# The Next Stage of Naval Electrical Engineering System Testing at the Power Networks Demonstration Centre

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## Synopsis

This paper gives an overview of the Power Hardware in the Loop (PHIL) system, that is now operational at the PNDC (a University of Strathclyde Research Centre), to extend the centres capability for marine electrical system testing. In this paper, the key components of the PHIL system and their corresponding interfaces are presented; representative case studies showing typical applications for the PHIL system at the PNDC are illustrated; and the next stage of future marine power system testing (flywheel energy storage) utilising the PHIL platform is discussed.

The objective of this test bed is to: facilitate integration of engineering systems into marine power system platforms; support the development of future electric ships; to de-risk the integration of the next generation of energy weapons and sensors; and to supplement and replace the need for ship demonstrators. This facility development and associated project plan involves a productive mix of industry, academia, UK MoD and US DoD.

The two key components of the PHIL test bed are: (1) A Real Time Digital Simulator (RTDS) system that is capable of simulating marine electrical systems in real time; and (2) A Triphase converter, a uniquely modular solution that can be re-configured for AC and DC output, used as the link between simulation and real hardware under test. The RTDS interface with the Triphase converter system employs fibre communication to issue control commands and receive measurement feedback. The hardware to be tested, connected to the Triphase, is interfaced directly to simulation in real time. In this paper it is demonstrated how a flywheel energy storage device could be directly connected to a simulated ship power system and operated in real time. This test setup would be used to evaluate the interaction between the ship power system and flywheel.

This test bed can be reconfigured for long term research and development for a multitude of ship power system solutions. The ship power system is represented in simulation which means it can be modified to represent existing or planned ship architectures. This facilitates testing of hardware planned for retrofit in existing ship power systems; and it allows future ship powers systems to be simulated and interfaced with existing hardware. Both options support reduced cost and life cycle time to develop ship power systems.

*Keywords:* Real Time Simulation; Power Hardware in the Loop; Flywheel Energy Storage

## 1 Introduction

The purpose of this paper is to present on the Power Hardware in the Loop (PHIL) test bed installed at the Power Networks Demonstration Centre (PNDC). This paper expands on the introduction of the PHIL platform presented in [1]. This paper re-introduces the key components of the PHIL test bed, how it operates as a system, how it can be configured in different modes of operation, the capability and opportunity it gives to long term research, and the next stage of planned research relating to flywheel energy storage technologies.

Section 2 reports on the components of the PHIL system and how it is operated in an end to end mode as a PHIL loop platform. Section 3 reports on the preliminary results from the PHIL demonstration in March 2017, this section illustrates the capability of the system when used to connect real world hardware to a simulated representation of a shipboard power system in real time. Section 4 discusses an application for the Triphase system, specifically interfacing and testing a flywheel energy storage device connected to the PHIL platform.

## 2 Overview of PHIL System

This section provides an overview of the PHIL system including: the Real Time Digital Simulator (RTDS) that is capable of simulating naval electrical systems in real time; and (2) the Triphase converter, a uniquely modular solution that can be re-configured for AC and DC output, which is used as the link between simulation and real hardware under test. This section also discusses how the two components are used together to form the PHIL platform and gives some examples as to how the PHIL platform can be used in different configurations.

**Author's Biographies**

**Dr. Kyle Ian Jennett** received the MEng. degree in electrical and mechanical engineering in 2009 and the PhD degree in electrical and electronic engineering in 2012 from the University of Strathclyde, Glasgow, U.K. He is presently a Research and Development Engineer at the Power Networks Demonstration Centre at the University of Strathclyde, Glasgow, U.K. At the Power Networks Demonstration Centre he leads the MoD research program and also leads the Demand Side Management theme. His research interests include power system modelling, real time simulation, ship power systems and future power systems encompassing converter interfaces and energy storage.

## 2.1 *Real Time Digital Simulator Overview*

Real time digital simulation has existed for some time [2] in a variety of different applications including power electronic controllers [3], superconductor railway applications [4] and mechanical pneumatic systems [5] among others. Real time simulation is the process of solving simulations in real world time e.g. 5 seconds of simulation runtime corresponds to 5 seconds of power system run time. There are various types of tools for implementing real time simulation, for example: Opal-RT [6], Simulink Real-time Simulation [7] and RTDS Technologies [8].

The RTDS platform was used for this application because of the body of experience and existing infrastructure within the University of Strathclyde [9, 10] . It is also an established technology with worldwide usage [8]. Specifically it is used at Florida State University (FSU) for Military research [11]. The University of Strathclyde have formed a working partnership with FSU and are collaborating using the shared RTDS platform.

### 2.1.1 *Hardware*

In the RTDS platform [8], real time simulation means calculating voltage and current at every node in the simulation after very small steps in time (so that the output of the simulation emulates real time). A node in RTDS corresponds to an interconnection of two power system components. For power system solutions the standard RTDS time step is 50 µs i.e. the RTDS calculates the voltage and current at every node in the simulation every 50 µs. The simulator is also capable of operating in small timestep mode at 1-4 µs, this smaller time step is typically used for simulating fast switching power electronic devices. The RTDS hardware is contained within cubicles as shown in Figure 1, this where the power system simulation solutions are solved, with more RTDS cubicles more complex and larger simulations can be simulated. The RTDS simulation is configured on a standard PC using the bespoke RTDS software ‘RSCAD’. RSCAD allows the user to configure the power system, run the model and observe simulation results.

Figure 1 RTDS Hardware (cubicles)

## 2.2 *Triphase Programmable Power Converter System*

The Triphase system being installed at PNDC is a flexible AC and DC test bench system utilising six 90 kVA power modules (total power capacity of the system is 540 kVA) with an associated control platform. The Triphase interface can be scaled in simulation to emulate a higher power rated interface (e.g. as may be observed in large warships), however, this is an area of future work and the limitations of this approach have not yet been investigated. The Triphase system is operational and ready for project utilisation. The Triphase system can be operated in AC and DC modes of operation, it has an AC voltage range of 0-480 V and a DC voltage range of 0-1300 V. The Triphase system has four modes of operation which are listed below::

Four operation modes: AC mode 1, AC mode 2, DC mode 1, DC mode 2.

- AC 1 – 1x3Ph output, 540 kVA, 0-480 Vrms, 3x 780Arms
- AC 2 – 2x3Ph output, 2x270 kVA, 2x0-480 Vrms, 2x3 390Arms
- DC 1 – 1x540 kVA output, -650...+650 Vdc, 1x±780 Adc
- DC 2 – 1x540 kVA output, 50...1300 Vdc, 1x±415 Adc

The six cabinet Triphase configuration is shown in Figure 2. The PNDC network has been upgraded with a new 1.2 MVA transformer to provide a dedicated power supply to the Triphase system. This dedicated supply allows parallel utilisation of the Triphase system and the existing PNDC network. The transformer has been uprated to facilitate future expansion of the Triphase platform.

Figure 2 Triphase System

### *2.3 PHIL System*

The PNDC PHIL system interfaces the RTDS platform over a dedicated fibre link to the Triphase system for real time measurement and control. This configuration enables AC and DC power systems to be modelled in RTDS and interfaced to the Triphase. For example, a power system could be simulated in RTDS and interfaced to a real piece of hardware (like a battery energy storage system). This capability facilitates end to end testing to examine the interaction between the simulated system and the hardware 'in the loop'. The PHIL system architecture is shown in Figure 3. The shipboard power system is modelled in the RTDS environment interfaces to the Triphase system using fibre communication. The Triphase can be fed a setpoint from a DC/AC node in simulation and the output from simulation is supplied to the device under test. The Triphase is effectively acting as a 'bridge' between the simulation and the real world hardware where the measured node value in simulation defines the output from the Triphase hardware.

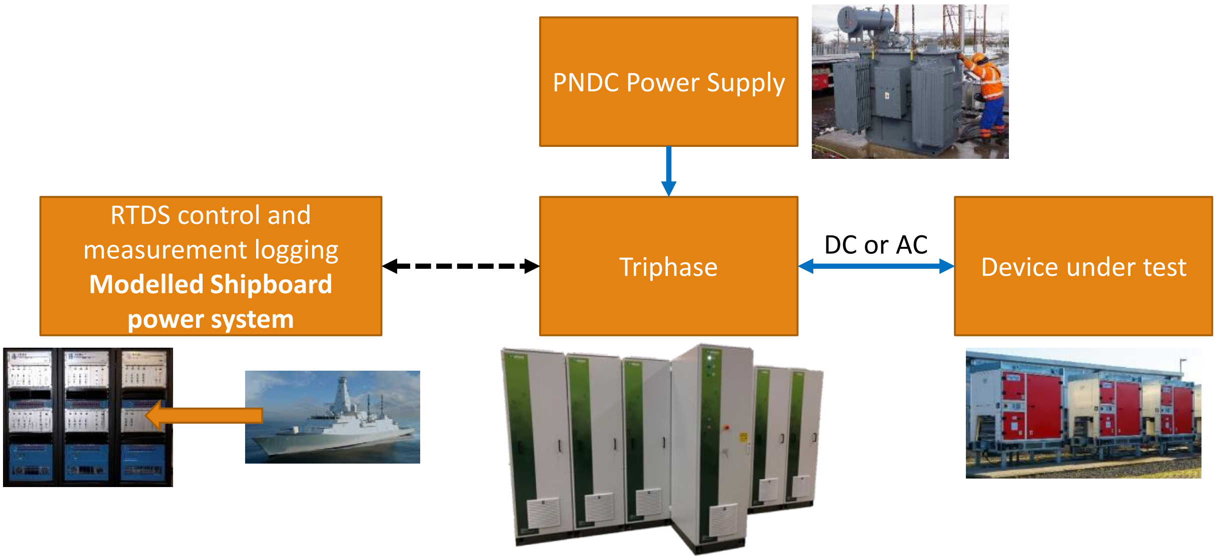

Figure 3 PHIL System

An example test of this system is illustrated in Figure 4 where the Triphase acts as the ‘bridge’ between the simulation and the real world hardware (in this case an energy storage device). In this example the diesel generator, switchboard, transformer and ship hotel load are all represented in simulation. A node on an AC feeder is monitored and sends a control setpoint to the Triphase hardware which sources and sinks real power to the energy storage device. The Triphase monitors the voltage and current at its interface and sends the measured data back into simulation to ‘close the loop’ between simulation and hardware. The Triphase can be thought of as the ‘star’ node on both sides of the simulation/real world interface gap.

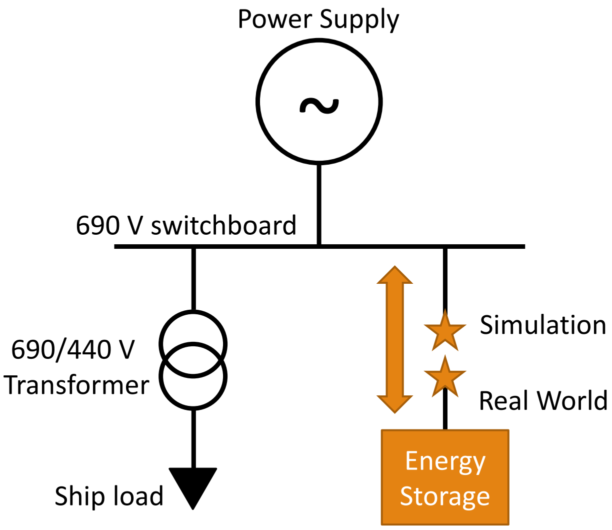

Figure 4 Example of PHIL Test

The Triphase system can also be operated in a back-to-back DC mode as illustrated in Figure 5. In this case both sides (three cubicles each) of the Triphase system are controlled as independent sources, one is configured in voltage source mode and the other is configured in current source mode. This configuration lends itself to projects where the characteristic of the hardware is known but the hardware is unavailable. The three Triphase cubicles on the right hand side (operated as a current source) can be controlled to emulate the hardware’s behaviour and sink or source real power to the actual hardware and back into the simulation (bridged by the left hand side Triphase Voltage Source).

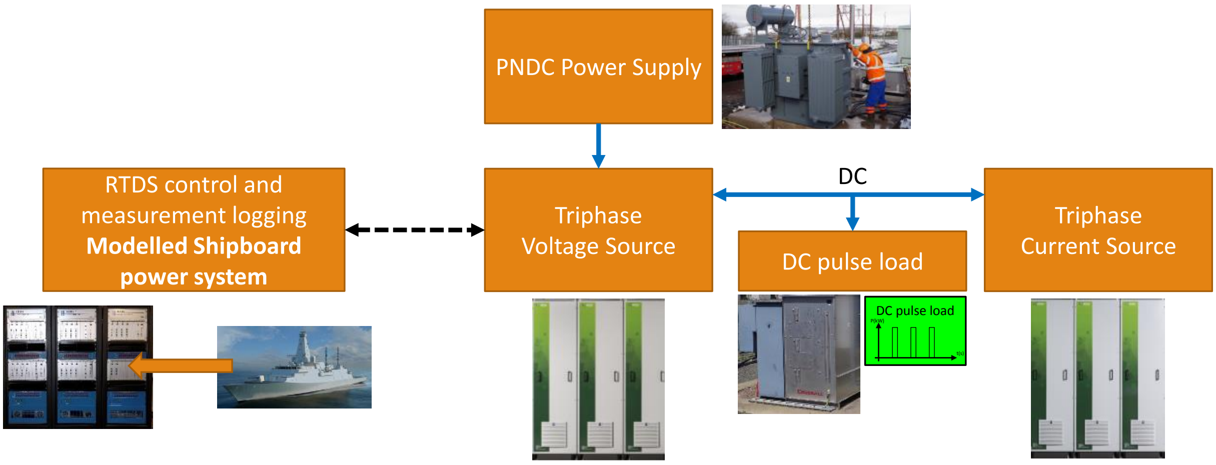

Figure 5 Triphase Operating in Back to Back DC Mode

## 3 Demonstration of PHIL at PNDC

The demonstration of the PHIL system at the PNDC (for MoD staff) was held at the end of March 2017. The objective of this demonstration was a proof of concept for this system while interfacing to a real time ship power system. This demonstration configuration is illustrated in Figure 6. In this demonstration the shipboard power system is feeding an AC step load. In simulation the AC load is connected to one of the switchboards. In the real world the Triphase acts as the bridge to simulation, the hardware is an AC loadbank in the PNDC network.

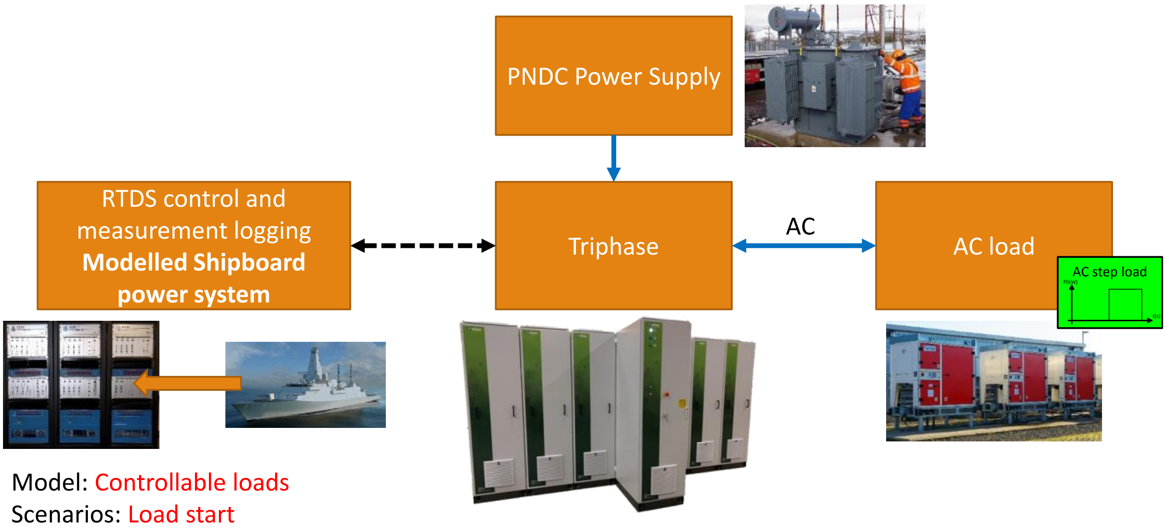

Figure 6 AC 1 Triphase Demonstration

An overview of the demonstration is shown in Figure 7. The process of closing the loop was completed in four stages to ensure stability of the simulation was maintained (as illustrated in the diagram):

- Stage 1 – The measured three phase voltage from a specific location in the shipboard power system is sent to the Triphase Simulink model. This Simulink model controls the output from the Triphase Programmable Power Converter.
- Stage 2 – The Triphase system is controlled to switch from default ‘dummy’ voltage setpoints to the measured three phase voltages from the RTDS shipboard power system model.
- Stage 3 – The load is connected to the Triphase system. As the Triphase system is being operated in voltage source mode the Triphase immediately begins injecting current into the load to maintain the voltage setpoint at the Triphase output terminals. The Triphase starts logging the three phase current that it is exporting to the load.
- Stage 4 – The Triphase measured three phase voltage is sent back to the RTDS model. At the interface point in the RTDS shipboard model the current is injected back into the simulation using a controllable current source block.

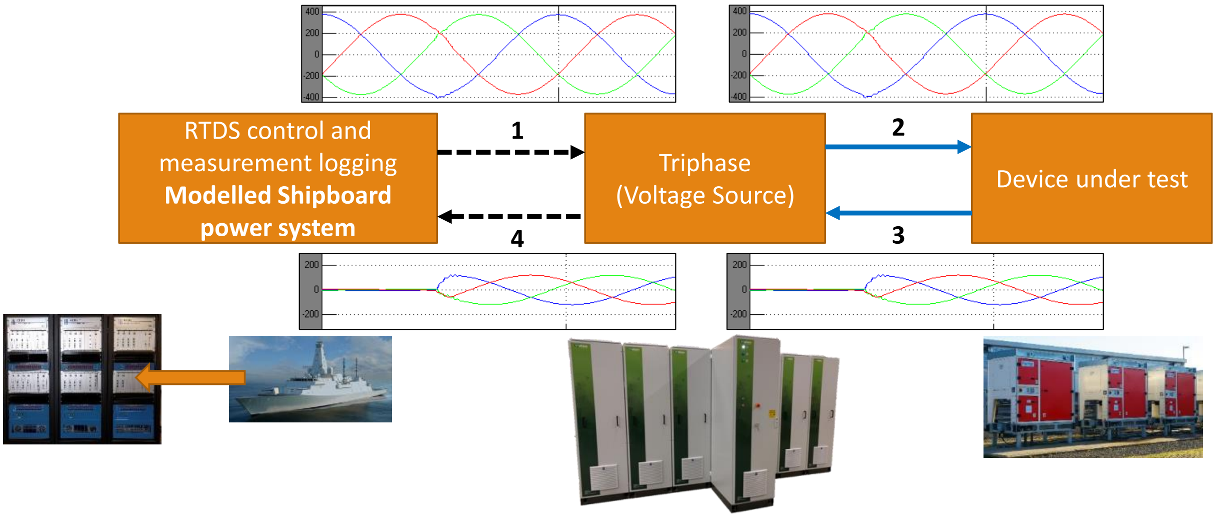

Figure 7 Overview of Demonstration

After the loop has been closed (stage 4 is complete) the shipboard power system model in RTDS and the device under test are linked in real time. This means a change in load causes a change in the voltage and current in simulation; and a change in the ship network voltage causes a change in the voltage and current applied to the load. In Figure 7, a step change in load is implemented causing a small voltage distortion and increasing in the current being supplied to the load (both in simulation and in hardware). Applying the techniques presented in [12], the communication delay inherent in the PHIL system was compensated for and the phase delay between voltage and current (supplying a resistive load) was removed as shown in the phase shift improvement from Figure 8 to Figure 9.

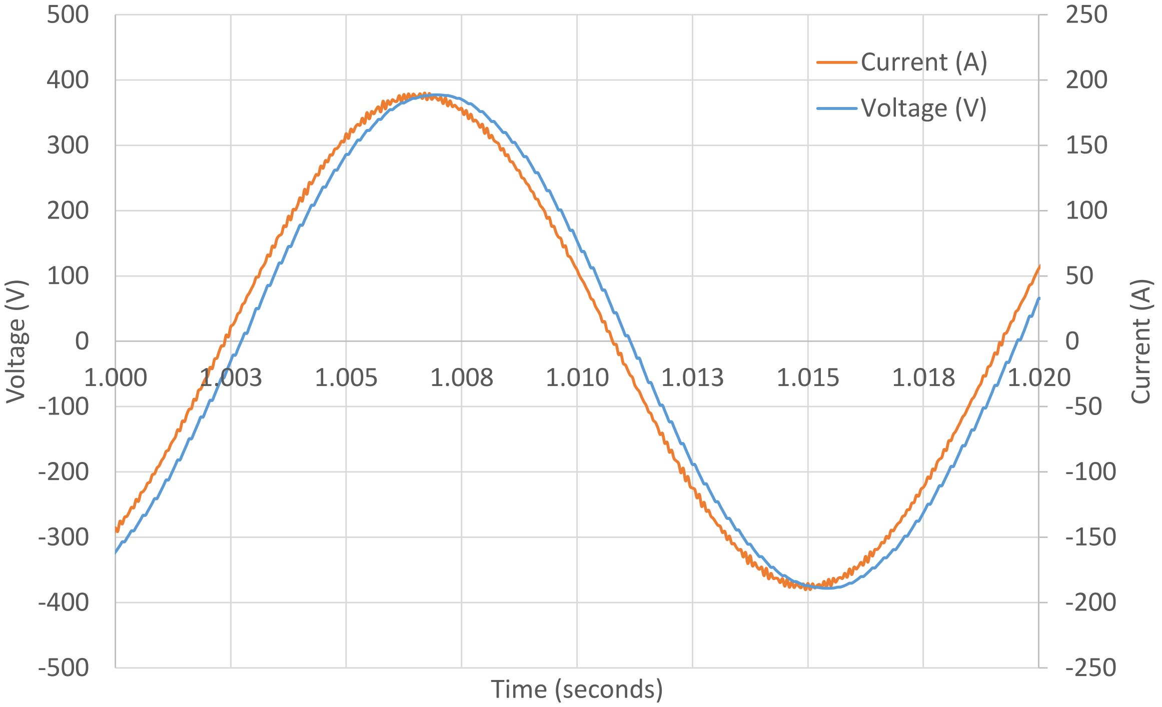

Figure 8 Phase voltage and current with resistive load: No correction

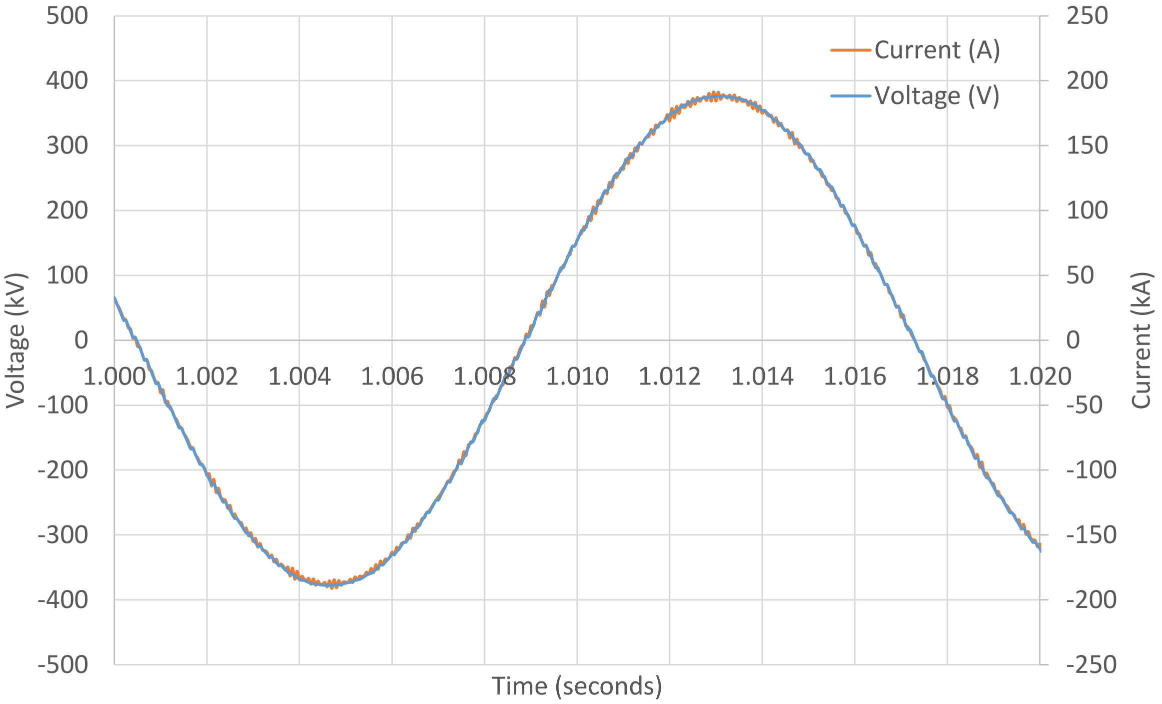

Figure 9 Phase voltage and current with resistive load: Correction applied

## 4 PHIL interface to Flywheel Energy Storage

This section of the paper discusses an application for flywheel energy storage in future marine power systems. This section provides an introduction to flywheel energy storage, gives an overview of the benefits of flywheel energy storage for marine power systems, discusses how flywheel technology could be evaluated using a PHIL (Triphase) test bed, discusses possible objectives of flywheel PHIL testing, and identifies some of the challenges associated with configuring and utilising the PHIL test bed.

### *4.1 Introduction to flywheel energy storage*

The UK Ministry of Defence (MoD) is in the process of developing prototype Laser Directed Energy Weapons (LDEW). These energy weapons are expected to improve naval combat capabilities and provide cost savings for existing and future warships [13]. The electrical demand profile of the LDEW system is a high-power pulse load, this has implications for the operation of the naval power system, specifically related to the capability of the system to supply the LDEW while maintaining continuous supply to the rest of the power system. The MoD are exploring the installation of Flywheel Energy Storage (FES) on naval platforms to support the high power pulse load demand of the LDEW. The LDEW is not the only type of high power pulse load expected to be retrofitted to existing and future naval power systems. Other equipment that may have a similar load characteristic include: rail guns, ballistic missile defence sensors, future electronic warfare systems [13], and electromagnetic unmanned aerial vehicle launchers [14].

### *4.2 Advantages of installing flywheels on ships*

The potential benefits for flywheel energy storage in naval applications have been discussed widely in the literature [13, 15, 16]. Flywheels are already used in a variety of applications including: formula one, public transport, and railway [13]. Flywheel energy storage lends itself to high power applications over a short duration i.e. on the order of seconds or milliseconds [15]. In comparison to other energy storage technologies flywheels can be considered as operating between capacitor and chemical cell technologies i.e. higher power than chemical cells and longer duration than capacitor technologies. This ‘mid-location’ in the energy storage spectrum makes them suited to applications like the LDEW. Other attributes associated with flywheels that make them suited to naval applications are listed in [13] and are summarised below:

- Minimal routine maintenance is required compared to chemical cell technologies.

- They are not degraded by environment, depth of charge, or number of use cycles like cell technologies can be.
- They can be completely turned off with no residual charge during periods when they are not required e.g. peacetime operation.
- They are modular self-contained units for: capacity scaling, redundancy, and for containing mechanical failures

### *4.3 Overview of PHIL to flywheel interface*

Figure 10 illustrates how a flywheel energy storage system might be connected in a shipboard power system. The image on the left shows a simplified power line diagram with a bi-directional rectifier connected on one feeder. This configuration assumes a DC 'network' including a flywheel energy storage system and a DC pulse load. This pulse load could be one of many electrical loads including: the LDEW, a rail gun, ballistic missile defence sensors, future electronic warfare systems [13], or electromagnetic unmanned aerial vehicle launchers [14]. In this case the flywheel is acting as an 'energy storage magazine' as discussed in [17]. The image on the right shows how the shipboard power system with flywheel energy storage may be implemented in a PHIL testing environment. In this example the interface point between the power system (simulated in the RTDS) and the real world hardware (interfaced by the Triphase system) is at the DC output terminals of the shipboard rectifier.

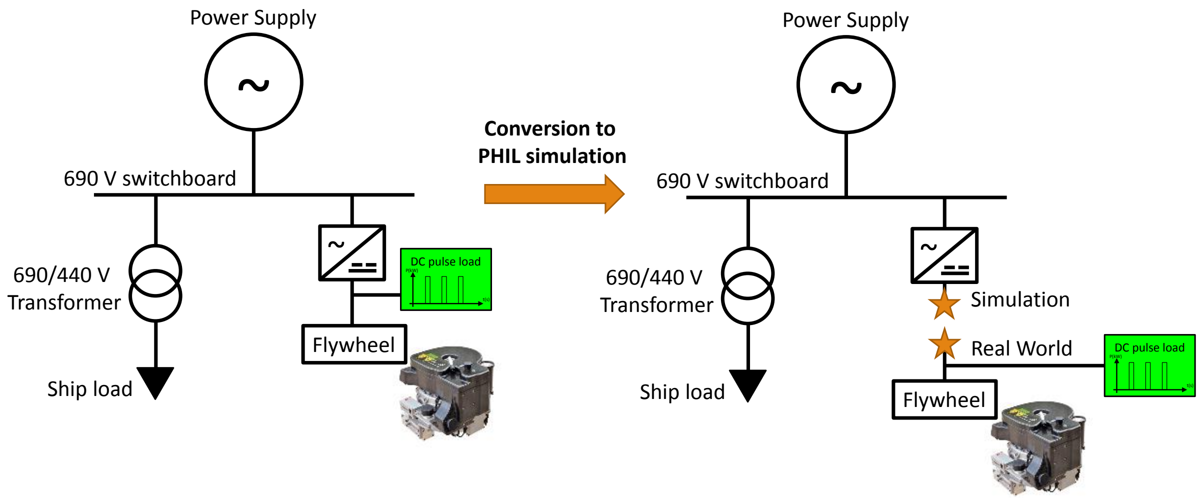

Figure 10 Flywheel shipboard power system application

### *4.4 Objectives of testing*

If a flywheel was interfaced to a PHIL testing environment there are a number of areas of study that could be explored. The primary focus of the study should be to characterise the interaction between the ship power system and the flywheel response. This may involve:

- Evaluating the power quality impact of different flywheel and load operational scenarios. The power quality impact test would look at evaluating if network voltage, frequency, and waveforms (harmonic distortion) remain within operational limits for different operational scenarios.
- Establishing the operational boundary and characteristics of the 'energy magazine'. Flywheels have a unique characteristic when compared to alternative energy storage mediums like cell technologies or supercapacitors [16], the nature of the technology impacts both the speed of response, and the total available energy. This test would stress test the flywheel to quantify the operational boundary for a load with:
    - Varying duty cycle, duration and magnitude: In [16] it is suggested that a typical laser load would have a duty cycle of 50% and a pulse duration of 5-7 seconds. If multiple LDEW were operating in parallel, or operated outside this expected duration, or if the energy magazine was to be used to supply another application (e.g. defence sensors) the duty cycle, duration and magnitude could be significantly increased. This would cause the energy magazine to decrease

    at a faster rate, and increase the duration required for recharge. This testing would look at the maximum possible and optimum: duty cycle, duration and magnitude for a specific load size and flywheel capacity.
    - Increasing distortion of the load waveform: Much of the literature [13, 17] assumes a square wave load profile for LDEW. However, multiple LDEW operating in parallel or non-LDEW loads may result in a non-square wave load profile that could impact the operation of the flywheel. Testing of increasing load waveform distortion would identify the limit at which load distortion begins to detrimentally impact power system operation, both with and without the flywheel energy store.
    - Varying from periodic pulse load to a stochastic pulse load: Again much of the literature [13, 17] assumes a periodic pulsed load from LDEWs. However, with multiple LDEWs, or other loads connected the response may be a stochastic demand. Testing of stochastic loads would identify if the flywheel is capable of supplying stochastic loads and under what conditions supply becomes problematic.
    - Varying loading conditions elsewhere in the ship: The loading conditions elsewhere in the ship will impact the ship power system capability to transfer power to and from the DC network. This test would evaluate the flywheel operation under extreme conditions i.e. high loading and loss of generation.
- Evaluating the interaction with the ship power system interface. In the proposed configuration there are two different power converters with independent control systems operating 'back to back' (the ship rectifier and flywheel rectifier). This test would evaluate the interaction between the two control systems to identify compatibility issues that could lead to instability for different operations (e.g. charge and discharge of the flywheel).
- Evaluating the response (including protection operation) of the flywheel to simulated and real world failures. This would involve:
    - Loss of generation in the simulated model
    - Loss of ship load in the simulated model
    - Electrical short circuits both in simulation and in real hardware
- Ship controller and flywheel controller interaction. The tests listed above have all considered power system responses and interactions. This test would look at how the flywheel responds in relation to the ship control system. This test would evaluate speed of response, the response to erroneous control commands, and the response to communication failure.

### *4.5 Testing challenges*

The propose PHIL test configuration is illustrated in Figure 11. In this diagram the shipboard power and control system is implemented in the RTDS. The RTDS controls the output of the Triphase, and the Triphase interfaces the simulation model to the hardware under test, in this case the flywheel energy storage.

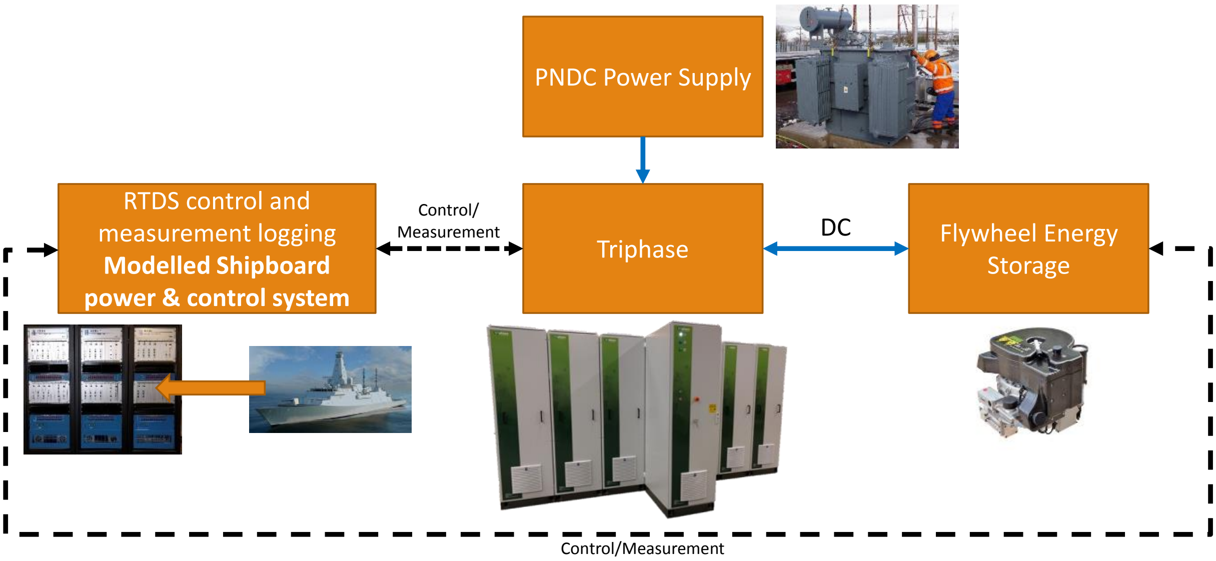

Figure 11 Flywheel test configuration

There are a two key challenges to PHIL testing of the flywheel system, as listed below:

- Development of the Power System and Control model. The model to be developed in the RTDS environment has to accurately emulate the ship power system and control system response. For an accurate test of the flywheels interaction with the ship; the ship model should be validated against real ship data.
- Interfacing the Triphase platform with the Flywheel Energy Storage system. The protection settings of the flywheel converter system may operate when interfacing to an emulated grid interface like the Triphase power converter. Residual current flow, low source impedance measurement, and instability in the closed loop response are all known factors that need to be considered when testing a device in a PHIL environment with a power converter interface.

## 5 Conclusions and Further Research

This paper has given an overview of the PHIL system, discussed the key components of the system and how the components interact. This paper has also demonstrated the capability of the PHIL system by reporting on the results of the system in operation. This paper expands on the introduction of the PHIL platform presented in [1] by presenting the next stage of planned research relating to flywheel energy storage technologies. The results presented in this paper illustrate the platforms capability to support a wide range of academic and industrial PHIL based projects, both in land based and naval power systems.

In terms of future plans for how the PHIL test bed will be utilised to support Naval Power System MoD projects. Further collaboration with FSU regarding the use of this platform is planned for 2017 and beyond. The first key area that is planned for mid-2017 will involve de-risking the integration of the next generation of weapons and sensors which demand high energy pulse loads (supplementing and ultimately replacing the need for ship demonstrators).

## Acknowledgement

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