Demonstrating the Power Hardware-in-the-Loop through Simulations of a Notional Destroyer-Class All-Electric Ship System during Crashback

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***Abstract*—In this paper, a notional destroyer-class all electric ship system, particularly its dynamic behavior during the crashback maneuver, is studied via real time Power Hardware-in-the-Loop (PHIL) experiments. By replacing one of the two propulsion systems of the ship with a down-scaled hardware motor-dynamometer set, the PHIL simulations are performed at two different power levels (first at 16 kW and then at 2.5 MW). It is shown through the simulation results that although the two propulsion systems are implemented in substantially different ways (i.e., one in hardware and the other in simulation) their dynamic responses during the crashback match very well. This also demonstrates the feasibility and reliability of using the PHIL simulation as an effective tool for testing the prototypes of novel apparatuses under the most realistic scenarios.**

***Index Terms*—Real-time simulation, crashback, all-electric ship, hardware-in-the-loop**

I. Introduction

In the past, hardware-in-the-loop (HIL) simulation has been used primarily for studying interactions of control and protection equipment with simulated power systems [1] and [2]. Figure 1 depicts the basic concept of a hardware-in-the loop simulation. The major part of a system, i.e. the integrated power system of an all-electric ship, is simulated on a real-time power systems simulator. One or more components of its control or protection system are available in form of actual pieces of hardware.

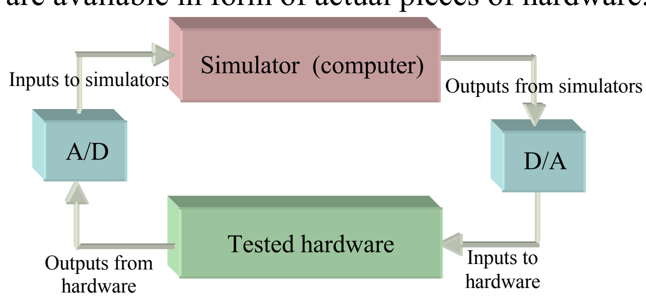

Figure 1 Basic concept of a HIL simulation setup

This hardware receives control signals from the simulation via digital to analog (D/A) converters. In return, it sends control signals back into the simulated system via analog to digital (A/D) converters. A dedicated computer based real-time simulation platform with adequate D/A and A/D conversion channels is required for this method. The inputs and outputs in Figure 1 are only required at control signal levels (i.e. typically within a range of +/- 10 V). Therefore, no significant power amplification is required.

Extending the concept of HIL into the realm of power equipment, where the tested hardware is no longer a control or protection device but, for example, a motor or power electronic converter, results in the so-called power hardware-in-loop (PHIL) simulations. The output from the simulator now has to be sent through an appropriate power amplification and conversion apparatus before imposed onto the power hardware. The nature of this power amplifier depends on the type of hardware under test and may range from a dynamometer for mechanical type simulations to power electronic converters for electrical type simulations. This concept has been used in the past primarily for automotive applications [3] and occasionally for electric power applications [4] at the lower power range of several kW.

A. Why HIL and PHIL

In the process of designing an all-electric ship, its components, and its subsystems HIL and PHIL simulations can be utilized in the future to

- aid in R&D through risk free, but versatile testing procedures,
- improve the performance and reliability of equipment and systems through testing of realistic operating scenarios, and
- mitigate risk associated with new technology deployment.

The advantage of HIL and PHIL is that the piece of hardware under test can be subjected to highly realistic, hence dynamic and transient conditions during testing. If at all, such conditions are otherwise often only possible during sea-going field testing or very elaborate land-based laboratory testing requiring essentially a full replication of the ship power system.

Therefore, researchers at the Center for Advanced Power Systems (CAPS) at Florida State University have been working for several years to set up a facility enabling PHIL simulations on a large enough power scale, either at the actual equipment rating or a reasonably reduced power rating.

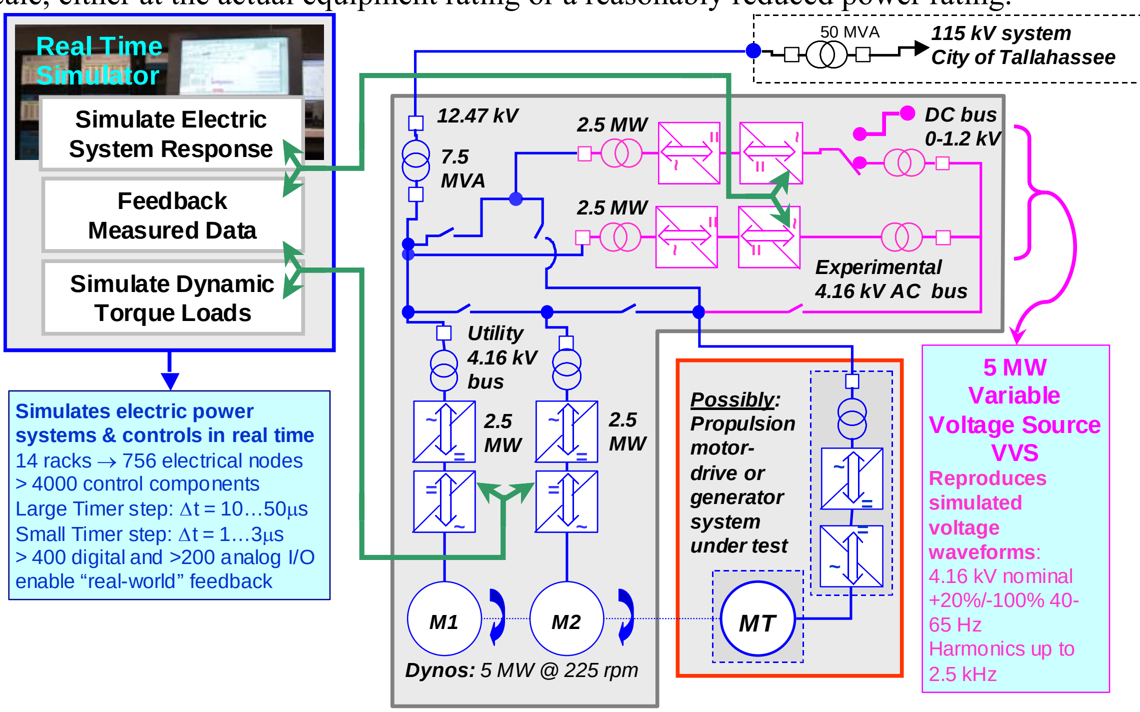

Figure 2 Single line diagram of the existing CAPS 5 MW hardware-in-loop test facility (items in magenta are currently being installed)

This paper first describes briefly the current PHIL facility at CAPS and its expansions soon to be commissioned. Thereafter, an example of a PHIL experiment carried out with the low power (16 kW) PHIL test equipment at CAPS is presented. This example is a full system simulation of a crashback maneuver of a notional destroyer class ship which is explained in great detail in a companion paper [5]. We then present another PHIL simulation with a 2.5 MW motor-dynamometer set which demonstrates the capability for such experiments at that power level. In the appendix we provide a short introduction to the stability problems inherent to PHIL and explain some possible solutions. The aim of this paper is to communicate how the new concept of PHIL may be applied to study complex system-equipment interactions for all-electric ship applications.

II. PHIL FACILITY AT CAPS

CAPS is in the process of establishing a very unique 5 MW (6.25 MVA) PHIL experimental facility with focus on all-electric ship applications. The single line diagram of this facility is depicted in Figure 2. Powered from a close-by 50 MVA/115 kV substation it consists of the following major sub-systems:

- A 14 rack setup of the commercial real-time power system simulator RTDS [7]. It allows the simulation of a substantially large power system (756 electrical nodes) and its components (machines, transformers, cables, converters) in real-time with typical time steps of 50 μs. Power electronic converter sub-systems can be simulated with even smaller time steps of typically 1.5 μs.
- Two 2.5 MW low speed (230 rpm) dynamometers with four quadrant variable speed drives (VSDs). The two machines can either operate in tandem against a machine under test up to 5 MW or against each other when no test machine is available. Speed and torque references can be provided directly from the RTDS system to the VSDs. In return, the RTDS receives instantaneously measured shaft speed and torque for PHIL operation.
- A PEBB based [6] four-quadrant power converter system (VVS) rated at 5 MW (6.25 MVA). The output of this VVS provides a 4.16 kV class experimental bus at which the instantaneous voltage waveform reference can be provided by the RTDS. In return, the RTDS receives instantaneously measured output currents for PHIL operation. This converter system is currently being installed and commissioned and is expected to be operational by early 2007.
- A down-scaled version of the VVS system with a power rating of 50 kW and the motor-dynamometer system rated at 16 kW (both not shown in Figure 2). This setup can be used to perform PHIL experiments on low power equipment and serves also as a means of risk mitigation for the high power system.

The high-power PHIL setup will allow for the first time to connect MW class electric power apparatus to an experimental bus which can represent any desired characteristic by means of real-time simulations. For example, the actual behavior of an all-electric ship or an islanded micro grid in the utility realm will lead to a measurable frequency decrease under overload conditions. Or the loss of a generator in such a system may lead to increased voltage distortions due to the increased system impedance. All these phenomena can be replicated at the 5 MW experimental bus in real time while the reaction of any load connected to it (i.e. the VSD of the motor under test in Figure 2) will properly reflect back into the simulation environment due to the close loop arrangement.

III. 15 KW PHIL EXPERIMENT

A. *Notional E-ship system*

The simulation capability used in this study is based on a concept for the IPS of a notional destroyer developed by the Syntek Corporation under contract to the Office of Naval Research [8] and [9]. This concept involves a power generation system, a propulsion system, and a DC zonal electric distribution system. A 13.8 kV medium voltage (MV) ring bus is supplied by two 36 MW main gas turbine, synchronous generators, and two 4 MW auxiliary gas turbine generators. The MV subsystem supplies two 36.5 MW propulsion motors (PORT and STARBOARD), a 3 MW shipboard radar, and three AC-DC power conversion modules that rectify 13.8 kV AC to 1 kV DC for powering port and starboard DC buses. The longitudinal DC buses feed 1 kV DC power to load centers in five zonal regions along the ship.

The CAPS E-ship model implements this notional IPS concept through the use of 116 parallel digital signal processors (DSPs) on nine racks of the RTDS as depicted in Figure 3. The electrical network is defined by 345 nodes and includes representation of all AC circuit breakers and DC disconnect switches. The simulation runs in real-time with a fixed time step of 80 μs.

B. Crashback Maneuver

To demonstrate the dynamic interactions between the electric ship system and the propulsion system, a crashback maneuver is performed. Besides faults or pulse power applications this maneuver is one of the more demanding maneuvers a ship electrical system may encounter. The goal is to stop the ship from full forward motion in the shortest possible time (in a straight line without any turning maneuvers). As described more detailed in [5] the crashback maneuver consists of four distinct phases.

- First the propeller speed decreases rapidly until the power flow in the propulsion motor reverses. As a consequence, the propulsion power decreases which requires the eclectic generators to follow this load shedding accordingly. The dynamic characteristic of the generator's prime movers is the limiting factor in the allowable rate of power decrease. Power control with adequate ramp rates is employed to ensure generator operation limits are not exceeded.
- Once the propeller speed is low enough such that the hydrodynamic torque reverses the propulsion motor start generating power. This power has to be rejected either by braking resistors within the motor's variable speed drive (VSD) or by the system's electrical loads, if the VSD allows regeneration into the electrical distribution system. Therefore, the regeneration power is usually limited to approximately 10% of the rated propulsion power.
- The second phase ends when the ship has slowed down to a speed where the requested regeneration power exceeds the power available from the propeller. At that point, the system goes through an unstable region of the hydrodynamic power curve which causes the propeller speed to rapidly reverse direction and the motor power becomes zero. After this transition the propulsion increases positive power demand from the electrical system and ramps it up, again limited by the loading characteristic of the generators.
- The final phase of the crashback is the least dynamic one where the ship speed decreases down to zero with the motor operating at a constant preset power level.

C. PHIL setup

In order to implement such a maneuver in a PHIL experiment the PORT side propulsion system of the entire power system simulated on the RTDS (see [5] for details) was substituted by a 16 kW motor-dynamometer set available at CAPS. Figure 3 depicts the setup. A step-up transformer TF1, a variable speed motor drive MD1, and an induction motor MT1 compose the hardware representation of the ship's PORT propulsion system. This system is supplied from a controllable power electronic building block (PEBB) -based PWM type converter acting as a voltage amplifier for the RTDS. It supplies the three instantaneous phase voltages (V_X) to the hardware propulsion system as if it is connected to the ship's 13.8 kV distribution bus. In order to include the dynamic interaction between the hardware and the simulated ship system the instantaneous phase currents (I_X) drawn by the hardware are measured and fed back to the simulator as current injections so that the simulated system "sees" the existence of the hardware. This is the first of three close loop feedbacks implemented in this experiment.

The second one is the power control loop. In this loop, the measured motor power (P_M) is sent back into the simulator where a power controller regulates the power and generates a torque command (T_M) for MD1. In this manner, the original power control of the ship PORT propulsion system is implemented through torque control in the motor drive.

The third feedback loop establishes the reproduction of the hydrodynamic torque load. A second motor-set (TF2, MD2, and MT2), powered from the lab's utility bus, is utilized as the load for the propulsion motor. This load motor (or dynamometer) reproduces the counter torque (T_C) computed from the hydrodynamic characteristics, the ship speed, and the measured propulsion motor speed (ω).

Since the power rating of the hardware is only a fraction of the notional power rating of 36 MW, appropriate signal scaling was applied as listed in TABLE 1. Please also note that in reality we only utilized one quarter of the full load of the 16 kW hardware motor set to achieve enough safety and overload margin.

TABLE 1 SIGNAL SCALING FOR 16 KW PHIL EXPERIMENT

Signal	Notional rating	Hardware rating	Scaling
MT1 power	36.5 MW	16 kW	2,281
MT1 speed	110 rpm	900 rpm	0.1212
MT1 torque	3.17 MNm	170 Nm	18,647
Line voltage	13.8 kV	208 V	66.3
Line current**)	1.53 kA	44.4 A	34.5

**) from power and voltage

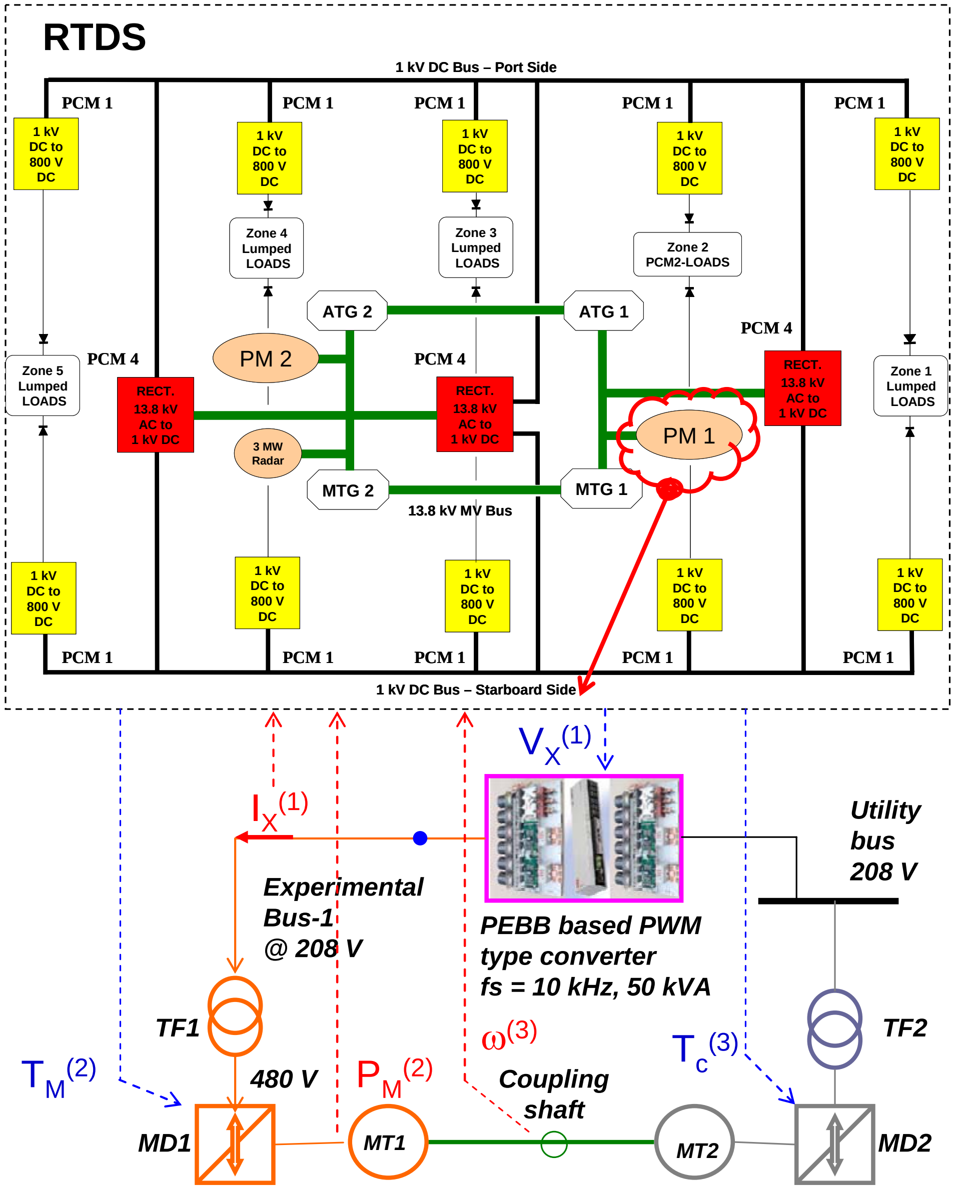

Figure 3: The PHIL system setup with the PORT propulsion system (PM1) of the ship system replaced by a 16 kW motor set (TF1, MD1 and MT1)

In the simulation, the interaction between the rest of the ship system and hardware propulsion system is achieved by connecting a three-phase current source to ship's 13.8 kV distribution bus instead of the originally connected, simulated propulsion system (shown in Figure 4). Therefore, the simulation ship system interacts with the hardware as if the hardware is connected there.

In order to asses the stability of the PHIL setup before the experiment was carried out a pure software simulation of the significant parts of the hardware arrangement was performed. There, the voltage amplifier and its load (the step-up transformer TF1 and the variable speed motor drive MD1) were modeled with sufficient detail. The PHIL arrangement was also modeled such that time delays and signals errors caused by the amplifier and the signal measurements could be replicated properly. From this simulation we found that a capacitor bank in parallel to the ship grid of 5 pu impedance (with respect to the motor drive rating) is necessary to stabilize the system throughout the entire maneuver. Some theoretical background on fundamental stability problems associated with PHIL simulations as well as more details on additional stabilization methods employed in this experiment are discussed in the Appendix.

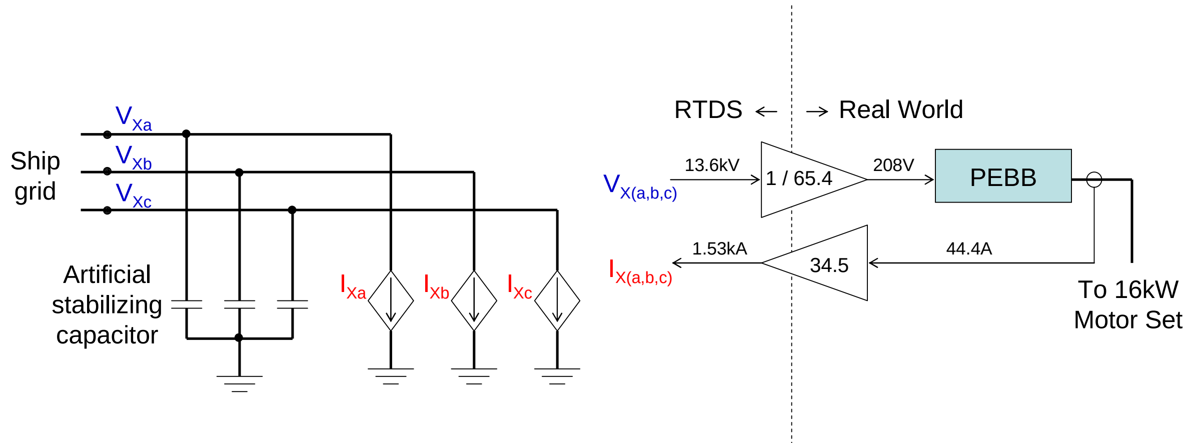

Figure 4: Represent the hardware with a current source in PHIL simulation

D. Results

To demonstrate the dynamic interactions of the electric ship system and the hardware propulsion system, the crashback maneuver is simulated with the PHIL setup described above. In this maneuver, the simulated electric ship is initially operated at full speed forward condition when a full power reverse command is activated. Four-phase power control logic is applied in the maneuver to achieve the minimum time required for the ship to stop without exceeding the allowable load rejection, power regeneration, and load pick-up limits.

The actual profiles of the request powers during these four phases in our simulation are illustrated in Figure 5. The legend “PreqPORT” refers to the requested power for the PORT side propulsion system (the “hardware” motor set) while the legend “PreqSTBD” refers to the STARBOARD side (the “software” propulsion system in simulation). We requested the rated power of 36.5 MW in both the forward and reverse directions. It shall be noted that a negative power during phase 2 really means regeneration while a negative power request in phases 3 and 4 actually result in power drawn from the ship’s generation system. This is because we chose to assign a negative sign to the power after propeller speed reversal. The maximum regeneration power was -4 MW, and the power ramp rate 5% per second. Because parameter differences exist in the two propulsion systems (especially in motor inertia), phase 2 is slightly longer for the “hardware” system.

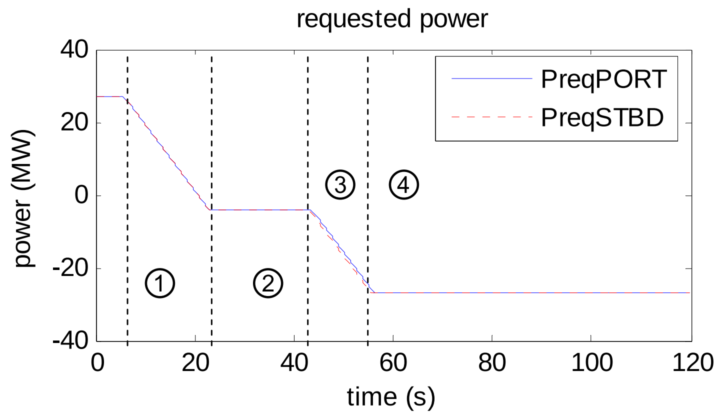

Figure 5: Four-phase profile of the requested power during the crash back maneuver

Figure 6 through Figure 9 show the ship speed, the power into the two propulsion motors, the propeller speeds, and the propeller torques during the crash back maneuver, respectively. By choice of parameters the ship required 82 s to stop and another 40 s to re-accelerate in the reverse direction. Despite the implantation of a compensation loop for the relatively low inertia of the hardware motor, small discrepancies between the two systems still appear in the plots of motor speed and torque, in particular during the fast speed reversal after phase 2. Nevertheless, overall the dynamic behaviors of the two propulsion systems match very well considering they are implemented in substantially different ways: the PORT side system in downscaled hardware format and the STARBOARD side system in pure simulation.

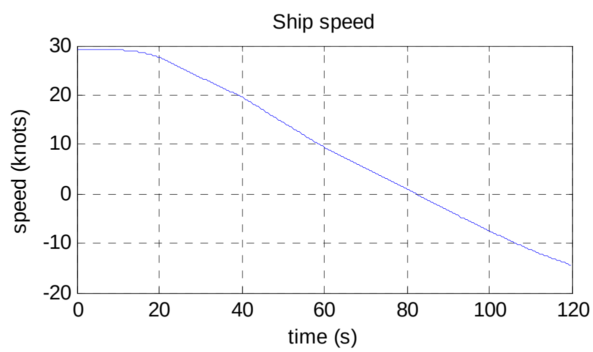

Figure 6: Ship speed during the crash back maneuver

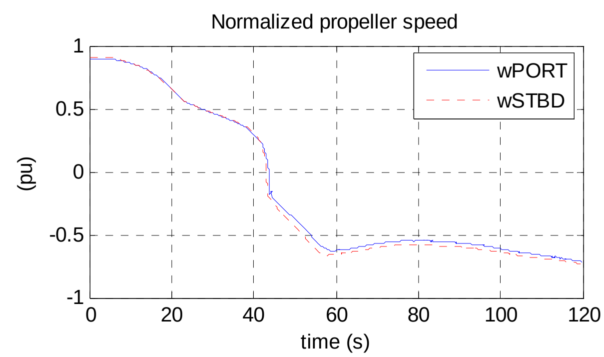

Figure 8: Propulsion motor speed during the crash back maneuver

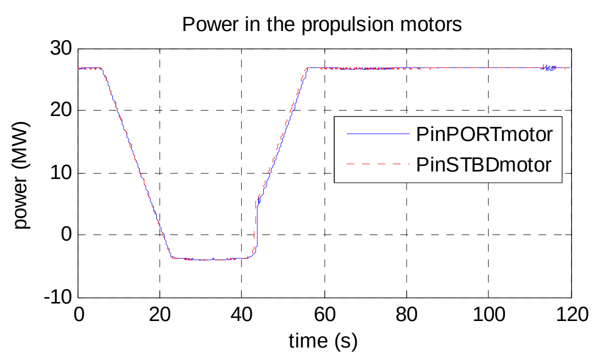

Figure 7: Active power injection in the propulsion motors during the crash back maneuver

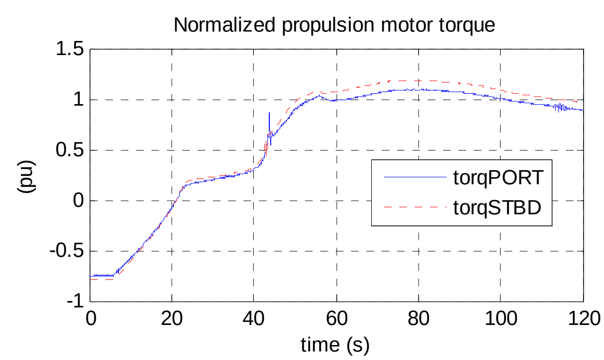

Figure 9: Propeller torque during the crash back maneuver (negative value means the torque is counter to the rotation speed)

A distinct discrepancy between the two systems appears when analyzing the electrical power into the two propulsion motor drives as shown in Figure 10. During the power regeneration mode, the active power into the PORT drive is higher than that into the STARBOARD drive. Actually, the power into the PORT drive only marginally falls below zero even thought he motor is regenerating power into the drive (compare with Figure 7). Two facts contribute to this behavior: first, the relatively large (1.5 kW, but for its rating still reasonable) power loss in the hardware motor drive plus step-up transformer, and second an extensive loss in the motor drive during regeneration (the root cause of this has yet to be examined). Because of the very different power ratings of the "hardware" motor and "software" motor (i.e., 16 kW vs. 36.5 MW), the reasonable power loss of 1.5 kW in the hardware motor-drive set becomes an unreasonably large 3.5 MW loss in the simulation.

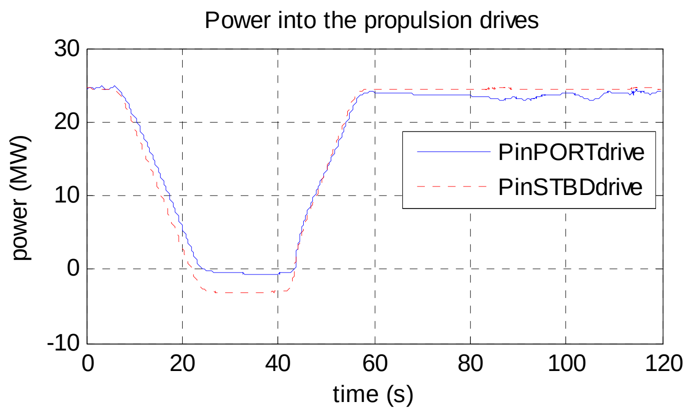

Figure 10: Active power into the propulsion motor drives during the crash back maneuver

Finally, Figure 11 plots the simulated ship bus voltage and the voltage reproduced by the PEBB-based amplifier during steady state operation of the propulsion drives. Limited by the achievable bandwidth, the amplifier reproduces the ship bus voltage with a noticeable time delay and a low pass filtering effect. If fast transient phenomena with time constants comparable to this time delay are to be studied, conceivable error will occur. However, in our study of the crash back maneuver the quality of voltage amplification is sufficient.

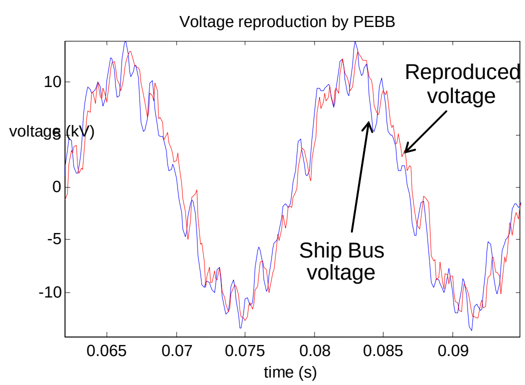

Figure 11: Ship bus voltage reproduction by the PEBB amplifier

IV. 2.5 MW PHIL Experiment

The crashback was also simulated in a hardware-in-the-loop experiment employing CAPS 2.5 MW induction machines (see Figure 2), one acting as the test motor and the other as the dynamometer. In the absence of the 5 MW VVS amplifier depicted in the figure (yet to be installed) this high power PHIL experiment was carried out with both of the 2.5 MW motor drives connected to the (stiff) 4.16 kV utility bus. The hardware-software loop in this experiment is thus confined to mechanical effects; electrical interactions between the hardware and a software electrical system are not considered. The dynamometers and their control are described in [10] and an example of their use in testing a 5 MW HTS motor may be found in [11]. They have also been recently used in the present opposing configuration to test the effectiveness of power control in reducing variations in the power drawn by a propulsion motor due to sea-state propeller loading [12].

The acceleration of the unloaded 2.5 MW motor at full torque and the time required to ramp from zero to rated speed under that condition may be made equal to the corresponding values for the 36.5 MW motor in the notional ship system of [5] by setting the top speed to 65% of the 450 rpm rated speed and the rated torque to 0.77 of the machine rated torque (the power of the machine is 2.5 MW at these "rated" conditions). Inertia compensation is then employed in the control of the dynamometer machine to make the net load inertia experienced by the test machine proportionally equal to that of the propeller in the real configuration. When combined with the torque load produced by the hydrodynamic propeller model, this inertia balance and scaling of the speed and torque lead to an experiment which accurately recreates the mechanical dynamics of the 36.5 MW system being studied.

As in the low-power HIL tests described above, the motor drives were operated in torque-control mode, with the torque references supplied by the simulator. The power-control motor controller used in these tests is similar to that employed in the tests reported above and discussed in more detail in [5]. A relatively unaggressive choice of gains was employed for the power control PI-loop, in order to avoid unnecessarily stressing the machines while the various aspects of the experiment were being set up and tested. These settings were, however, sufficient to provide good following of the power reference at the ramp rates considered. Much more aggressive settings were used in the constant-power control experiments described in [12] and would probably be feasible in the present context with further testing.

The results of a crashback test with this setup are shown in Figure 12. The maneuver was initiated from a steady state at 95% forward power, with shaft speed at 62.3% machine speed (62.3%/65% = 95.8% scaled speed) and the simulated ship speed at 30.9 knots. The power ramp rate was set at 10%/s and the regeneration limit was set at 15%. The maneuver ended with 95% reverse power. Since there was no particular reason to put the machines into (true) overload for the present tests, the torque was limited to 97% of the true, unscaled torque. This corresponds to approximately 125% of rated, scaled torque, which is an overload level similar to that assumed in [5]

Performance is seen to be similar to that of the above experiments with the 16 kW motors and to the power-control simulations of the companion paper [5]. The main differences lie in the maximum torque limitations, which cause the increase of reverse speed and power to be delayed after the regeneration period. Time to stop was 66.4 seconds and the head reach was 2.7 ship lengths, similar to those seen in the simulations with equivalent regeneration levels. Particularly important to assessing the validity of the HIL experiment is monitoring the difference between the load model torque computed by the simulator and the measured shaft torque (Figure 12 (a)); this difference is seen to be generally fairly small, though the load model predicts a rapid variation at the point the motor shaft speed passes through zero that is not reproduced well.

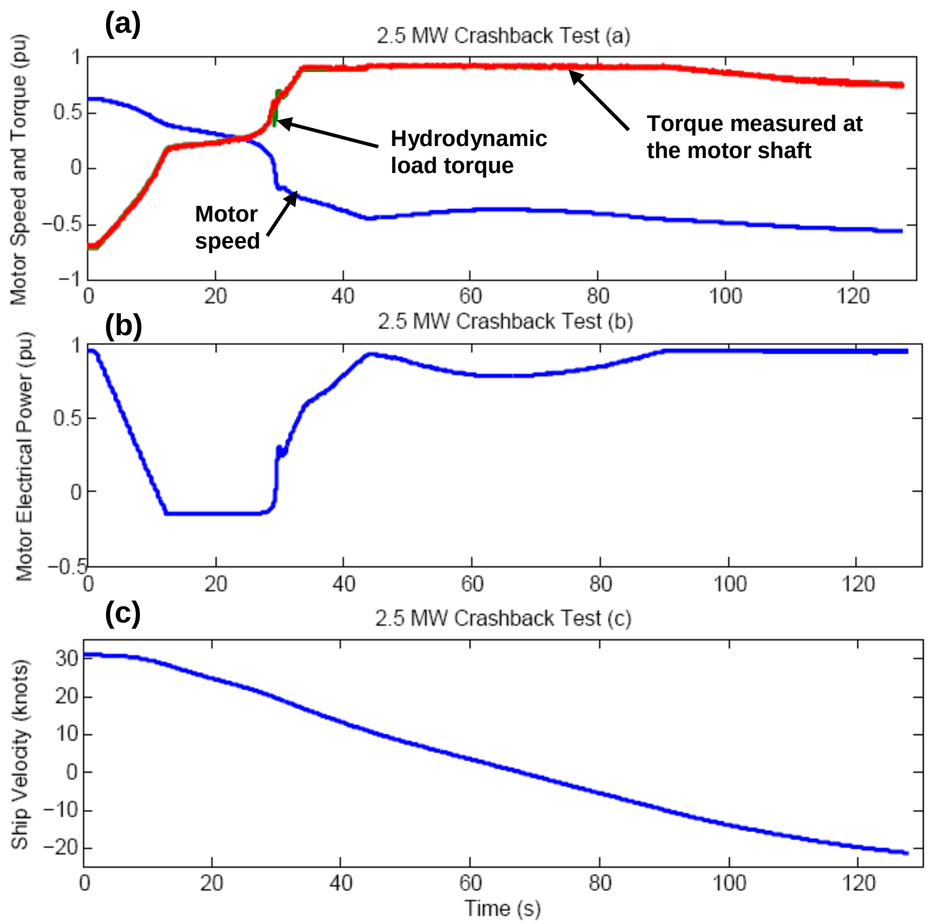

Figure 12: Results of 2.5 MW crashback test: (a) Measured motor speed and torque, (b) Measured motor electrical power, (c) Simulated ship velocity

V. Conclusions

In this paper we introduced the concept of power hardware-in-the-loop simulations (PHIL), discussed the unique PHIL setup at the Center for Advanced Power Systems at Florida State University and presented results from low and high power PHIL experiments In particular we conclude that:

- The feasibility of the PHIL method has been demonstrated for a dynamically demanding scenario such as the crashback maneuver.
- PHIL can be used to study both the behavior of a novel piece of equipment under most realistic operating scenarios and the interaction of such equipment with the rest of the simulated system even if inadequate models for a pure software simulation exist (i.e. due to proprietary reasons)
- Improving the closely coupled feedback between the hardware and the simulation remains an area of active research. In particular, the issues surrounding the inherent instabilities in PHIL simulations require better solutions. The goal is to allow for testing of different types of power equipment connected to a large variety of “virtual” power systems under varying operating conditions without the risk of encountering any instability.

VI. Appendix

A. Stability Issues in PHIL Simulations

The fundamental challenge with HIL simulations is to establish a closely coupled feedback loop between the simulated system and the hardware. For electrical system PHIL simulations this requires a relatively high bandwidth of the power amplifier in order to properly track AC power system voltage and current signals which, in most realistic cases, exhibit high frequency distortions. Improving upon this close loop feedback for PHIL is an ongoing area of research at CAPS.

To illustrate the stability issue in a PHIL simulation, we start from a simple example. Figure 13 illustrates the PHIL implementation of a voltage divider circuit whose load impedance Z_L is a real hardware resistor while the other part of the circuit, the voltage source V_S and it's internal impedance Z_S is simulated. In order to facilitate this, a voltage amplifier reproduces the simulated voltage v_1 as v_2 and imposes it onto the load resistor. The current i_2 drawn by that resistor is measured and fed back into the simulated circuit by means of a controlled current source i_1. As we will show below, even though the original circuit is always stable, its PHIL implementation under certain conditions may not.

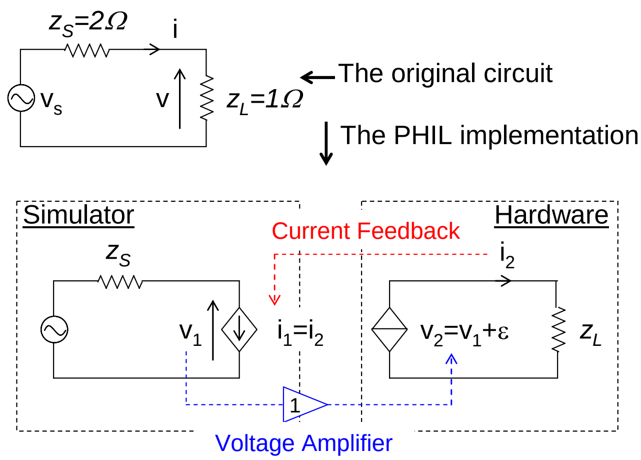

Figure 13: A voltage divider circuit showing PHIL instability issues

Suppose at time t_k, an error ε occurs during the voltage amplification of v_2. In the present arrangement the primary source of error is the accumulated time delay caused by the sampling time of the simulation and the response of the voltage amplifier. However, other sources of error such as D/A conversion or signals noise may also contribute. The corresponding error in current i_2 is:

$$\Delta v_2(t_k) = \varepsilon \;\&\; i_2 = v_2 / z_L \rightarrow \Delta i_2(t_k) = \varepsilon / z_L \tag{1}$$

When this erroneous current is fed back to the simulator, it causes further error in the voltage v_1

$$\Delta v_1(t_{k+1}) = -(z_S / z_L)\varepsilon \text{ since } v_1 = v_s - z_S * i_1 \tag{2}$$

When this new v_1 is sent out to the amplifier at the next time step, the original error becomes amplified by a factor of $-(z_S/z_L)$. Therefore, if $z_S/z_L > 1$ (here we assume a resistive voltage divider), the error will keep oscillating with increasing amplitude until it hits the hardware limit. In practice, it is impossible to avoid error occurring in the signal amplification and transmission, and therefore this PHIL setup will by no means generate stable result.

Since any electrical system can be regarded as a Thevenin equivalent circuit, at least for a short period of time, the conclusion above can be applied to more generic conditions. To assure a PHIL system to be stable, the magnitude ratio of the equivalent source impedance to the load impedance must be less than one. For frequency dependent devices, their impedances at the frequency of interest can be compared.

One way to stabilize the system above is to alter the PHIL interface into the one shown in Figure 14. In this new setup, the amplifier reproduces the simulated current and the voltage is fed back by means of a controlled voltage source. Therefore, the amplification factor of the error is changed to $-(z_L/z_S)$ which, in the example above, now has a magnitude smaller than one. Therefore, any error will be effectively damped and the system stability is ascertained. However, in practical systems where this magnitude ratio is not constant and is fluctuating around one, neither setup works. This is exactly the problem we encountered in our ship simulation. Therefore, at present we mitigated the instability by artificially paralleling a capacitor bank to the interfacing point in the simulation. This effectively reduces the system source impedance, especially at high frequency range, to a value smaller than the hardware impedance. While this is by no means a satisfying solution overall, it allows us to demonstrate, for the time being, the basic concept of the PHIL simulation. Moreover, the system impedances in the system of choice are notional in the first place. Therefore, this stability problem may not exist at all in other cases. Nevertheless, further improvement of the interface is definitely required and is, in fact, subject of an ongoing research project at CAPS.

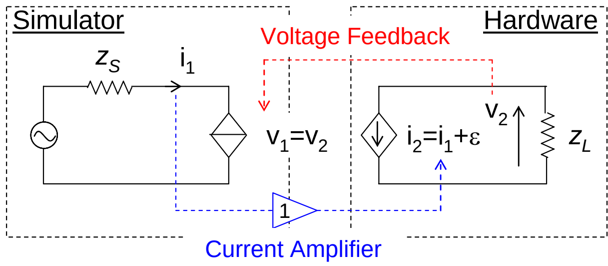

Figure 14: Revising the PHIL interface changes the stability criteria

Another method we applied in our PHIL simulation for system stability is to limit the waveform shape of the interface output voltage with FFT (Fast Fourier Transformation) and IFFT (Inverse FFT). Before the ship bus voltage is sent out for amplification, it is first decomposed with FFT into frequency components up to 19th harmonic. Any harmonic with higher frequency is discarded because the bandwidth of our PEBB based amplifier is only 1 kHz. However, we believe that this decomposition is still adequate to keep most of the frequency information of the original bus voltage. An appropriate magnitude limit is applied to each frequency component so that when they are composed back together, the resulting voltage is still similar to the original ship bus voltage in normal conditions while during instabilities, the resulting voltage can be effectively maintained in a safe range. This method is essentially a protection measure for the PHIL simulation. Compared to the hard protections inherent in the interface amplifier and the motor set, this soft level protection has faster response and lower risk.

VII. Acknowledgement

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