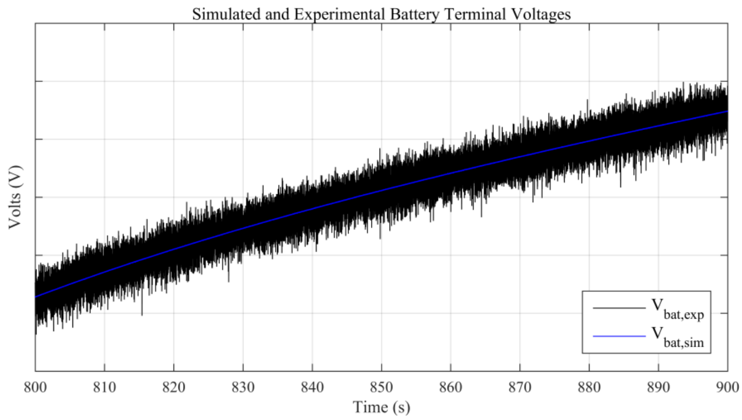

Figure 12: Simulated and experimental battery terminal voltages during 20 minute PHIL experiment – zoomed on peak of charge.

The dynamic performance of the emulation is demonstrated in Figure 13 where the change in voltage at the transition from charge to discharge is followed accurately at the emulated battery terminals. Both the steady state and dynamic performance demonstrate that the physical ROS is being presented with an accurate representation of the simulated battery terminal characteristic. Additionally, the shape of the voltage waveform is largely as expected indicating that the battery model is being stimulated appropriately.

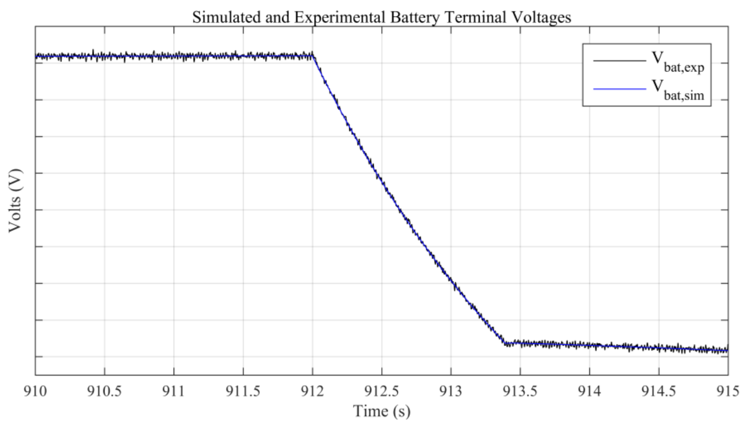

Figure 13: Simulated and experimental battery terminal voltages during 20 minute PHIL experiment – zoomed on charge to discharge mode change.

A battery is an excellent candidate for PHIL due to its slow dynamics. The real-time simulation model can achieve excellent fidelity under these conditions since the trade-offs required to achieve real-time operation are minimised. Furthermore, the experimental system can offer significantly faster dynamics than the battery, which minimises the impact of implementing the PHIL experiment.

While this experiment has been carried out at low power, the experimental control systems and the simulation model are fully transferable to higher power levels. The excellent performance is also expected to be maintained, as shifting both the experimental and simulation systems to higher power should allow the experimental system to remain significantly faster than the simulation.

CONCLUSION

Through life test and evaluation of the power and energy system for a naval platform is difficult due to the complex functional requirements, continuous upgrade cycles and advanced bespoke equipment. To meet these challenges, testing is increasingly being conducted in dedicated land based test facilities, prior to installation into a platform. However, this approach requires a great deal of effort and cost. Therefore there are strong imperatives to maximise such utilisation while minimising overall program budget.

Hardware-in-the-Loop (HIL) is a technique which enables a real item of equipment to seamlessly interact with a virtual real-time simulation. It provides a means to realistically emulate operation of a system at almost any point. This paper has discussed the basic concepts behind HIL. Through a number of examples and a case study, the application and opportunities that HIL can provide for test and evaluation of maritime platforms have been demonstrated. The strength of HIL is its ability to realistically emulate key components of a system, and realistically stimulate real items without the full complement of equipment. This provides a tool for designers to manage schedule and cost risks via more thorough testing. The concept can also benefit the through life support of a platform, from the design stage, to long term research and development of new technologies to maintain a capability edge. Ultimately, HIL provides a tool to scale and customise the testing regime according to the risk appetite, while trading off against the required fidelity and effort.

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