Test Report

Dry Testing of the Azura PowerPod at Energy Hydraulics Ltd

Williwaw Engineering

Prepared for

University of Hawaii – Hawaii Natural Energy Institute

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Revisions

Revisions

Revision #	Date	Revised By	Pages
Revision 0	9/12/2014	Terry Lettenmaier	Initial Release

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1. Introduction

This document describes "dry testing" of the PowerPod for the Northwest Energy Innovations (NWEI) half-scale Azura wave energy converter (WEC). These tests took place at Energy Hydraulics Ltd (EHL) in New Plymouth, New Zealand between July 30 and August 17, 2014. The PowerPod is the top of the Azura device that includes the float and power take-off (PTO); the PowerPod bolts to the Azura hull to make up the complete WEC device. PowerPod dry testing was conducted in order to validate operation of the PTO on dry land following hydraulic and electrical modifications that were made by EHL in late 2013 and early 2014. These tests were conducted in preparation for the deployment of the complete half-scale Azura for a one year period at the US Navy's 30-meter grid-connected Wave Energy Test Site (WETS) located at the Marine Corps Base Hawai'i (MCBH).

2. Test Plan

The NWEI document "Test Plan for Dry Testing at EHL" is included in Appendix I of this document. Included in this test plan is a description of the test article, test objectives, test setup, test instrumentation, and detailed plans describing the specific tests performed. Tests were conducted per this test plan except where noted in this report.

3. Timeline

A timeline for the PowerPod dry tests is shown in Table 3-1 below. The bulk of PowerPod testing was performed from July 1 to 17, 2014 while Terry Lettenmaier (Williwaw Engineering) was on site at EHL to work with EHL staff performing the tests.

Table 3-1 Timeline for PowerPod dry testing

Test	Date
Generator insulation resistance test	May 23, 2014
Insulation resistance tests and 24 V power supply pre-test	June 19, 2014
24 V power supply tests and no load bench tests	July 1-6, 2014
Calibration of cRIO power measurements	July 7, 2014
Bench testing with load bank	July 8-10, 2014
Thermal test	July 10, 2014
Bench testing with PowerOne inverter	July 10, 2014
Assembly of PowerPod	July 11-15, 2014
PowerPod testing with load bank	July 16, 2014
Thermal testing of 24 V power supply	July 18, 2014
PowerPod testing with PowerOne inverter	July 17-23, 2014
Change boost transformer ratio from 1:1.5 to 1:2	July 28, 2014
Final PowerPod testing with PowerOne inverter	August 4-5, 2014

4. Test Setup

Descriptions of the detailed test setups are included in Section 4 of the test plan (Appendix I), along with electrical diagrams.

All tests were initially performed as “bench tests” with both the PowerPod hydraulics and electrical system removed from the PowerPod structure and located on benches or the floor in order to easily access equipment while troubleshooting and correcting problems. Photographs of this arrangement are shown in Figure 4-1. During these tests the hydraulic cylinders that are normally driven by the PowerPod float were replaced by equivalent test cylinders that were mechanically coupled to a driving cylinder. Both the test and driving cylinders are part of a custom test rig that was previously built for this purpose. The driving cylinder was connected to a diesel powered hydraulic power pack through controlled valves. These valves could be controlled by pre-set sinusoidal or random position profiles loaded into a control computer. Electrical loading was provided by either a resistive load bank or the PowerOne inverters as described in the test plan. The diesel power pack used for these tests is shown in Figure 4-3; the same power pack was used for both bench testing and final PowerPod testing.

During bench testing, the cooling system for the diesel power pack could not provide sufficient cooling to continuously operate at high load for periods of time longer than about 15 to 30 minutes. The power pack was frequently shut down to give it time to cool for this reason. This did not significantly affect most results but did limit the duration of the thermal test described in Section 10.3.

Numerous minor changes were made to both the hardware and cRIO software during bench tests in order to correct minor assembly and design problems. When possible, tests were later repeated with the fully assembled PowerPod. In those cases, results from final PowerPod tests are presented in this report rather than the initial bench test results.

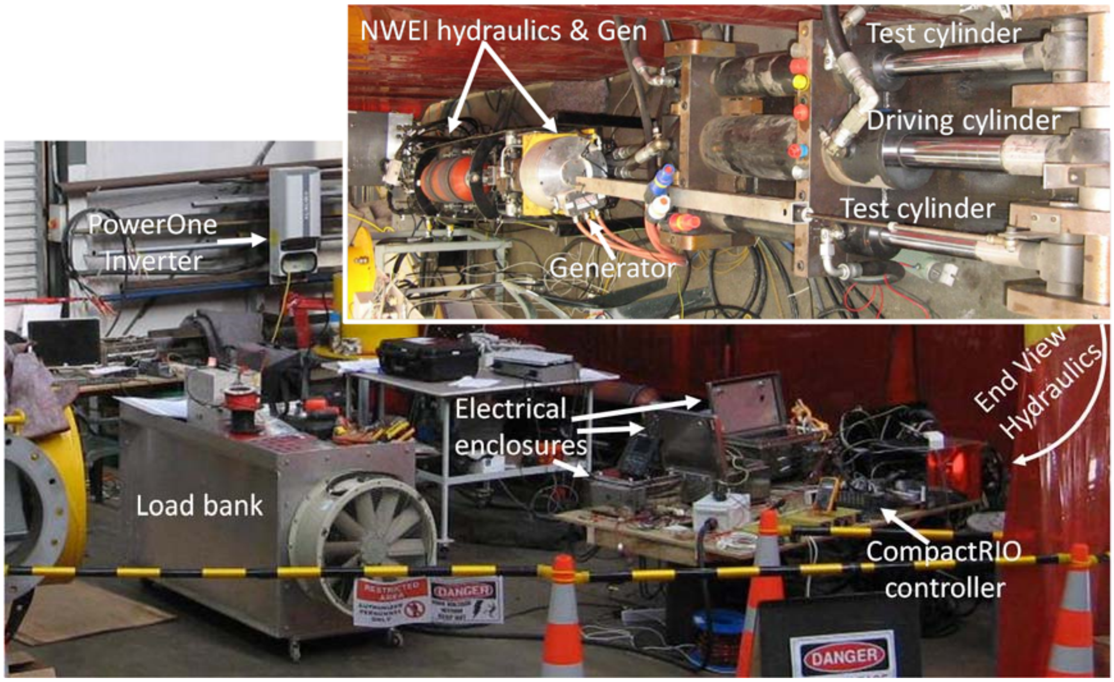

Figure 4-1 Bench test setup with equipment external to PowerPod structure

After bench testing was complete, the PowerPod was assembled with all hydraulic and electrical components installed in the PowerPod structure, and the assembled PowerPod was tested. See Figure 4-2 for a photograph of the setup used to test the assembled PowerPod. The driving cylinder from the bench test rig was used to drive the float bracket, with the float removed, through a set of connecting rods built for this purpose. The two test cylinders from the bench test were left attached to the test rig but were inactive; no hydraulic pressure was applied to those cylinders. Hydraulic power was provided to the driving cylinder by EHL's diesel power pack. A distant view of the test setup including the power pack is shown in Figure 4-3. When running tests, water was occasionally sprayed by hand on the main bearings inside the PowerPod through the open hatches to cool the main bearings.

Due to the short moment arm between the connection points of the connecting rods to the float bracket and the center of the main bearings, large forces existed in the connecting rods and driving cylinder when operating with this setup. This caused deflections in the support structure for the driving cylinder when operating at higher power. Temporary supports were welded to the PowerPod structure (see Figure 4-2) to reduce these deflections. To avoid test rig damage, output power was usually limited to a maximum of about 3 kW to 4 kW for tests run with this setup, and operation was limited to sinusoidal wave profiles. Testing was not performed with random wave profiles to avoid the high impulse type loads that would have occurred.

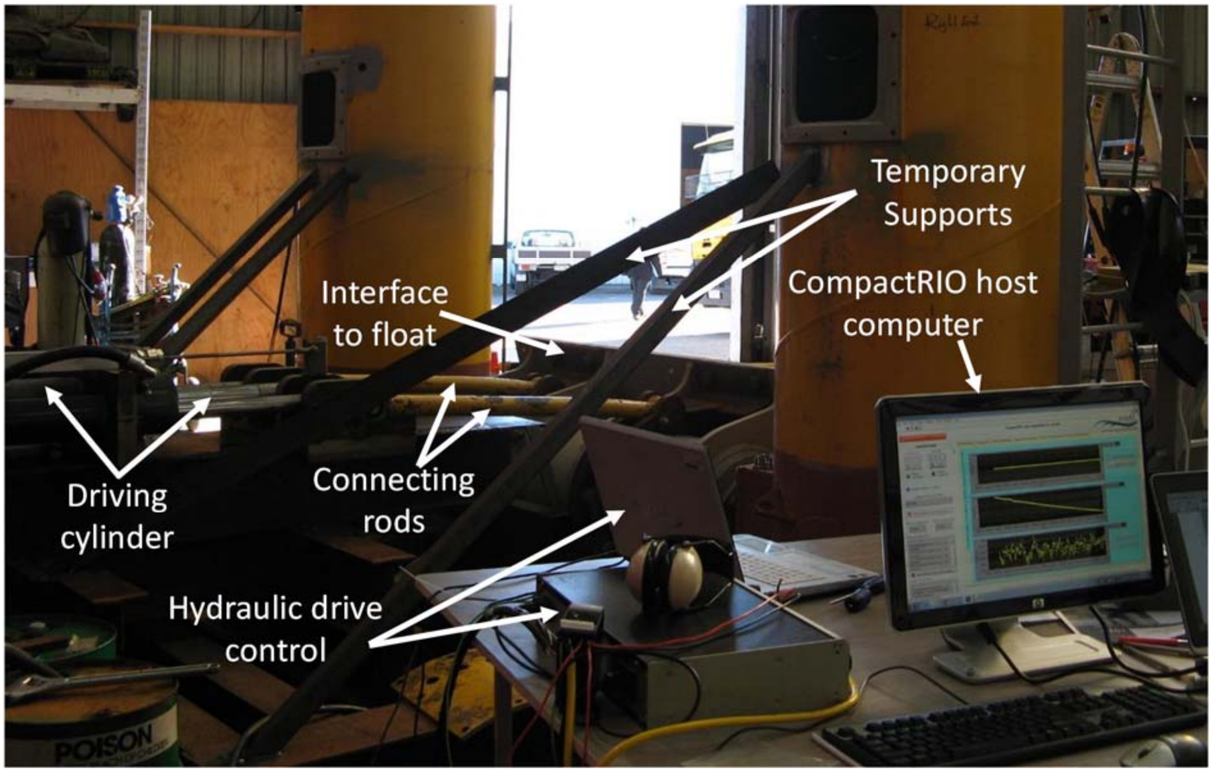

Figure 4-2 Close up view of final test setup with PowerPod assembled

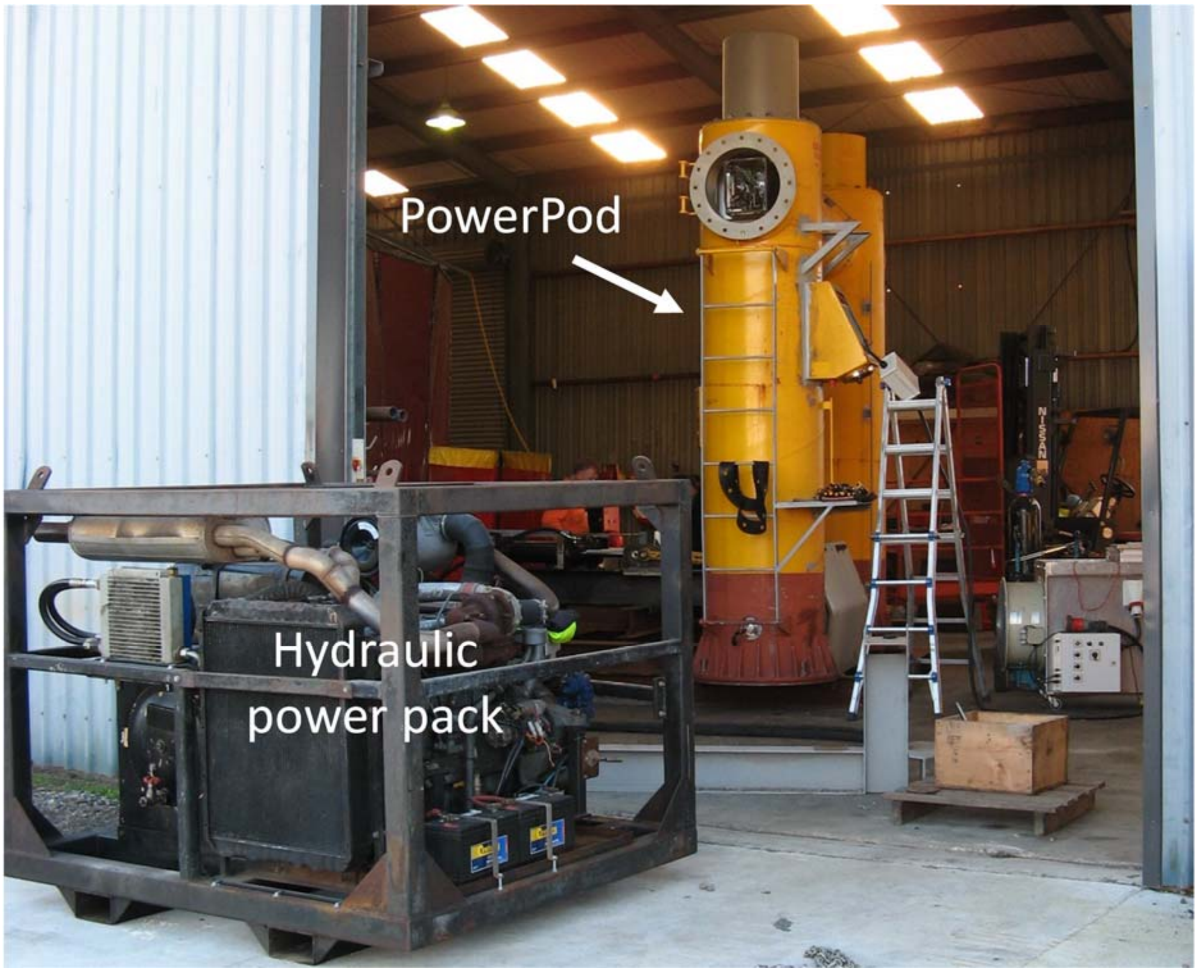

Figure 4-3 Distant view of final test setup with PowerPod assembled

5. CompactRIO Sensor Checks

A significant portion of the dry test was dedicated to commissioning the CompactRIO data acquisition and control system, and verifying its control outputs and sensor measurements. Different sensors were tested during different parts of the dry test depending on the specific methods used to check each sensor. See Table 5-1 for a list of CompactRIO outputs and sensors, and references to the specific sections of this document where their operation was verified.

Table 5-1 CompactRIO sensor check references

Ref	Sensor	Sensor Check Method	Refer to Test Report Section
	Xfmr line A, B, C volts	Calibrated power meter	9
	Xfmr line A, B, C current		
	Dc volts	Voltmeter	8.2.8
	Dc current	Comparison of power measurements	10.4
HZ01	Generator rpm	Hand held strobe	8.2.5
	Motor disp. command	No load motor speed	8.1.1
	LEV 200 relay drive	Voltmeter	8.1.2
	Gen line A, B, C volts	Calibrated power meter	9
	Gen line A, B, C current		
	24 Vdc	Voltmeter	8.2.3
	Subsea J-box oil level	NA – not yet installed	NA
LT01	Hydraulic tank level switch	Changed programmed threshold and observe switching	8.2.1
TT02	Hydraulic tank temp switch		
AS01	Float Angle 1	Static measurement	8.2.7
PT09	Water Pressure 1	Static measurement	8.2.4
PT08	Gen Side Cyl (Closed)	Transducer calibration outside system then data check during operation	11.5
PT07	Gen Side Cyl (Rod)		
PT05	Motor Inlet		
PT06	Motor Outlet		
TT01	Gen Temp	Room temperature check	8.2.2
	Xfmr winding temp		
AS02	Float Angle 2	Static measurement	8.2.7
PT10	Water Pressure 2	Static measurement	8.2.4
PT01	Filter side extension	Transducer calibration outside system then data check during operation	11.5
PT02	Filter side retraction		
PT04	TTP pressure		
PT03	TP1 pressure		
FT01	Hydraulic flow	Rough check of data during operation	8.2.6

6. Test Results: Insulation Resistance Tests

Insulation resistance tests were conducted per Section 5.1 of the test plan (Appendix I). These were the first tests performed during bench testing; this equipment couldn't be accessed after the PowerPod was assembled. The results are listed in Table 6-1. A Kyoritsu KEW6016 multifunction tester was used to make the measurements. All measured resistances exceeded the minimum expected values of 100 MΩ for the generator alone and 10 MΩ for other measurements.

Table 6-1 Insulation resistance test results

Connection	Test Voltage	Measured Resistance (MΩ)
Generator alone	1000 Vdc	280
Generator to boost xfmr	500 Vdc	54
Boost xfmr to dry box	500 Vdc	39

7. Test Results: 24 Volt Power Supply Tests

24 V power supply tests were conducted per Section 5.3 of the test plan (Appendix I). These tests were performed as part of the PowerPod bench testing between July 1 and July 6, except that temperature testing was performed after PowerPod assembly on July 18 (see Section 3 for timeline of PowerPod testing). Detailed voltage measurements are included in Appendix II. The power supply operated properly throughout the tests with its output voltage between 24.0 V and 24.2 V with normal loads applied. Further results recorded and noted during these tests are as follows:

- The 24 V power supply consists of three Synqor power supply modules that operate in parallel to increase reliability. Input current to the three modules were measured by measuring voltage across the 5 Ω resistors at the input to each module. Results, listed in Appendix II, show an imbalance as high as 60% between the input current for each module. Synqor engineers confirmed that this is to be expected because each module is operating at a relatively low percentage of its 600 W rating.
- Tests were performed with each of the three Synqor power supply modules shorted one at a time (at the anode of the paralleling diodes) to simulate an internal failure of one module. The power supply output voltage remained at 24 V with the short, but a 50 ms wide, 1 V pulse occurred twice per second when the modules were shorted; see the oscilloscope recording of output voltage shown in Figure 7-1. This pulsed voltage is apparently due to the short circuit protection of the shorted module. This pulsed output voltage is not expected to affect operation of 24V powered equipment if this type of failure occurs. The average input current to the shorted module measured zero during this test.

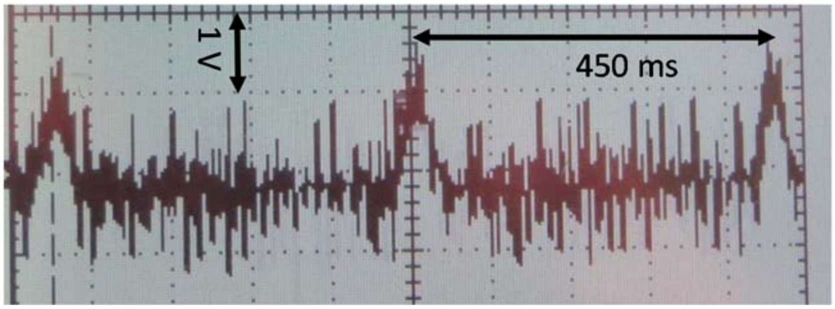

Figure 7-1 Power supply output voltage with one Synqor module shorted

- Steps in input voltage from 220 V and 300 V and 300 V to 220 V had no effect on the output voltage of the power supply. See oscilloscope plots in Figure 7-2 and Figure 7-3, respectively. No disturbance in output voltage resulted from the input voltage steps.
- No oscillations in power supply output voltage were observed throughout the tests. All oscilloscope measurements of output voltage were all similar to those shown in Figure 7-2 and Figure 7-3 before and after voltage steps.

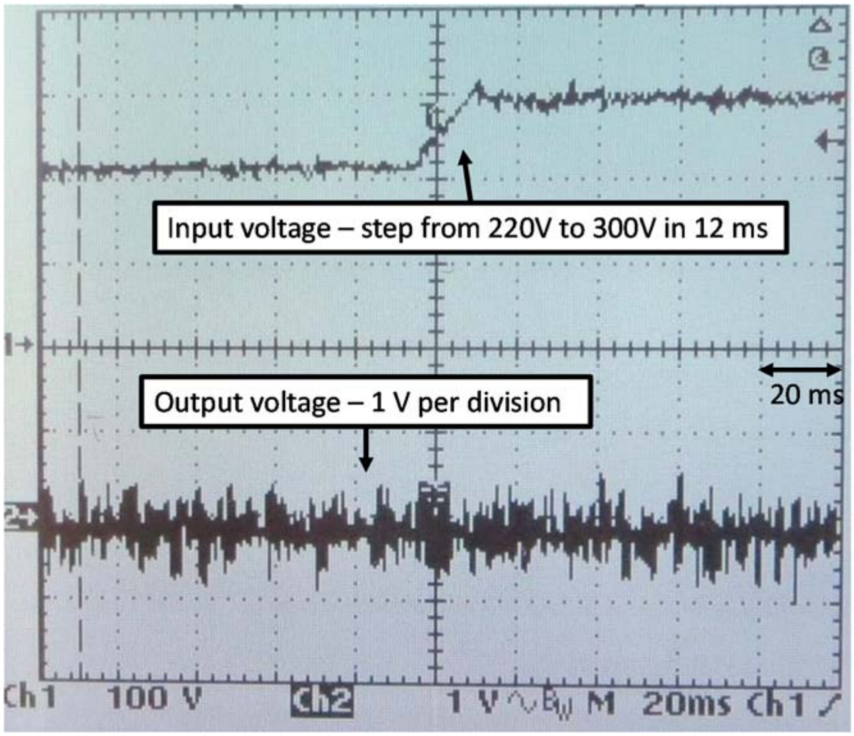

Figure 7-2 Power supply input and output voltages with 220V to 300V input voltage step

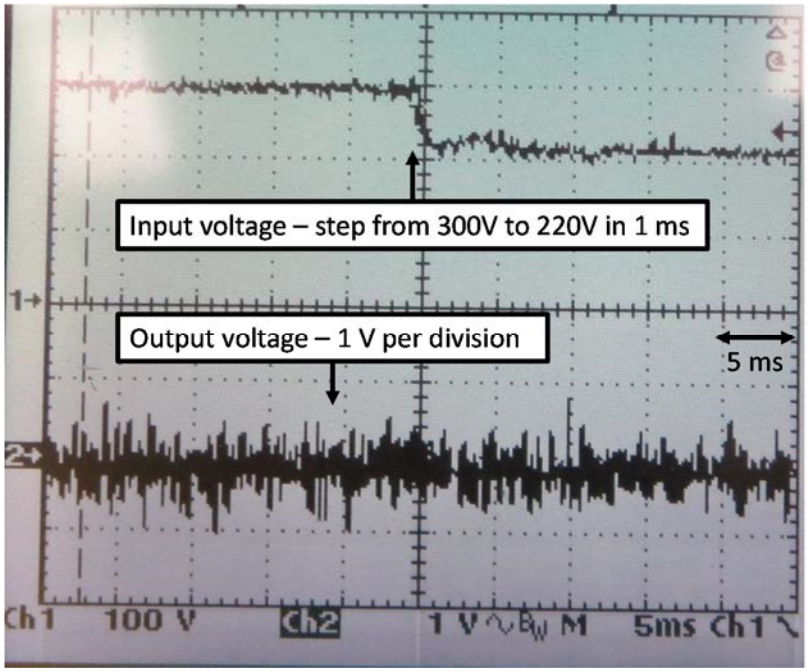

Figure 7-3 Power supply input and output voltages with 300V to 220V input voltage step

- Temperature test results for the 24 V power supply are shown in Figure 7-4. Temperature tests were conducted after final assembly of the PowerPod. The power supply is located inside the PowerPod dry box (see photo in Figure 7-5). The dry box cover was installed during temperature testing. During this temperature test, a 1.0 Ω external resistor was temporarily wired to the power supply output in order to provide approximately 600 W of additional load. Power supply temperature testing was conducted without movement of the float. The results show that after temperatures stabilized, ambient temperature inside the dry box was approximately 15 ˚C above external ambient, and the temperature of the heatsink for the Synqor power supply modules was approximately 35 ˚C above external ambient. While temperature tests were performed with a relatively cool external ambient of less than 15 ˚C, it is expected that external ambient temperature could reach 35 ˚C during the Hawaii deployment. In that case, an internal drybox ambient temperature of 50 ˚C and a power supply module heatsink temperature of 70 ˚C can be expected based on the temperature rises above ambient measured during these tests. Because all drybox components are rated for 60 ˚C or higher and the Synqor power supply modules are rated for a baseplate temperature of 90 ˚C, the temperature results indicate that the power supply should operate reliably throughout the Hawaii deployment.

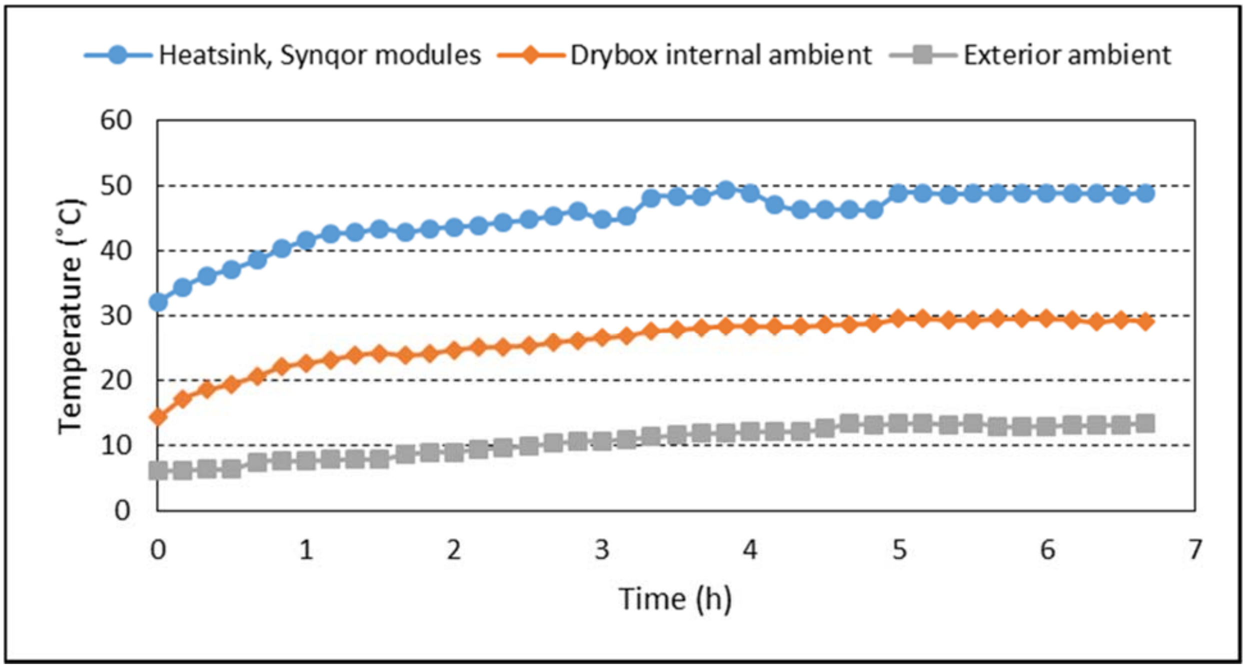

Figure 7-4 Temperature test results for 24 V power supply

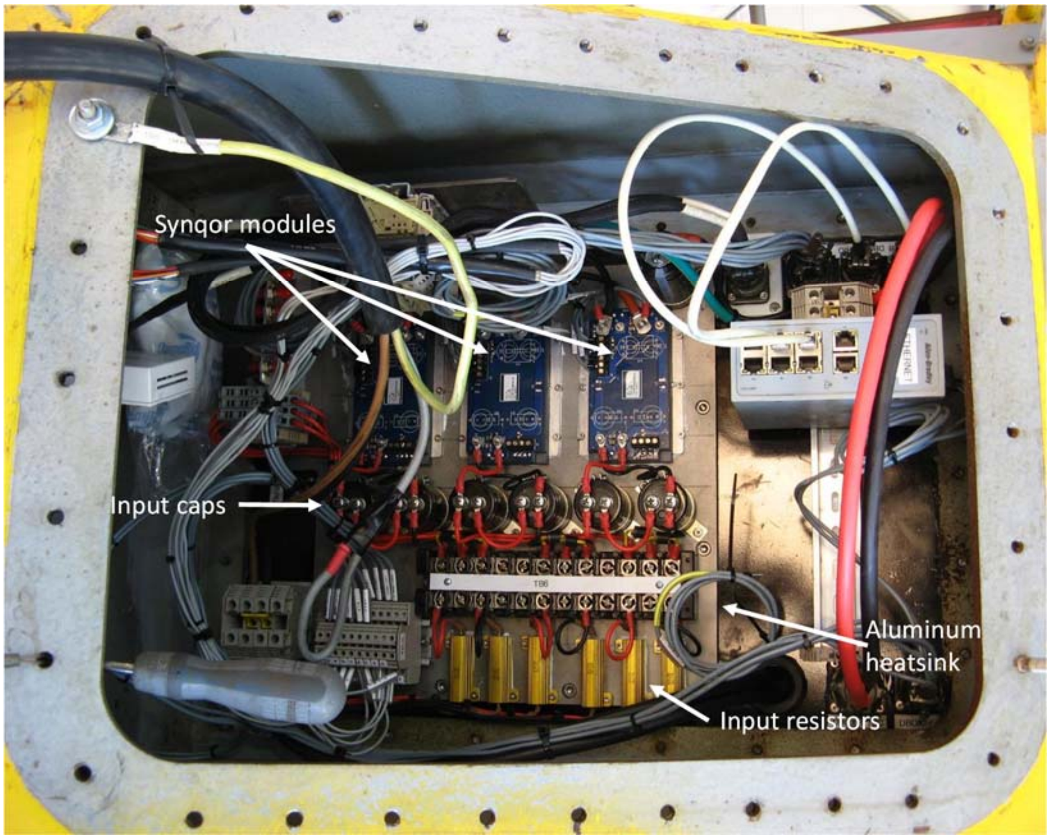

Figure 7-5 Photo of power supply assembled inside PowerPod drybox

Conclusions for 24V power supply tests**:** The results indicate that the 24 V power supply can be expected to operate reliably during the deployment. This power supply is a custom design for the Hawaii deployment that must operate with wide input voltage fluctuations due to voltages in the subsea cable used to transmit ancillary power from shore to the device at sea. Tests indicate that the 24 V output will be stable with the input voltage fluctuations expected and component operating temperatures will be low enough for reliable operation during the deployment.

8. Test Results: No Load Testing

No load testing was conducted per Section 5.4 of the test plan (Appendix I). The primary objective of these tests was to test operation of the outputs and inputs of the CompactRIO controller prior to operation at load. Tests were also performed to assess the effect that step changes in motor displacement had on motor speed and to determine the effectiveness of the hydraulic speed limiting control. Most of these tests were performed during bench testing before final assembly of the PowerPod. A set of no load characterization data was also collected for future reference after the PowerPod was assembled.

8.1 CompactRIO control outputs

The CompactRIO controller on board the device provides the command for hydraulic motor displacement and also controls three contactors that connect and disconnect the output of the generator from the rest of the system. These two outputs were assessed during no load operation as described below. The CompactRIO system also provides control of the grid interconnect inverter that will be located on shore via a second onshore CompactRIO controller. Tests of the output to the inverter are described in Section 11.

8.1.1 Motor displacement command

Hydraulic motor displacement is controlled by the CompactRIO using an analog output that drives a Parker driver module, which in turn drives a solenoid in the motor that directly controls the motor displacement. The Parker driver provides the higher current needed to drive the solenoid and also a “dither” in the solenoid drive current that keeps the solenoid from sticking.

Per motor specifications, displacement is expected to be at a maximum 80 cc/rev when the solenoid current is less than 200 mA, and linearly change to a minimum (20 cc) when solenoid current is increased to 500 mA. After configuring the Parker driver, a series of no load speed measurements were made with the test rig stroke and period left constant, with a range of analog outputs from the CompactRIO. The results are shown in Table 8-1. The speed measurements are all peak speeds through two cylinder cycles of the test rig. The motor displacement was known to be 80 cc/rev for the first row of data because speed did not change when Parker driver current was changed to zero. Motor displacement for other rows was calculated from the speed in the first row (speed is inversely proportional to motor displacement).

The Parker driver and motor displacement data from Table 8-1 is plotted in Figure 8-1 against CompactRIO output current. The plot of motor displacement is nearly linear with respect to the CompactRIO output, and can be approximately represented by a linear trend line. The slope and offset of this linear trend line was used to map the motor displacement command in the CompactRIO software to the CompactRIO 0-20 mA current output.

Table 8-1 No load data used to set up CompactRIO motor displacement command

CompactRIO output (mA)	Parker driver output (mA)	No load motor speed (rpm)	Calculated Motor displacement (cc/rev)
7.88	204	300	80.0
10.101875	287	375	64.0
12.32375	369	500	48.0
13.555625	415	650	36.9
14.2275	440	850	28.2
14.899375	465	1000	24.0
15.57125	490	1200	20.0
15.84	500	1250	19.2

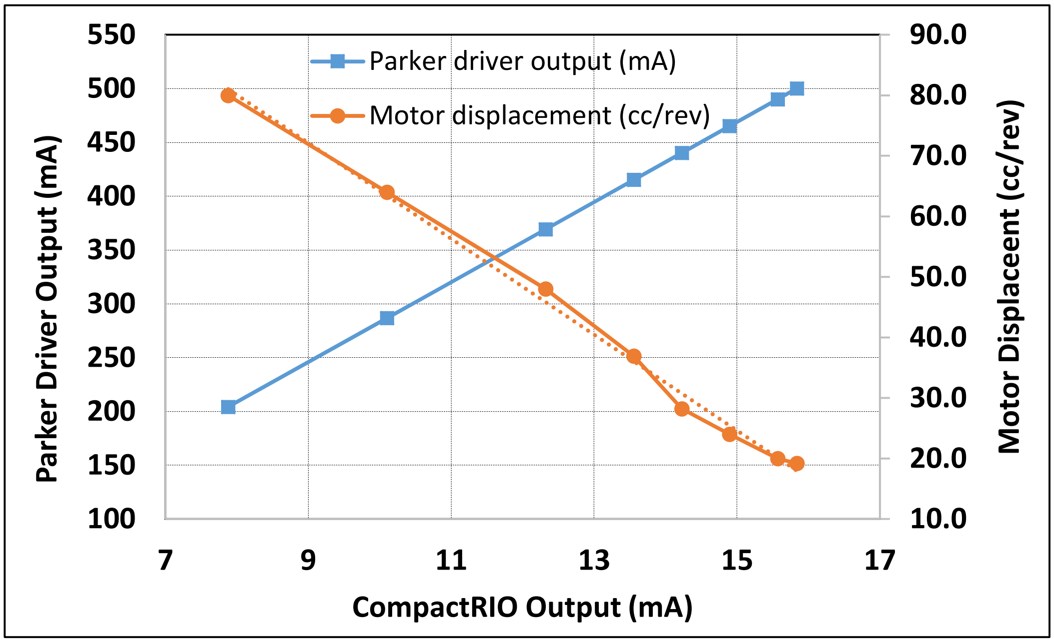

Figure 8-1 Parker driver current and motor displacement vs. CompactRIO output

8.1.2 Contactor control

A set of three LEV 200 contactors connected in line with each phase of the generator output are controlled by the CompactRIO. These contactors, closed during normal operation, disconnect the generator from the rest of the system and the subsea cable when faults occur or the system is shut down. After these contactors are open, the CompactRIO controller delays closing these contactors again after faults are cleared and the system is enabled until a generator output voltage of 10 V or less is measured, in order to minimize inrush current to capacitors on the dc output of the system.

Proper function of this output was assessed by observing the CompactRIO measurements of generator and transformer voltage outputs that indicate voltage on the two sides of the contactors when the system was enabled and disabled. The contactors always opened and transformer voltage was zero when the system was disabled. When the system was then enabled, the contactors did not close unless generator voltage was less than 10V.

Although basic function of the contactor outputs was verified as described above, it was also observed that when 24V power to the CompactRIO controller was cycled off while the three contactors were off, the three contactors momentarily closed. This was caused by an unexpected output glitch from the CompactRIO analog output module during controller power down, shown in Figure 4-1. This momentary closing of the LEV 200 contactors could cause a large inrush current into the dc capacitors under some conditions, possibly resulting in damage. Cycling of CompactRIO control power is occasionally necessary when software faults occur. This problem was not resolved during the dry tests, but further investigation was later done by National Instruments (NI), who determined that this behavior is typical of that particular output module. To correct this problem, the NI 9265 analog current output module in use with the CompactRIO controller during the dry tests will be replaced with an alternate NI 9269 output voltage module per NI's recommendation in Hawaii prior to deployment. NI tested the NI 9269 module and verified that this module has no output glitch at power down.

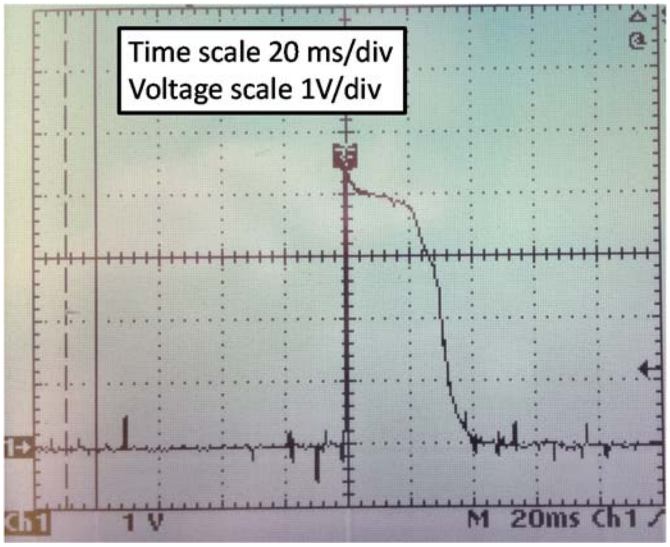

Figure 8-2 Output glitch in CompactRIO contactor control output when control power is turned off

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8.2 CompactRIO sensor checks

Proper operation of CompactRIO sensors that could be checked out at no load were verified as follows.

8.2.1 Hydraulic tank level and temperature switches

During bench testing the hydraulic tank level and temperature switches were checked by adjusting their switching thresholds above and below the known tank level and the ambient temperature, respectively, and observing the fault indicators on the CompactRIO host display change states. The thresholds were then set for a tank level of 250 mm and a temperature of 70 ˚C.

8.2.2 Boost transformer and generator temperature sensors

The boost transformer and generator temperature sensors were checked by comparing temperature data between these two sensors and an internal temperature sensor that measures CompactRIO controller temperature during bench testing. Temperatures readings from the three sensors were within 2 ˚C after the complete system (including power to the CompactRIO) had been shut down for over 12 hours.

8.2.3 cRIO 24V power supply measurement

The CompactRIO measurement of 24 Vdc power supply voltage was checked by measuring supply voltage with a voltmeter and comparing to the CompactRIO reading during bench testing. The two measurements matched within 0.2 V.

8.2.4 Water depth sensors

The water depth sensors will be installed on the NWEI hull before deployment in Hawaii. A preliminary test was done with the sensors held by hand and dropped to the bottom of a 0.6 m barrel of water while connected with their normal wiring to the CompactRIO. Initially, the CompactRIO readings indicated only a fraction of the 0.6 m depth change. The water depth sensors use a pressure sensor that is covered by a rubber membrane. Experimentation showed that the measurements were accurate when the same test was performed with the rubber membrane removed, also, readings were poor when the space between the rubber membrane and pressure sensor was not completely filled with water. This led to replacement of the rubber membrane with a thinner piece of neoprene material. The test was then repeated; see the resulting data recorded by the CompactRIO in Figure 8-3. This data was recorded while repeatedly dropping the two water depth sensors to the bottom of the 0.6 m deep water in the barrel then pulling them back out of the water together. The results show a change in depth very close to the expected 0.6 m. If possible, further testing will be performed in deeper water in Hawaii prior to deployment. The measurements both have a zero offset of approximately 3 m; a zero correction will be added to the CompactRIO software after the sensors are installed on the hull in Hawaii.

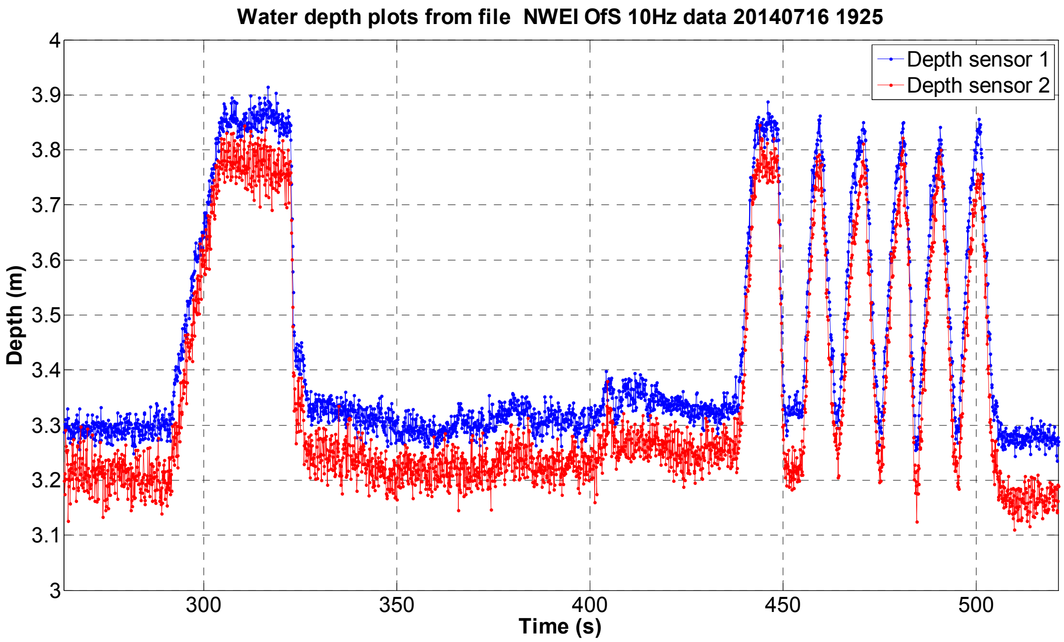


Figure 8-3 Water depth data recorded while sensors moved between 0 m and 0.6 m depth

8.2.5 Motor speed sensor

Accuracy of the motor speed sensor was checked using a stroboscope type rpm meter sighted on the motor shaft during the bench tests, and comparing peak motor speeds through each hydraulic cylinder stroke to the CompactRIO speed reading. Another rough check was made by comparing the CompactRIO generator output voltage to the motor speed measurement and verifying consistency with the generator voltage constant. Both checks indicated that the speed measurement is accurate. Because the motor speed sensor provides a constant number of pulses per revolution and the CompactRIO calculates motor speed using a highly accurate clock, small percentage errors are unlikely in the measurement so these checks indicate highly accurate speed measurements.

8.2.6 Hydraulic flow sensor

A rough assessment of the hydraulic flow sensor was made using data recorded during low speed, no load operation, when accumulator pressure was less than the 50 Bar pre-charge. This data is plotted in Figure 8-4. The flow sensor measures hydraulic flow between the hydraulic rectifiers and the hydraulic accumulator, so that the flow measurement is the sum of hydraulic flow into the accumulator and the hydraulic flow into the hydraulic motor. While motor flow can be calculated from motor speed and displacement, accumulator flow is more difficult to estimate. When pressure is less than the 50 Bar accumulator pre-charge, however, accumulator flow is zero and sensor flow equals motor flow. This low pressure condition only occurs at low flow. For the data shown in Figure 8-4, at a peak motor speed of 290 rpm, a 17 lpm flow was measured with the motor displacement set to 80 cc/rev. Actual peak flow is expected to be 290 rpm * 80 cc/rev * 0.001 l/cc = 23 lpm, so the 17 lpm measurement is about 25% lower than expected. The plots in Figure 8-4 do clearly show that the measured flow follows motor speed as expected. Most likely the sensor readings are low because this data was recorded at such a low percentage of the full range sensor reading (300 lpm).

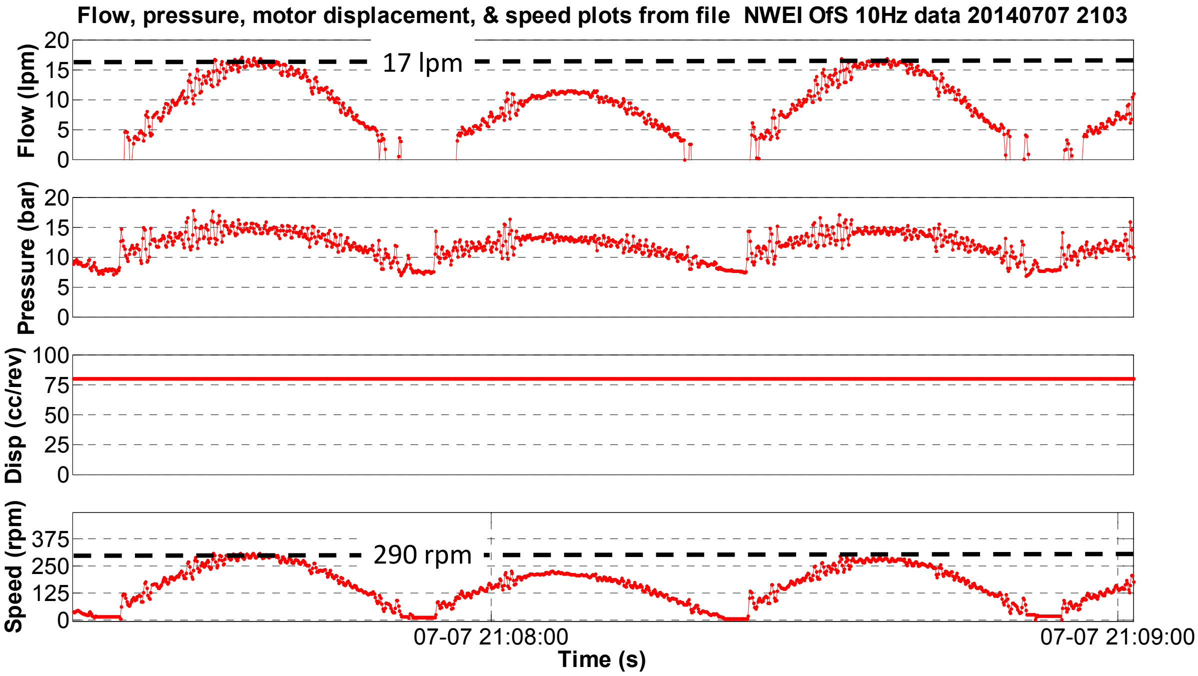


Figure 8-4 Data used to assess hydraulic flow sensor

8.2.7 Float angle sensors

The zero angle reading of both float angle sensors were set in the CompactRIO software to correspond to a float position perpendicular to the NWEI hull, with the float on the dry box side of the PowerPod. A level was used to determine the zero angle of the float, as shown in Figure 8-5. The vertical orientation of the PowerPod was also verified with the level.

A rough check of the sensor angle readings relative to their zeros was later made during operation; both sensors had nearly identical readings that were consistent with expected angles.

Figure 8-5 Method used to determine zero position of angle sensors

8.2.8 Dc voltage sensor

The dc voltage sensor was checked by comparison to a digital voltmeter that was connected to the dc output. Dc voltage held relatively steady even during generator speed variations at no load, due to the large capacitors connected to the dc output. The multimeter voltage reading matched the CompactRIO dc voltage measurement within 1%.

8.3 Effect of steps in motor displacement and hydraulic overspeed control

During initial no load operation at low speed during the bench tests, steps were made to the CompactRIO motor displacement command to determine the effect on motor speed and voltage. Data recorded during a step increase in motor displacement is shown in Figure 8-6 and Figure 8-7. While the long term effect of increasing motor displacement is to decrease motor speed, a significant short term increase in speed occurs immediately after the step in motor displacement. This occurs because the accumulator is discharged due to the increased motor displacement; note that hydraulic pressure rapidly decreases and hydraulic flow rapidly increases. The high flow after the change in motor displacement causes the increase in motor speed. This same effect occurred during load testing, and makes the use of motor displacement control to limit motor speed in order to limit generator voltage ineffective. A rate limit for the motor displacement command was later implemented in the CompactRIO control to avoid this type of speed transient; see Section 10.1 for results of testing at load with this implemented.

The data shown in Figure 8-6 and Figure 8-7 was recorded while the generator overvoltage relay was reduced to 20% (120V) from its normal setting of 43% (259 V). This overvoltage relay closes a hydraulic valve that dumps hydraulic pressure in order to limit overspeed and overvoltage. This valve was closed when generator rms voltage, shown in the top plot of Figure 8-7, exceeded 120V. It was verified that the valve did close during this test by observing a LED on the valve that lights and hearing the audible noise that occurs when the valve closes. Although this hydraulic overspeed control does have some effect on motor speed, it does not tightly limit speed and voltage to less than the relay setpoint; peak voltage reached 150V during this test as shown in Figure 8-7. Note that this testing was done with a boost transformer ratio of 1:1.5, and the transformer ratio was changed to 1:2 during final PowerPod tests. While this will not change generator voltage, the transformer and dc voltages will be 33% higher for equivalent operation during Hawaii deployment.

During normal operation, output voltage needs to be limited to less than the maximum voltage rating of the inverter. Prior to dry testing, the control implemented in the CompactRIO depended on both motor displacement control and overspeed limiting via two redundant overvoltage relays, one measuring generator voltage and one measuring dc voltage, to limit inverter voltage. The test results show that these methods will not effectively limit inverter voltage, however, and the following design changes were made as a result: 1) a dump load overprotection system will be added at the inverter input on shore that will switch in a low resistance load when inverter voltage exceeds a threshold, and 2) the dc overvoltage relay, which had a maximum voltage rating of 600 Vdc, was removed from the design so that all components at the PowerPod dc output are rated for 800 Vdc or greater. The generator overvoltage relay, which sees much lower voltage, is still in place. Due to time constraints, the on shore dump load overprotection system was not tested during dry tests but will be added to the system prior to deployment in Hawaii.

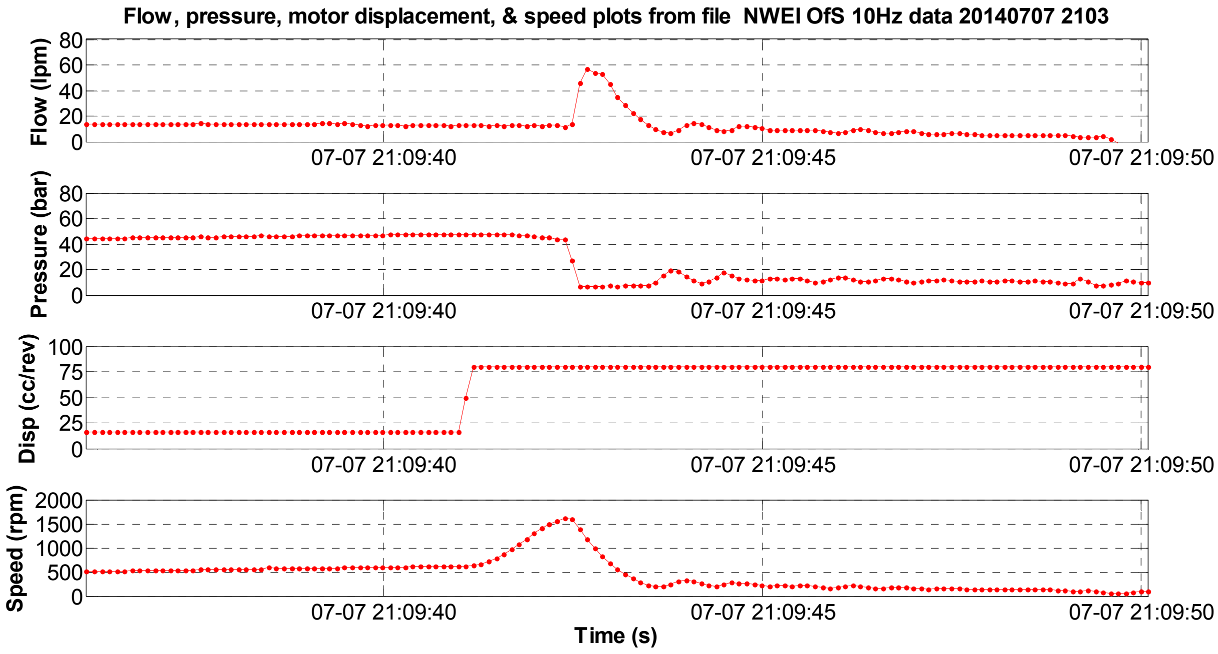


Figure 8-6 Data recorded during step increase in motor displacement with no load

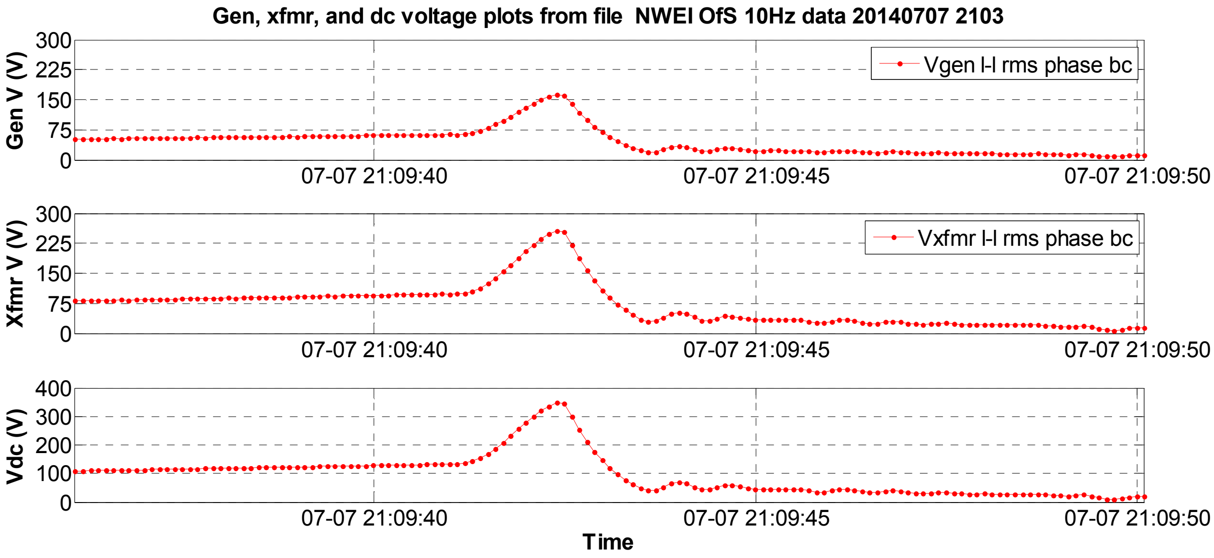


Figure 8-7 Voltage data recorded during step increase in motor displacement at no load

8.4 Characterization data recorded at no load

See Appendix III for plots of characterization data recorded at no load during PowerPod tests. Note that these results were recorded with a boost transformer ratio of 1:1.5; because the transformer ratio was later changed to 1:2, transformer and dc voltages will be 33% higher for equivalent operation during Hawaii deployment.

8.5 Conclusions for no load tests

Proper operation of most CompactRIO controller inputs and outputs was verified during the no load tests, although some anomalies were noted as follows:

- A glitch regularly occurred in the contactor control when control power to the CompactRIO controller was turned off. This glitch output can cause the contactors to momentarily close which could cause high inrush currents and possible damage. This problem will be corrected prior to deployment in Hawaii by replacing the NI 9265 output module used with the CompactRIO with a NI 9269 output module.
- The accuracy of the water depth sensors was improved by changing the rubber membrane covering the pressure sensors inside with a thinner membrane. The water depth measurement was not zeroed during the dry tests and this will be done prior to deployment in Hawaii.
- The hydraulic flow sensors could only be checked at low flow during the dry tests, and under this condition read 25% lower than expected. More accurate flow measurements are expected at higher flow but this could not be verified during the dry tests.

No load test results showed that rapid increases in hydraulic motor displacement cause a significant short term increase in motor speed, even though the long term effect of higher motor displacement is to decrease motor speed. This effect makes it impractical to limit maximum motor speed by controlling motor displacement. Tests also showed that the hydraulic dump valve that closes when generator voltage exceeds a threshold has a limited effect on generator speed. Because motor speed is not well limited by the hydraulic system, a dump load bank system will be added at the inverter input on shore in Hawaii to limit maximum inverter voltage. The dump load bank will be controlled by the on shore CompactRIO controller and will be switched on when inverter voltage exceeds an overvoltage setting. When the dump load bank is switched on, inverter voltage will be reduced because the higher dc current that results will increase the voltage drop in the subsea cable resistance and will also apply greater load to the generator.

9. Test Results: Calibration of CompactRIO Power Measurements

A calibration check of the CompactRIO power measurements was done per Section 5.5 of the test plan (Appendix I). This was done during bench testing prior to PowerPod assembly, with the generator output disconnected and power sourced from a 400 V, 50 Hz supply. A Hioki model 3169-20 three phase power meter was used to make independent power, voltage, and current measurements. This device has an accuracy of better than 1% of readings for power measurements and 0.5% of readings for both current and voltage measurements.

The resistive load bank was used for these tests. The highest resistance setting for the load bank on hand was 20.7 Ω in a three phase wye configuration; at 400V this gave a minimum test power was approximately 16 kW. One set of measurements was made at this level. In order to make a lower power measurement, the “boost” transformer that was later connected with a 1:2 ratio for deployment was connected in reverse for a 2:1 step down ratio, giving a 200 V output to the load bank. This resulted in a power of approximately 4 kW for a second set of measurements.

Results for the power calibration checks are shown in Table 9-1. Generator and transformer output power measurements are both made by the CompactRIO. A third, dc power measurement was not checked during this test. During the first test (row 2 of Table 9-1), the transformer was out of the circuit so the same power was measured at both the generator and transformer outputs. During the second test, the transformer was in the circuit so the voltages at the generator output point and transformer output point were different by a 2 to 1 factor; these results are shown in row 2 and row 3 of Table 9-1, respectively. Results show that the cRIO transformer power measurements were within 0.5% of the Hioki measurements and the cRIO generator power measurements were within 1.5% of the Hioki measurements. The cRIO transformer power measurement is made with more accurate voltage and current sensors and will to be used to assess device output power.

Table 9-1 CompactRIO Power Measurement Calibration Data

Loading Method	Gen Voltage Avg 3Ø Vll-rms (V)	Gen Current Avg 3Ø I-rms (A)	Xfmr Voltage Avg 3Ø Vll-rms (V)	Xfmr Current Avg 3Ø I-rms (A)	Gen Power cRIO (W)	Xfmr Power cRIO (W)	Power Hioki Meter (W)	Gen Power Meas. Error	Xfmr Power Meas. Error
400 V No load	406	0.1	408	0.0	2	6	0	0.00%	0.00%
400 V 20.7 ohm wye	402	22.4	404	22.7	15593	15894	15810	-1.37%	0.53%
200 V 20.7 ohm wye[1]	403	5.2	NA	NA	3654	NA	3710	-1.51%	NA
200 V 20.7 ohm wye[2]	NA	NA	193	11.3	NA	3677	3660	NA	0.46%

[1] Power meter measurement made at location of cRIO generator transducers on high voltage side of boost transformer

[2] Power meter measurement made at location of cRIO transformer transducers on low voltage side of boost transformer

Results for voltage and current measurements made by the cRIO and Hioki meter during this test are listed in Table 9-2 for reference. Measurements all match with an error less than 1% except that the phase A transformer current measurement is higher than expected. This anomaly was not noticed until after completion of the test and is inconsistent with the close match between the transformer and Hioki voltage and power measurements.

Table 9-2 Comparison between CompactRIO and Hioki voltage and current measurements

	CompactRIO						Hioki Power Meter					
Conditions	**Vgen_ab**	**Vgen_bc**	**Vgen_ca**	**Igen_a**	**Igen_b**	**Igen_c**	**Vab**	**Vbc**	**Vca**	**Ia**	**Ib**	**Ic**
400 V No load	403.8	406.8	405.9	0.1	0.1	0.1	407.5	409.1	408.0	0.3	0.3	0.3
400 V 20.7 ohm wye	400.3	403.2	402.1	22.3	22.4	22.4	404.1	405.9	404.2	22.5	22.6	22.6
200 V 20.7 ohm wye	401.1	403.6	403.5	5.2	5.2	5.3	404.6	406.1	405.4	5.3	5.3	5.3

	CompactRIO						Hioki Power Meter					
Conditions	**Vxfmr_ab**	**Vxfmr_bc**	**Vxfmr_ca**	**Ixfmr_a**	**Ixfmr_b**	**Ixfmr_c**	**Vab**	**Vbc**	**Vca**	**Ia**	**Ib**	**Ic**
400 V No load	406.7	408.8	407.0	0.0	0.0	0.0	407.5	409.1	408.0	0.3	0.3	0.3
400 V 20.7 ohm wye	402.9	404.8	403.6	22.9	22.7	22.5	404.1	405.9	404.2	22.5	22.6	22.6
200 V 20.7 ohm wye	192.8	193.8	193.6	11.8	11.0	10.9	193.0	194.1	193.8	10.9	10.9	11.0

Conclusions for CompactRIO power measurement calibration tests**:** The results show that the cRIO accurately measures output power, especially in the case of the transformer output power measurement. As expected, the transformer output power measurement is more accurate than the generator power measurement and should be used to assess device output power during the deployment. The generator power measurement is a secondary measurement that can be used to assess device performance if a problem occurs with the transformer power measurement during deployment.

10. Test Results: Testing with Resistive Load Bank

Testing of the PowerPod under load, both during bench tests and final PowerPod tests, was first done with a resistive load bank prior to the inverter testing described in Section 11. Testing with the load bank could be performed before the inverter control was functional, and the load bank is less susceptible to damage in the case of overvoltage. Because the inverter is normally controlled for constant resistance, the remainder of the system operates the same with the resistive load bank as with the inverter. CompactRIO motor displacement control algorithms were tested and a thermal test was performed with the load bank per Section 5.6 of the test plan (Appendix I). Prior to testing the control, a rate limit for the CompactRIO motor displacement command was implemented and tested. These tests were all performed during bench testing prior to PowerPod assembly. After PowerPod assembly, further test runs were done with the load bank in order to record characterization data with different load bank resistances and motor displacement settings, for future reference.

10.1 Assessment of rate limit for CompactRIO motor displacement command

A rate limit was implemented for positive changes to the CompactRIO motor displacement command to eliminate the speed transients observed during no load testing, described in Section 8.3. A series of test runs were made with different settings of this rate limit, and the results are shown in Figure 10-1. Each test run was performed with the load bank set for a wye resistance of 20 Ω (the load bank was connected directly to the transformer output). The test rig was operated to give an average output power of approximately 4500 W. The far left plots show data recorded with no rate limit, giving a 30 to 80 cc/rev/s step change in motor displacement. A significant speed transient occurred, similar to that observed during the no load tests. The three other sets of plots show the effect of different rate limits. With a 1 cc/rev/s rate limit (far right plots), only a very small speed transient was observed. This rate limit setting was left in place and will be used during the Hawaii deployment.

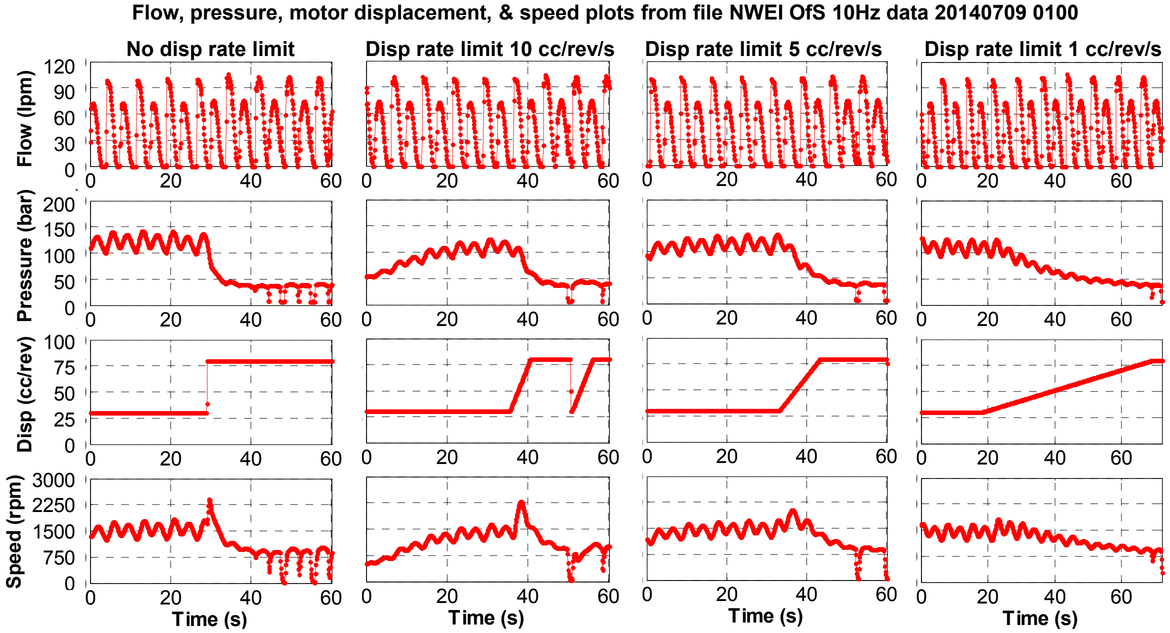


Figure 10-1 Data recorded with different motor displacement rate limits

10.2 Testing of CompactRIO hydraulic motor control algorithms

CompactRIO control of motor displacement was tested during bench tests while the test rig was operated with a random wave profile that had an energy period of approximately 7.5s. The load bank, set for a resistance of 15 Ω, was connected to the dc output. Initially, the system was operated with a constant motor displacement of 50 cc. The results are shown in Figure 10-2. The objective for the CompactRIO motor displacement control is to approximate constant damping by maintaining a constant pressure to average flow ratio. One method of control is to simply hold motor displacement constant. The plots in Figure 10-2 show that when motor displacement was held constant, pressure does change a small amount in proportion to average flow. The average flow was calculated with a 7s running average for these tests.

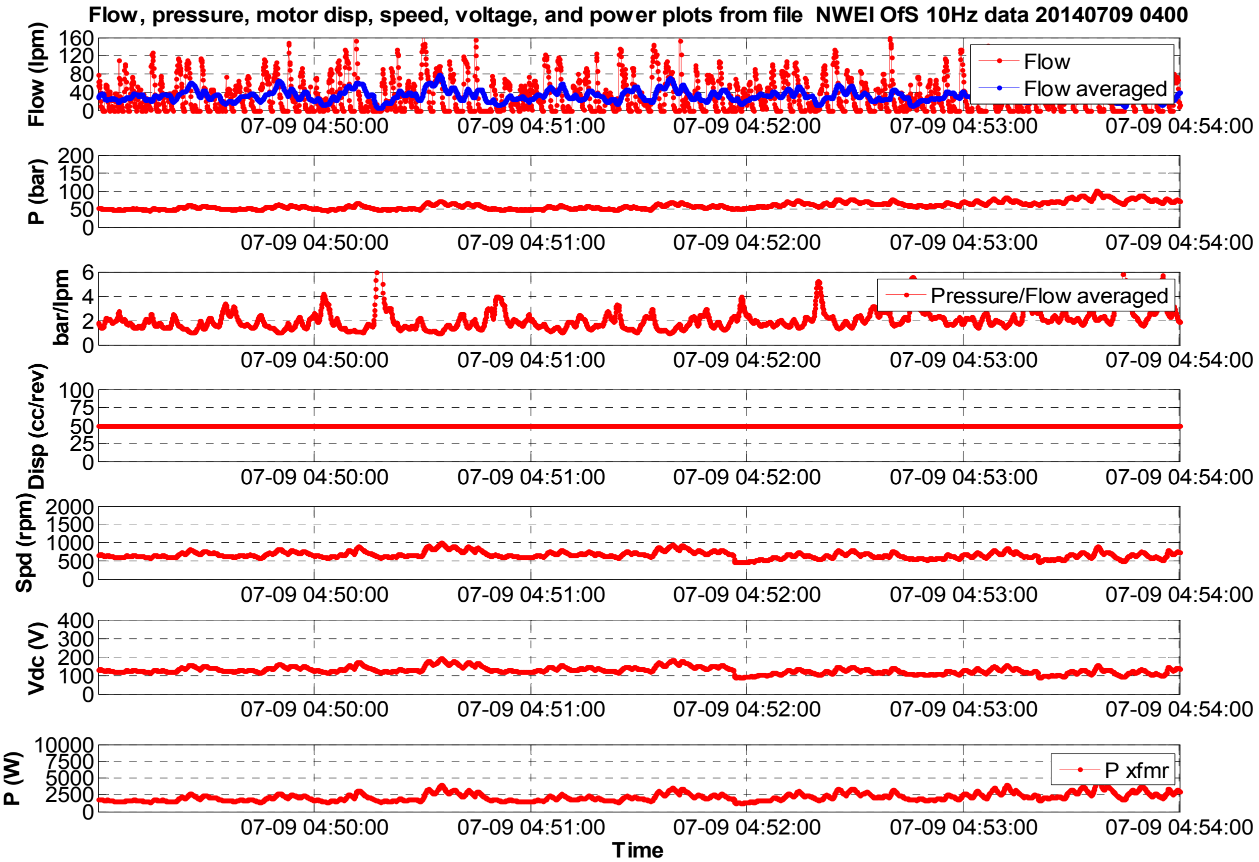


Figure 10-2 Plots for random wave movement with constant motor displacement

Testing was also performed with a proportional-integral (PI) loop controlling pressure as described in the test plan (see Figure 12 of the test plan in Appendix I for a diagram of the PI control). The proportional gain was set to 1.6 and the integral gain set to 0.8. These settings, initially determined from simulations, were found to give the best response during testing as well. Results with the PI loop operating are shown in Figure 10-3. For this test run, a setpoint of 3 was used for the ratio of pressure to average flow. The PI loop increases displacement when the pressure to average flow ratio is above the set point and decreases displacement when this ratio is below the set point. The actual ratio of pressure to average flow is shown in the third plot, while the motor displacement is shown in the fourth plot. Due to the accumulator in the hydraulic system, pressure can’t change as rapidly as commanded so motor displacement is often at its minimum 30 cc/rev or maximum 80 cc/rev. Note that the rate limit affecting the motor displacement command that is described in Section 10.1 is not in place when PI control is active. Compared to the results shown in Figure 10-2 with constant motor displacement, however, pressure changes much more with the PI control. Much greater speed fluctuations also occur this control, and effective voltage limiting will be necessary to protect the inverter when this control is used during the Hawaii deployment. Note that the results shown in Figure 10-3 were recorded with a boost transformer ratio of 1:1.5, while a transformer ratio of 1:2 will be used during the Hawaii deployment which will give 33% higher dc voltages.

These tests were performed with random wave elevation data that was recorded by a TRIAXYS wave buoy off the Oregon coast during 2012 WET-NZ tests. Because data for WEC float movement during that test was not available, this wave elevation data was simply applied directly to the float. It is expected that slower float movements will actually occur when it is loaded during ocean deployment, which should improve performance of the control and reduce the speed fluctuations.

Further testing of the PI control loop was not performed with the inverter, to avoid overvoltage damage without a dump load resistor control in place at the inverter input. The dump load and control will be installed in Hawaii prior to deployment.

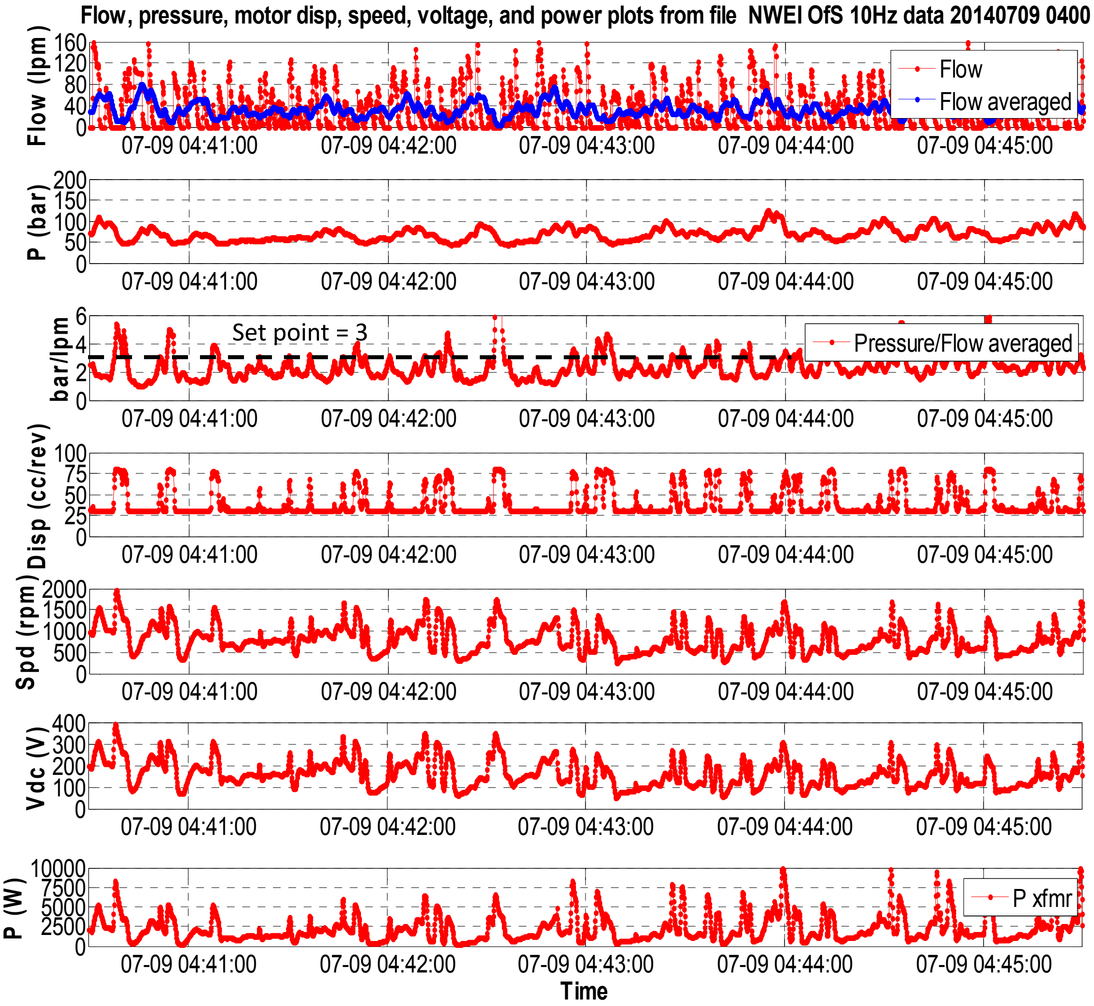


Figure 10-3 Plots for random wave movement with PI control of motor displacement

10.3 Thermal test

A thermal test of the PowerPod electrical power system was conducted on July 10 in the “bench test” configuration before final assembly of the PowerPod. The system was operated with the load bank, set for a resistance of 15 Ω, connected to the dc output. The test cylinders were driven with a 7.5s period and a stroke sufficient to give a peak power of approximately 18 kW and average power of 8.5 kW. The results of the thermal test are plotted in Figure 10-4. Plots of dc voltage, current, and power are shown in Figure 10-5 that are representative of the operating conditions throughout the test. The thermal test was stopped after 38 minutes because the diesel driven hydraulic power pack used to drive the test rig overheated. As can be seen in Figure 10-4, component temperatures had not completely stabilized when the test was stopped, but it does not appears that they would not have increased by more than another 10˚C before stabilization. Also, the ambient temperature in Hawaii may be as high as 35˚C during the deployment, or about 15˚C higher than the ambient during the temperature test. This means that actual component temperatures could be as much as 25˚C higher during the Hawaii deployment than during this temperature test.

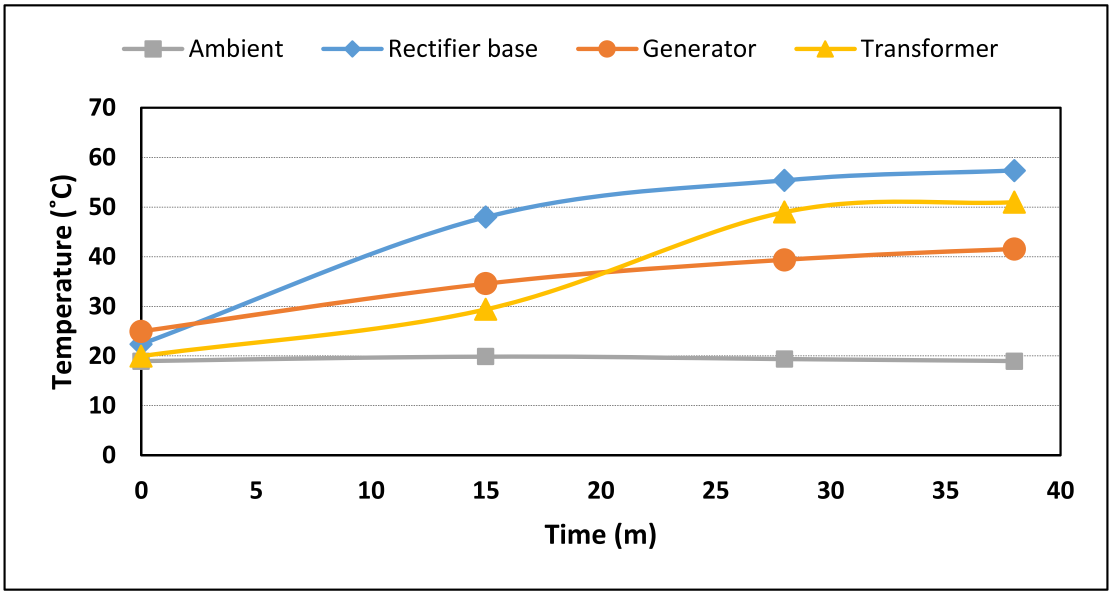


Figure 10-4 Thermal test results

Maximum winding temperature ratings for the transformer and generator, respectively, are 120˚C and 130˚C, while temperatures of 52˚C and 42˚C, respectively, were measured at the end of the thermal test. Even assuming 25˚C higher temperatures during the Hawaii deployment, both winding temperatures will be 40˚C less than their ratings.

Assessment of the rectifier temperature is more complicated because its maximum temperature rating is for its silicon junction and not the heatsink base where temperature was measured during the thermal test. This rectifier is a Microsemi MSD200-12, and it has junction temperature rating of 150˚C. The maximum temperature at its heatsink base depends on the power dissipated in the device. Calculations of the maximum base temperature for 40 A dc current are shown in Table 10-1. Power dissipation is approximately 100 W under this condition and the resulting maximum base temperature is 105˚C. The actual base temperature measured during the test was 58˚C. Adding 25˚C to account for the short duration of the thermal test and higher ambient temperatures in Hawaii, the rectifier base temperature is expected to always be 20˚C lower than this maximum temperature.

Table 10-1 Maximum base temperature calculations for Microsemi MSD200-12 rectifier module

Dc current	40	A
Power loss (from data sheet for 40A)	100	W
Junction-case thermal resistance	0.45	˚C/W
Heat rise Junction-case (P * R_{JC})	45	˚C
Max rectifier junction temperature	150	˚C
Max rectifier base temperature	105	˚C

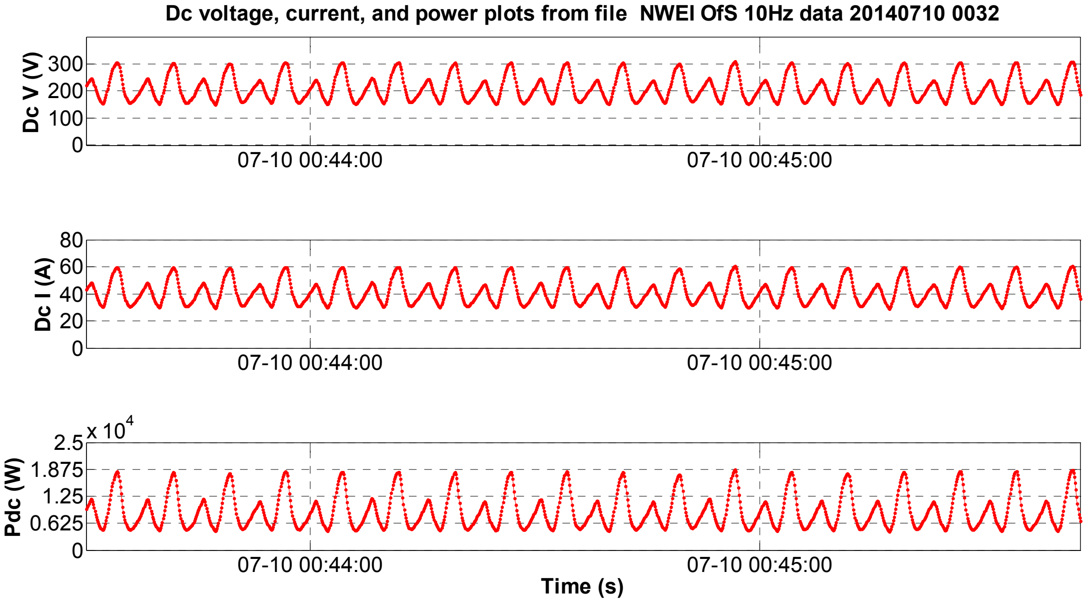


Figure 10-5 Operating conditions during thermal test

10.4 CompactRIO dc power and dc current sensor checks

Accuracy of the dc current sensor and the dc power measurement was not checked during the calibration tests described in Section 9 because those tests were performed with the load bank connected to the ac transformer output, so there was no dc current. The only method available to check accuracy of the dc power measurement and dc current sensor was to compare dc power data to transformer power data recorded at the same time during the load bank tests. The transformer power measurement was checked previously during the Section 9 calibration tests so is known to be accurate. This data comparison is shown in Figure 10-6, using data recorded during the thermal test described in the previous section. During that test, the load bank was connected to the dc output so dc current and power was measured. The results show that the dc power measurement is 0-150 W, or 0-1.5% lower than the transformer power measurement. The actual dc power, however, is expected to be about 100W lower than the transformer power due to losses in the three phase rectifier bridge, so the dc power measurements are actually within 1% or less of the dc power. Dc power is calculated by multiplying the dc current and dc voltage measurements together for each data sample. The dc voltage measurement was checked previously with a volt meter (see Section 8.2.8) and is known to be accurate within 1%. Since the dc power measurement is accurate within 1%, it follows that the dc current measurement must be accurate within at least 2%.

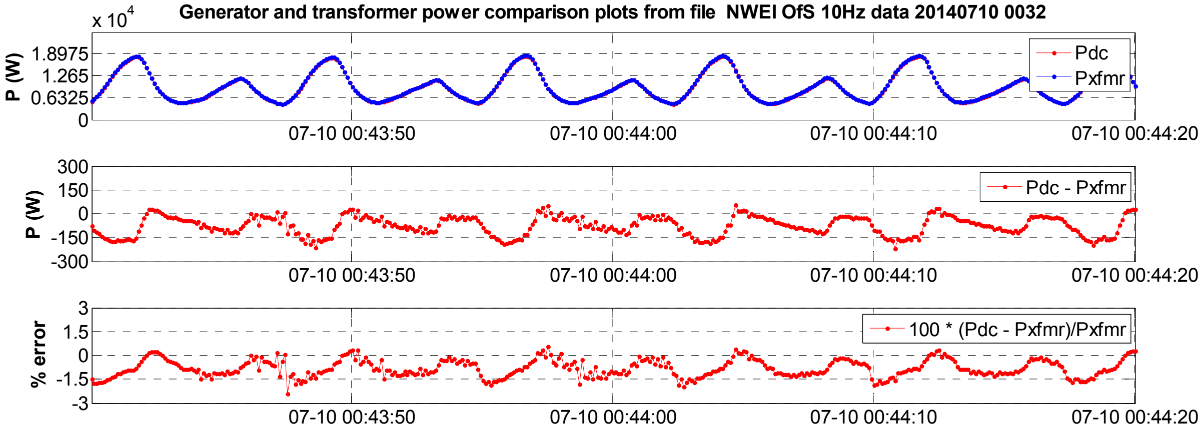


Figure 10-6 Comparison of dc and transformer power measurements

10.5 Characterization data recorded with load bank

See Appendix IV for plots of characterization data recorded while the PowerPod was operating with the load bank. Note that these results were recorded with a boost transformer ratio of 1:1.5; because the transformer ratio was later changed to 1:2, transformer and dc voltages will be 33% higher for equivalent operation during Hawaii deployment.

10.6 Conclusions for resistive load bank tests

The following conclusions can be made from tests results for the load bank tests:

- A rate limit of 1 cc/rev/s applied to positive changes of the CompactRIO motor displacement command eliminates transients in the motor speed response. This rate limit was left implemented in the control for the remainder of the tests, but is not active during PI control of motor displacement.
- The best approximation of constant damping control was achieved with PI control of hydraulic pressure, although hydraulic pressure does not vary as much as desired due to the hydraulic accumulator. When using this control, significant speed and voltage fluctuations occur that will need to be limited to avoid damaging the inverter.
- Results of a thermal test predict that all electrical power components will operate well below their maximum temperature ratings.

11. Test Results: Testing with PowerOne Inverter

Due to time constraints, only a small amount of testing was performed with the PowerOne inverter during bench testing. A significant amount of inverter testing was performed with the assembled PowerPod however, and those results are presented in this section. As discussed in Section 4, it was not feasible to test the assembled PowerPod with random wave profiles or output power above about 3 kW due to limitations of the test rig, so inverter testing was not performed under those conditions. Testing with the inverter focused on achieving stable operation with sinusoidal float movement. Tests were run per Section 5.7 of the test plan (Appendix I), which includes a diagram of the inverter control. During initial inverter testing, unstable operation occurred until a change was made to the power versus frequency curve implemented in the inverter. The inverter will be controlled to operate with constant resistance (current proportional to voltage) during the Hawaii deployment. After the inverter power versus voltage curve was changed, operation was stable except at low values of resistance. Near the end of the PowerPod tests, the ratio of the boost transformer that steps up generator voltage in the PowerPod was increased. The higher transformer ratio effectively increases the load resistance applied to the generator without increasing the operating resistance of the inverter, and with this change stable operation was achieved with the lowest resistance settings expected for the Hawaii deployment.

11.1 Power versus frequency curve configuration for PowerOne inverter

During initial testing with the PowerOne inverter, response of the inverter was slower than expected and operation was unstable at higher power. Performance was later improved by configuring the inverter with a different power versus frequency curve that maps the output power command for the inverter to the frequency of the pulse input signal from the on shore CompactRIO controller. Initial testing was done with a linear curve using a 100 to 1000 Hz pulse input frequency. This was later changed to a linear curve from 30 to 150 Hz, and a corresponding change was also made to the CompactRIO pulse output. Plots of data recorded with the two different settings are shown on the left and right side of Figure 11-1, respectively. In the left plots, recorded with the original configuration, a 2 Hz oscillation occurred and inverter current did not closely follow the current commanded by the CompactRIO controller. The right plots show the improved results and how the inverter responds to a rapid change in voltage after configuring the inverter with the 30 to 150 Hz power versus frequency curve. In both cases the inverter is controlled for constant resistance, or current proportional to voltage with a resistance setting of 25 Ω.

The pulse input to the PowerOne inverter was designed by PowerOne to interface with its own circuit that generates a pulse signal from a wind turbine generator. NWEI is adapting this input to operate with its CompactRIO controller. The inverter was left configured with the 30 to 150 Hz power versus frequency curve for the remainder of the dry tests and this configuration will be used during the Hawaii deployment.

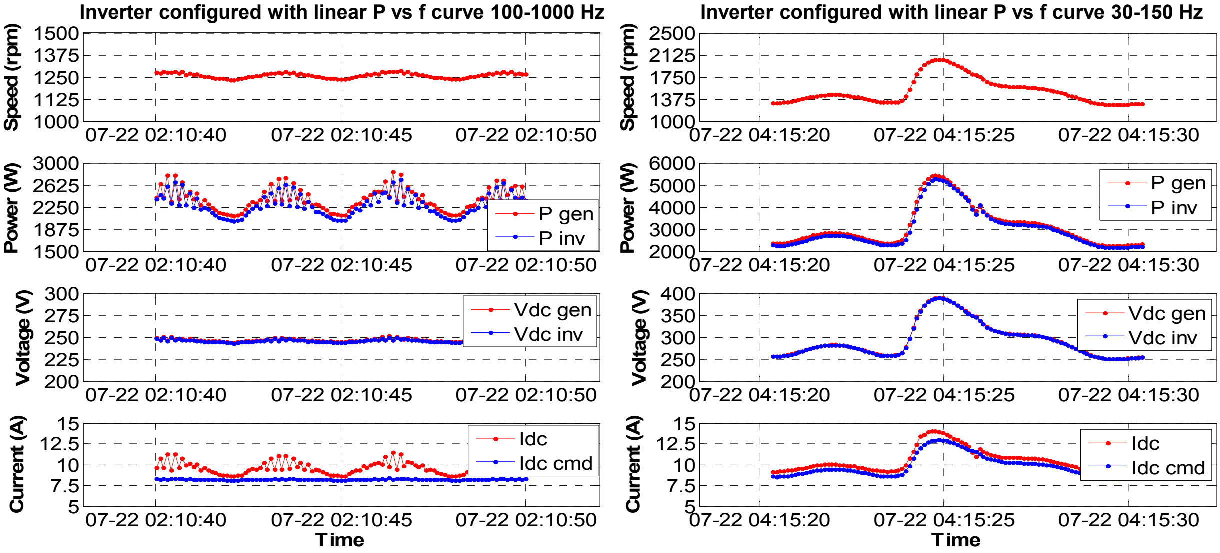


Figure 11-1 Effect of power versus frequency curve on PowerOne inverter performance

11.2 Inverter operation at low resistance with 1:1.5 transformer ratio

The inverter is controlled by the CompactRIO to provide a constant resistance load with a setting that is referred to as “R_{dc}“ in this report. Different R_{dc} settings will be used during the Hawaii deployment, depending on the amount of damping that is implemented in the control. The range of R_{dc} settings that will be used during the deployment is unknown, however, based on results of the 2012 WET-NZ deployment in Oregon it is anticipated that R_{dc} settings as low as 10 Ω might be used if the boost transformer that steps up the generator voltage in the PowerPod is configured with a 1:1.5 ratio. The boost transformer changes the effect of R_{dc} on the system in inverse proportion to the square of the transformer ratio. The boost transformer that steps up the generator voltage was configured with a 1:1.5 ratio for most of the dry tests. Operating the inverter with low values of R_{dc} tends to cause inverter instability, however, due to the relatively high resistance of the subsea cable that will be connected in series with the inverter during the Hawaii deployment. The PowerOne inverter controls power to be equal to a control input from the CompactRIO controller, and unstable operation can be expected when the inverter voltage is not significantly greater than the voltage in the subsea cable, or when the commanded resistance is not well above twice the subsea cable resistance. During the dry tests, four one ohm resistors were used to reproduce the effects of the subsea cable resistance. Tests were performed with decreasing values of R_{dc} to determine how low of settings will be feasible during the Hawaii deployment. A significant instability was observed when of R_{dc} was reduced below 11Ω. Plots recorded while transitioning R_{dc} from 11 Ω to 10 Ω are shown in Figure 11-2. A noticeable instability occurs after the transition to 10 Ω. A minor instability can also be seen in the 11 Ω data as well. Only when R_{dc} was increased to above 12 Ω (three times the subsea cable resistance) was this instability completely eliminated.

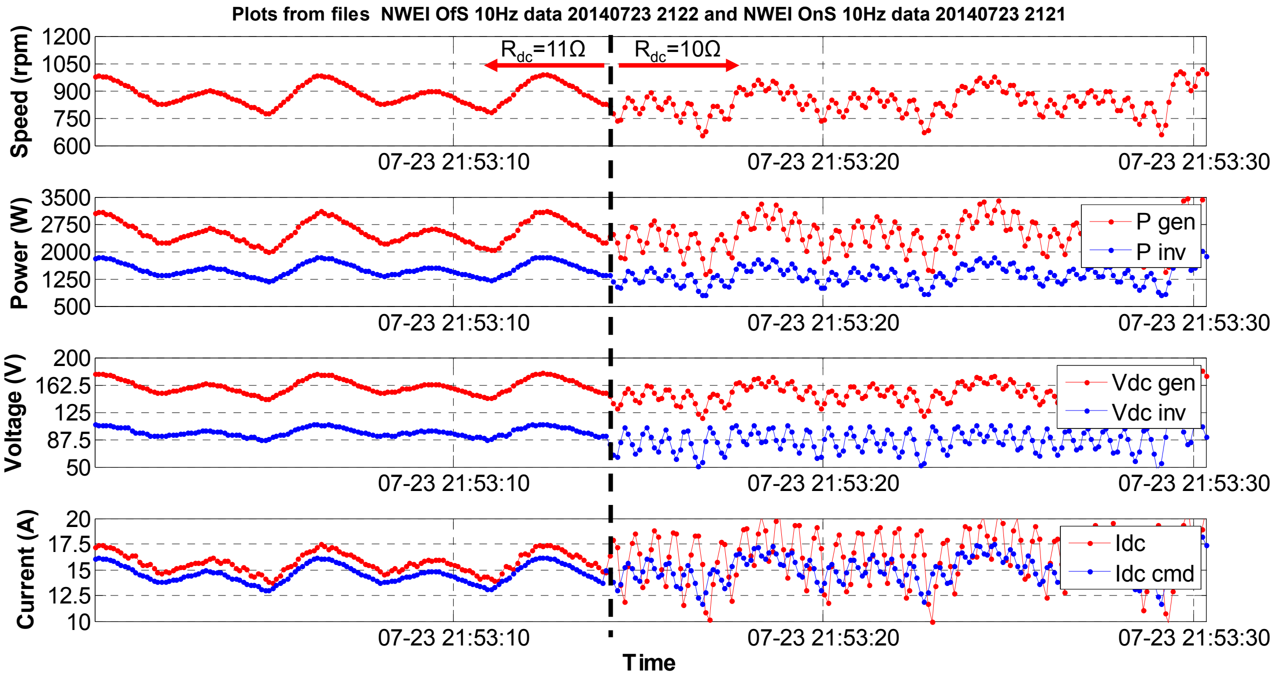


Figure 11-2 Comparison of inverter operation with R_{dc} = 11 Ω and R_{dc} = 11 Ω (1:1.5 transformer ratio)

11.3 Inverter operation with 1:2 transformer ratio

Near the end of the PowerPod tests, the boost transformer ratio was increased from 1:1.5 to 1:2 so that the inverter will operate with higher R_{dc} settings during the Hawaii deployment. It is not possible to reconfigure the transformer again during the Hawaii deployment. This change effectively decreased the resistance at the generator (boost transformer primary) by a factor of two relative to the R_{dc} setting at the inverter. With a boost transformer ratio of 1:2, R_{dc} settings of less than 20 Ω are not anticipated during the ocean deployment, while it is anticipated that R_{dc} settings as low as 10 Ω may have been desirable with a 1:1.5 transformer ratio. Inverter instabilities were observed for R_{dc} less than 12 Ω during earlier tests (see Section 11.2). In addition, the dry tests were performed with a simulated subsea cable resistance of 4 Ω and the actual resistance of the subsea cable could be a little higher, perhaps 5 Ω, which would make the inverter unstable at higher R_{dc} than 15 Ω. The disadvantage of the higher transformer ratio is higher inverter voltages that will need to be clamped by the dump load and control that will used to limit inverter voltage during the Hawaii deployment.

After the boost transformer ratio was changed from 1:1.5 to 1:2, tests were done to confirm that the inverter operated properly with an R_{dc} of 20 Ω. Plots of inverter operation while R_{dc} is changed from 25 Ω to 20 Ω are shown in Figure 11-3. No instability occurred. This was expected because the transformer ratio should not have affected operation of the inverter.

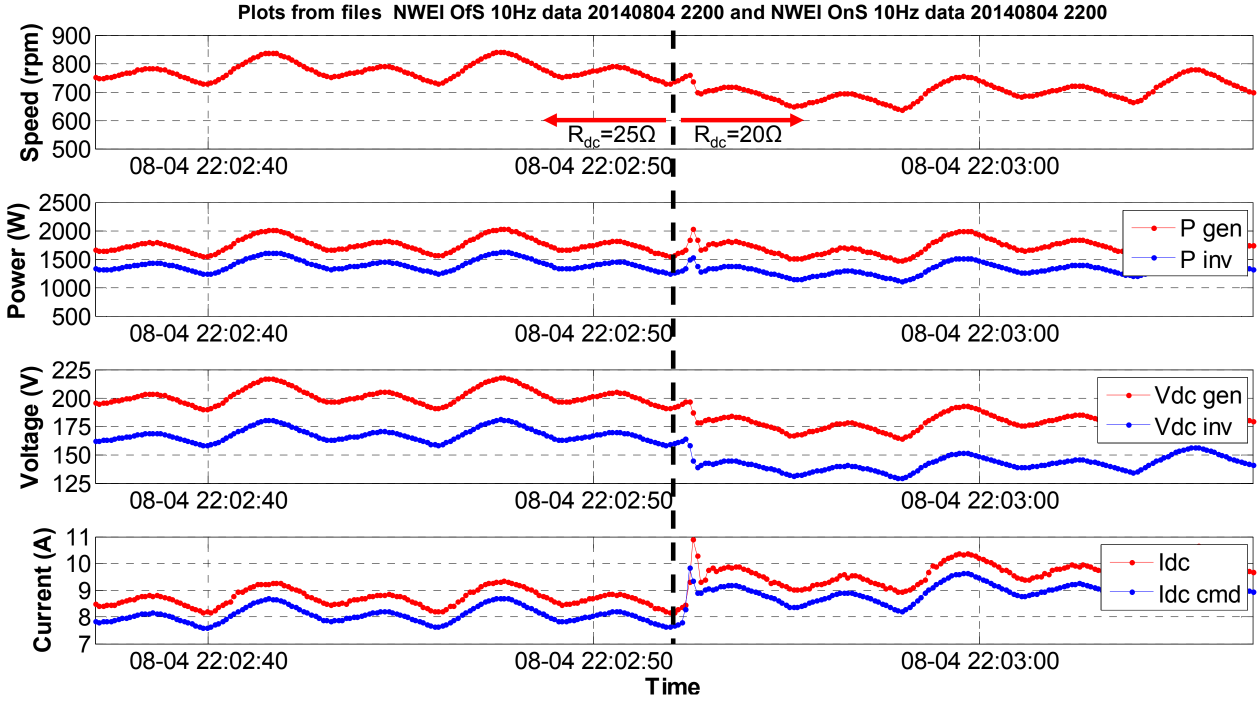


Figure 11-3 Comparison of inverter operation with R_{dc} = 25 Ω and R_{dc} = 20 Ω (1:2 transformer ratio)

11.4 Characterization data recorded with inverter

See Appendix V for plots of characterization data recorded while the PowerPod was operating with the inverter at the end of the dry tests. This data was recorded with the final boost transformer ratio of 1:2.

11.5 CompactRIO hydraulic pressure sensor checks

The hydraulic pressure sensors connected to the CompactRIO were calibrated by EHL outside the PowerPod prior to the dry test. The CompactRIO controller was configured with the scalings and offsets from that calibration before the beginning of the dry test. It was not feasible to accurately check the pressure sensor measurements with the sensors installed in the PowerPod hydraulic system. A “reality check” was made by observing pressure data recorded while the PowerPod was being tested. See the pressure sensor data included with the characterization data in Appendix V. Three of the sensors, PT01, PT04, and PT06, are open and read negative pressure. These sensors are not critical and because they are difficult to access will not be repaired prior to the Hawaii deployment. The remainder of the pressure data is consistent with what is expected.

11.6 Conclusions for inverter testing

The following conclusions can be made from tests results for the inverter tests:

- The PowerOne inverter operated best when configured with a power versus frequency curve with a 30-150 Hz input range.
- Instabilities were observed in the PowerOne inverter when it was controlled by the CompactRIO with R_{dc} settings of less than 12 Ω, or three times the series resistance that was used to simulate the subsea cable.
- The boost transformer in the PowerPod was reconfigured with a 1:2 ratio for the Hawaii deployment. R_{dc} values of less than about 20 Ω are not expected to be necessary during the Hawaii deployment with this transformer ratio. The higher transformer ratio will increase voltages at the inverter input,

12. Test Results: Abnormal Operation Tests

Tests of abnormal operating conditions were conducted per Section 5.8 of the test plan (Appendix I). Inverter overvoltage control, the response to a fault shutdown by the CompactRIO controller, and the response to 24 V control power loss were tested while the assembled PowerPod was operating with the PowerOne inverter near the end of the dry tests.

12.1 Voltage limiting with inverter control

Maximum voltage at the inverter inputs will be limited during the Hawaii deployment by increasing load current when inverter voltage exceeds overvoltage limits. This will limit voltage by loading down the PowerPod generator and increasing the voltage drop in the subsea cable resistance. Two separate methods will be used to limit overvoltages: 1) inverter current will be increased when voltage exceeds a first overvoltage threshold, and 2) a dump load bank will be switched on when voltage exceeds a second, higher overvoltage threshold. It is preferable for voltage to be limited by inverter current rather than by load bank current because inverter power is output to the grid while load bank power heats up the control room. The inverter response is slower than the load bank control, however, so in some cases both overvoltage controls will act simultaneously. An overvoltage threshold of about 475 V will be used for the inverter while a higher overvoltage threshold of about 550 V will be used for the dump load bank so that in most cases the inverter limiting alone should be sufficient. The inverter overvoltage control overrides the normal inverter current when voltage exceeds the limit, so that inverter current is in proportion to the difference between measured voltage and the overvoltage limit, up to a maximum inverter current limit. An overvoltage gain setting determines the ratio between the inverter current and overvoltage.

The inverter overvoltage limiting control, implemented in the CompactRIO, was tested during the dry tests. In order to test this control within the limits of the dry test rig capability, the overvoltage threshold was reduced to 260 V and a step in output voltage was induced by rapidly increasing the inverter R_{dc} setting. Plots of the results are shown in Figure 12-1. The overvoltage threshold was set to 450 V for the left plots, making the voltage limiting inactive. Inverter voltage increases to about 400 V after the step in R_{dc}. The overvoltage limit was set to 260 V for the right plot. The overvoltage gain was set to 1 A/V. Voltage is limited to about 310 V by the overvoltage control due to higher inverter current. Note that a 2 Hz oscillation exists while the overvoltage control is active. The overvoltage control is functional with this oscillation but it is not desirable. This oscillation occurs for the same reason that oscillations occur when low R_{dc} settings are used with the inverter (see Section 11.2). It may be possible to decrease these oscillations if a more complicated control that includes a derivative gain is implemented at a later time, but it was not feasible to experiment with this during the dry tests due to time constraints.

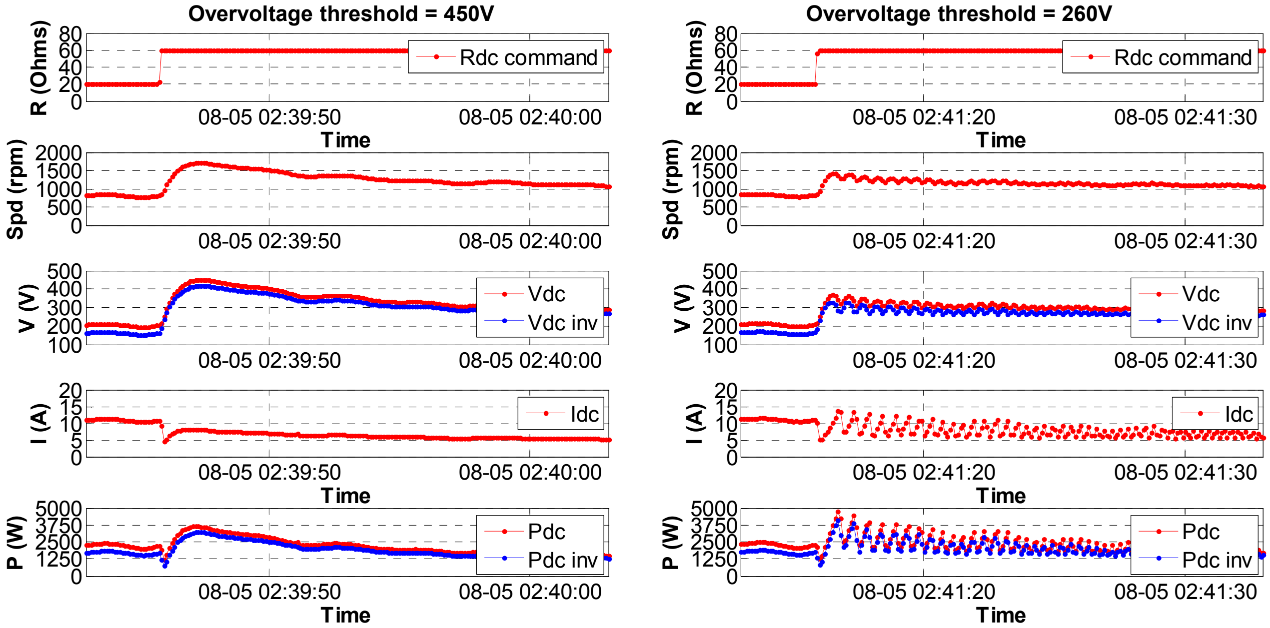


Figure 12-1 Tests of inverter overvoltage limiting with step increases in R_{dc}

12.2 Response to faults

The CompactRIO controller will shut down the control and put the system into a “safe state” with hydraulic motor displacement at maximum (80 cc) and generator output contactors open when fault conditions are detected. Faults monitored include loss of communication with the onshore controller and loss of inverter grid. The system can also be put into the safe state manually through the host computer interface. When put in the safe state, inverter current is decreased to zero, the generator contactors opened, and motor displacement commanded to maximum, with the increase in motor displacement limited by the maximum ramp rate (1 cc/rev/s) implemented per Section 10.1.

The response of the system to a fault was tested at the end of the dry tests by putting the CompactRIO control in the safe state while the PowerPod was running normally with a constant motor displacement of 30 cc/rev. The results are shown in Figure 12-2. A significant speed transient results from the loss of load, and this causes a generator voltage transient. The peak generator voltage is 350 V; generator voltages as high as 600 V will not cause damage (the generator overvoltage relay has a 600 V rating). Note that the hydraulic dump valve closes for generator voltages above 190 V (the setting implemented with the 2:1 boost transformer ratio). There is no transient in the transformer or inverter voltages, however, because the generator contactors open.

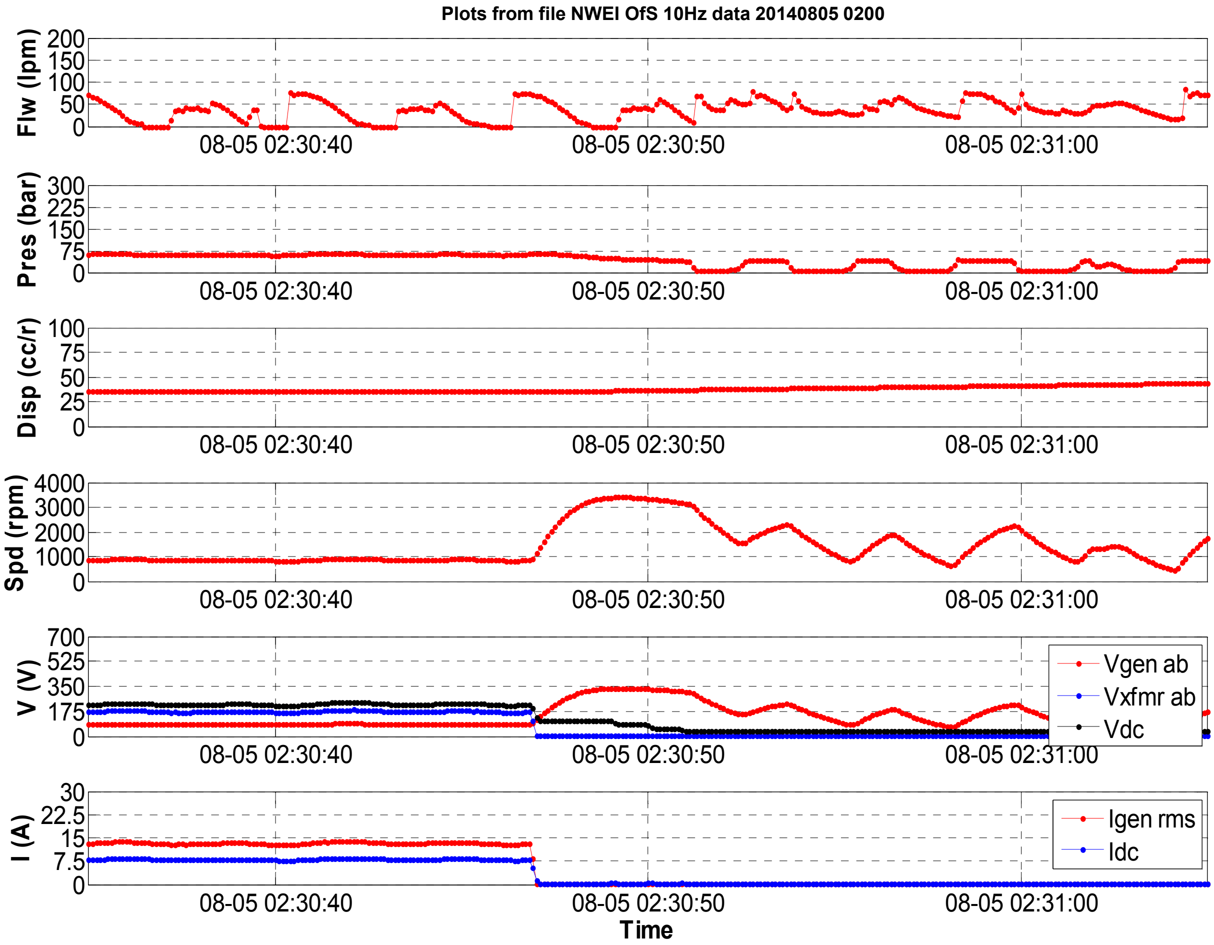


Figure 12-2 Response of system when CompactRIO control is transitioned to safe state

12.3 Loss of 24V control power

The 24 V power for all the PowerPod control components including the CompactRIO will be lost during the Hawaii deployment if the 220 V dc ancillary power that is transmitted from shore is cut off. This should be unusual because the 220 V dc power supply will be powered by an uninterruptable power supply (UPS) during the deployment. The response of the system to the loss of control power is similar to fault response described in 12.2, except that 1) the motor displacement rapidly transitions to 80 cc (maximum), and 2) the hydraulic dump valve will not close regardless of generator voltage. When 24 V power is cut off, motor displacement rapidly transitions to maximum because solenoid power is lost, the generator contactors open because coil power is lost, and the hydraulic dump load stays in its normally open state.

A test was performed to simulate loss of 24 V power during inverter tests of the assembled PowerPod. Because data is not recorded by the CompactRIO after 24 V power is shut off, a test was done to simulate this occurrence without turning off 24 V by eliminating the motor displacement ramp rate and stopping the CompactRIO control. The results are shown in Figure 12-3. This test was performed with a boost transformer ratio of 1:1.5, before it was reconfigured for the final ratio of 1:2, so equivalent transformer and dc voltages with the final transformer ration will be 33% higher. The response is very similar to the fault response shown in Figure 12-2, except the speed transient is different because of the faster increase in motor displacement. Generator voltage increases to about 300 V (equivalent to about 400 V with a 1:2 boost transformer ratio), while transformer and inverter voltage decreases because the contactors open. The hydraulic dump valve opened momentarily because generator voltage exceeded 260 V (the setting used with 1:1.5 boost transformer ratio). While this would not occur during an actual 24 V power loss it does not appear that his had a significant effect on the results.

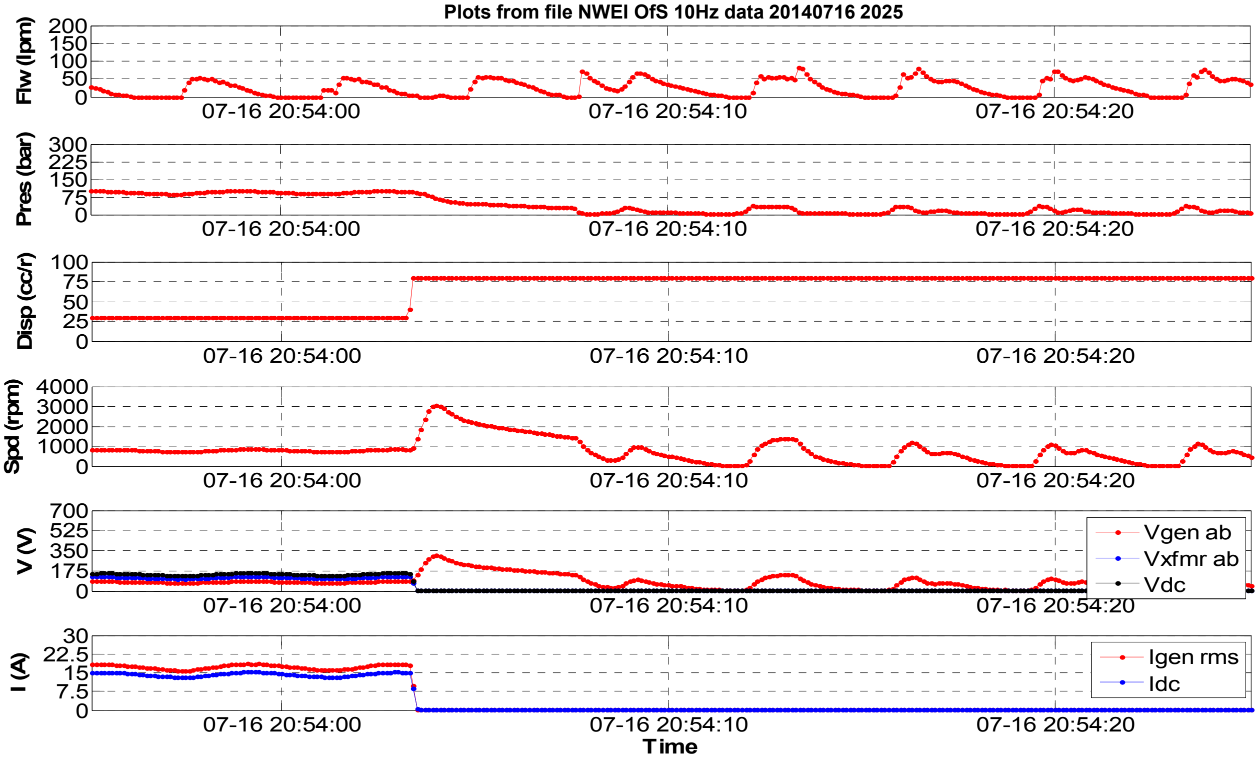


Figure 12-3 Simulated loss of 24V control power (1:1.5 boost transformer ratio)

12.4 Conclusions for abnormal operation tests

The following conclusions can be made from the test results for the abnormal operating tests:

- Inverter overvoltage control implemented in the CompactRIO functions properly to reduce inverter voltages during abnormal operation. This control is relatively slow, however, and will be supplemented by a faster acting dump load bank overvoltage control during the Hawaii deployment.
- The system can be expected to safely shut down after faults are detected by the CompactRIO controller or loss of 24 V control power occurs.

13. Conclusions and Lessons Learned

Proper operation of the Azura PowerPod was successfully demonstrated during the dry tests. Based on the results of these tests, the device can be expected to operate properly during the Hawaii deployment. Specific conclusions and lessons learned during these tests are described in the following subsections.

13.1 24 V power supply

Test results indicated that the 24 V power supply will reliably provide control power during the deployment. This power supply, which is a custom design for this deployment, will need to operate with wide fluctuations in input voltage due to resistive voltages in the subsea cable. Stable operation of this power supply was demonstrated with input voltage variations more rapid than will occur during the deployment and a wide range of loads.

13.2 CompactRIO controller

Operation of the CompactRIO control and data acquisition system was successfully demonstrated during the dry tests. Proper operation of all inputs and outputs were verified with the minor exceptions described below:

- A glitch in the contactor control output occurs during power down of the CompactRIO controller that can cause the contactors to close momentarily. This will be corrected prior to the Hawaii deployment by replacing the existing NI 9265 output module with a NI 9269 output module that does not have this problem.
- The hydraulic flow sensor readings may be low by as much as 25% based on the check made of this sensor at low flow. Although the readings are expected to be more accurate at higher flow, a check of this sensor at higher flow was not possible during the dry tests.
- Three of the hydraulic pressure sensors are not functioning. These sensors are not critical to PowerPod operation.
- The water depth sensor measurement appears to be operating properly but will be zeroed and possibly re-checked at greater depths in Hawaii prior to deployment.

13.3 Overvoltage control

Extensive testing of different generator speed and overvoltage control methods was conducted during the dry tests which led to the following conclusions:

- Rapid increases in hydraulic motor displacement cause a significant short term increase in motor speed, even though the long term effect of higher motor displacement is to decrease motor speed. This effect makes it impractical to limit maximum motor speed by controlling motor displacement. A 1 cc/rev/s maximum rate limit for changes in motor displacement was implemented in the CompactRIO control to avoid rapid increases in motor displacement.
- The hydraulic dump valve that closes when generator voltage exceeds a threshold has a limited effect on generator speed. While the dump valve does reduce

generator speed transients, it can't be relied on alone to clamp generator speed to below a maximum limit.

- Test results showed that overvoltage control using the inverter to increase load current when inverter voltage exceeds a limit decreases the maximum voltages that occur. This control is relatively slow, however, and gives a soft response that does not clamp voltage to below a maximum limit.
- A dump load bank and control will be implemented on shore prior to the Hawaii deployment that is expected to give fast control that will limit inverter voltage to below a maximum limit. This will be used in combination with the inverter overvoltage control described above.

13.4 Damping control of hydraulic motor displacement

Controlling the hydraulic motor displacement using proportional-integral (PI) control of motor pressure gives the best approximation of constant damping possible with the Azura PTO system. With constant damping, the force applied to the WEC float is proportional to the vertical speed of the float. Under ideal conditions, with constant damping the hydraulic pressure in the PTO is proportional to hydraulic flow. The test results show that PI control of hydraulic pressure causes pressure to vary in response to a running average of the hydraulic flow as desired. Because the hydraulic accumulator in the PTO resists changes in pressure, however, the PI control often can't change pressure as quickly as needed for ideal damping even though motor displacement is switched alternately between minimum and maximum limits. This is a limitation of the hydraulic system, and can't be corrected by changes to the control method.

When using PI control of motor pressure, significant speed and voltage fluctuations occur that will need to be limited to avoid damaging the inverter. These speed and voltage fluctuations are caused by the rapid changes in motor displacement that are necessary with this control.

13.5 Thermal testing

Results of thermal tests indicate that all electrical power components and 24 V power supply components will operate well below their maximum ratings during the Hawaii deployment.

13.6 PowerOne inverter instabilities

Instabilities can be expected to occur in the PowerOne inverters if the R_{dc} resistance setting in the CompactRIO controller is less than three times the subsea cable resistance. The subsea cable resistance will be about 5 Ω for the Hawaii deployment, so if the R_{dc} setting is kept above 15 Ω no instabilities are expected. The lowest R_{dc} setting anticipated for the Hawaii deployment is about 20 Ω with the current PowerPod generator boost transformer ratio of 1:2.

13.7 System shutdown after faults and loss of control power

Tests of the CompactRIO control during the dry tests indicate that the system is expected to safely shut down after faults are detected or a loss to 24 V control power occurs.

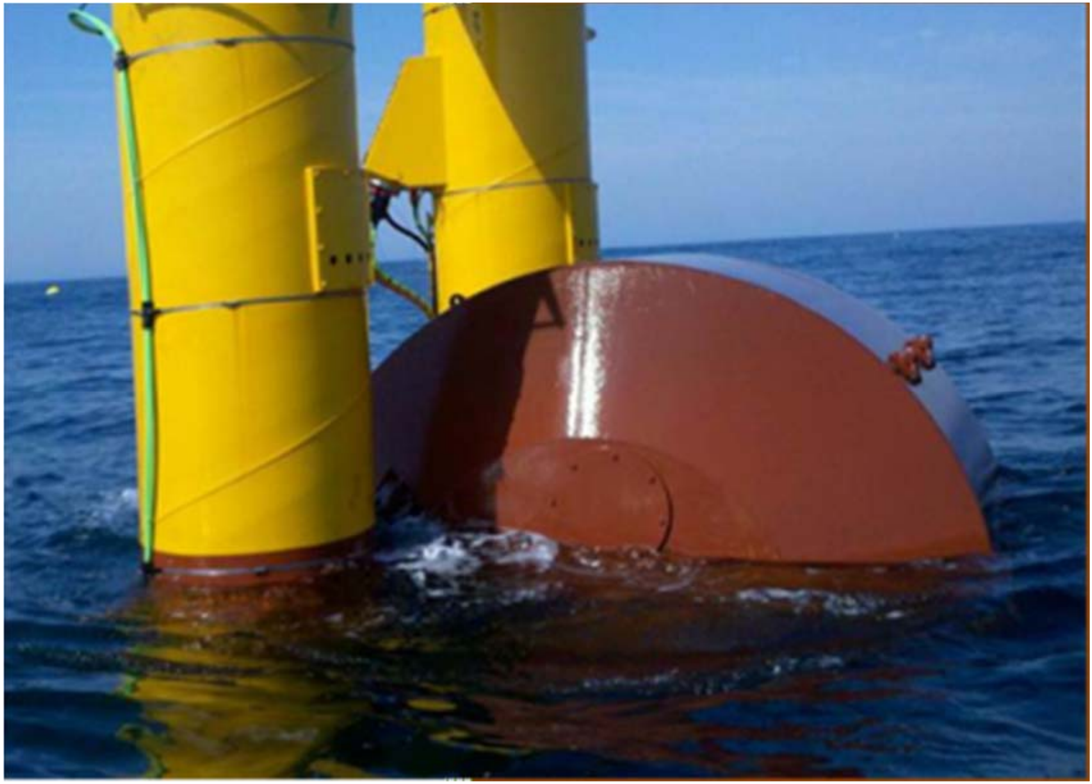
Appendix I

Test Plan

NWEI Wave Energy Demonstration at the Navy's WETS 30m Project Site

2014

Test Plan for Dry Testing at EHL



Northwest Energy Innovations

7/14/2014

TABLE OF CONTENTS

1. INTRODUCTION

This document describes dry testing that will be performed on the PowerPod of the Northwest Energy Innovations (NWEI) wave energy converter (WEC) device at the Energy Hydraulic Limited (EHL) facilities in New Plymouth, New Zealand in 2014. This testing will be conducted in order to validate operation of the PowerPod on dry land following the hydraulic and electrical modifications that will have been made by EHL in 2013-2014. Following completion of these tests, the NWEI PowerPod will be shipped to Hawaii, and the NWEI device will be deployed for a one year period at the US Navy's 30-meter grid-connected Wave Energy Test Site (WETS) located at the Marine Corps Base Hawai'i (MCBH).

2. OBJECTIVES

1. Measure insulation resistance to chassis ground for the electrical generator and power circuitry.
2. Verify stable operation of the 24V ancillary power supply with fluctuating input voltages and fluctuating loads.
3. Verify that the offshore CompactRIO installed on board the device functions properly to collect data from all sensors in the system.
4. Verify that sufficient cooling is provided for reliable operation of all electrical power components at full power.
5. Verify operation of the PowerOne inverter with the electrical system of the device.
6. Verify the control functions of the CompactRIO data and control system that consists of the offshore CompactRIO (installed on board the device) and the onshore CompactRIO (to be installed onshore in Hawaii) together with the complete hydraulic and electrical system of the PowerPod.

3. TEST ARTICLE

The test article is described in the latest revisions of the following documents:

- NWEI Test Plan - NWEI Wave Energy Demonstration at the Navy's WETS 30m Project Site
- EHL drawing "Hawaii As Built Hydraulic Diagram"
- AFI drawing WED0020-752-01, revised by EHL, "DOE Oregon Wave Generator Electrical and Control Drawings (Kaneohe Bay Deployment)"
- EHL drawing 6747-Layout-E00 "DOE Oregon Wave Generator Electrical Layout Drawings (Kaneohe Bay Deployment)"
- Offshore NWEI CompactRIO Channel List (included in Appendix A)

4. TEST SETUPS

The tests setups described in the following subsections will be used for the test procedures described in Section 5.

4.1. Insulation resistance test setups

The three different test setups shown in Figure 1, Figure 2, and Figure 3 will be used for different insulation resistance tests described as follows:

- The Figure 1 setup will be used to test the generator alone, while it is disconnected from all other circuitry. A 1000 Vdc test voltage will be used for this test.
- The Figure 2 and Figure 3 setups will be used to test circuitry on either side of the boost transformer independently, while all equipment is connected in the circuit. These tests will be performed at a 500 Vdc test voltage.

Power conductors will be jumpered together for these tests as shown in the figures. Because these will be very low power tests, small wire jumpers may be used.

An insulation resistance or megohmmeter ("Megger") will used to perform these tests per Table 1.

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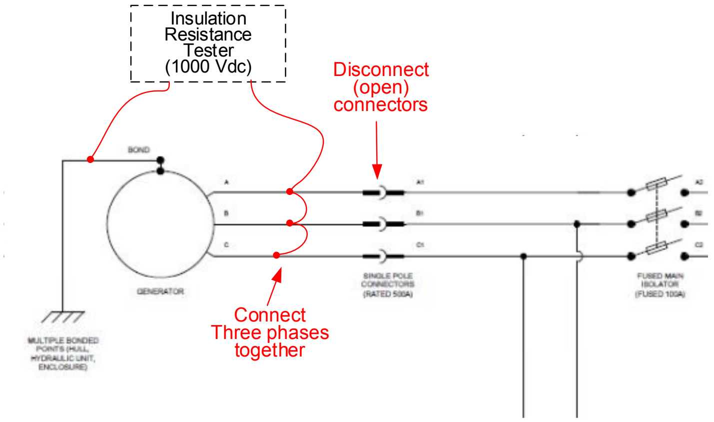


Figure 1 Setup for insulation resistance test of generator alone

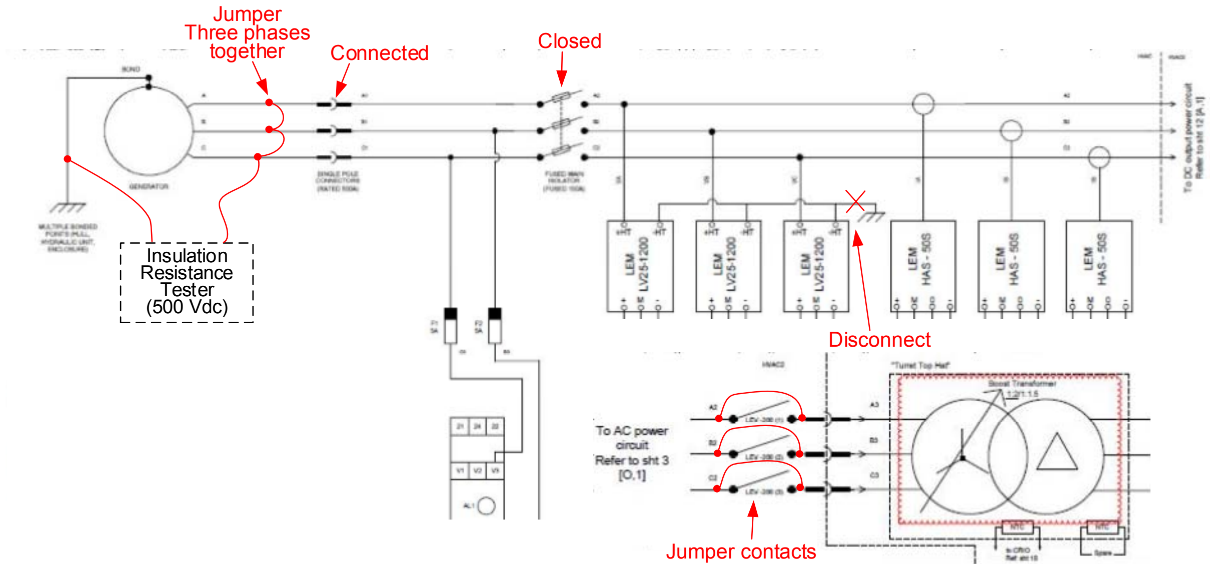


Figure 2 Setup for insulation resistance test of generator to boost transformer

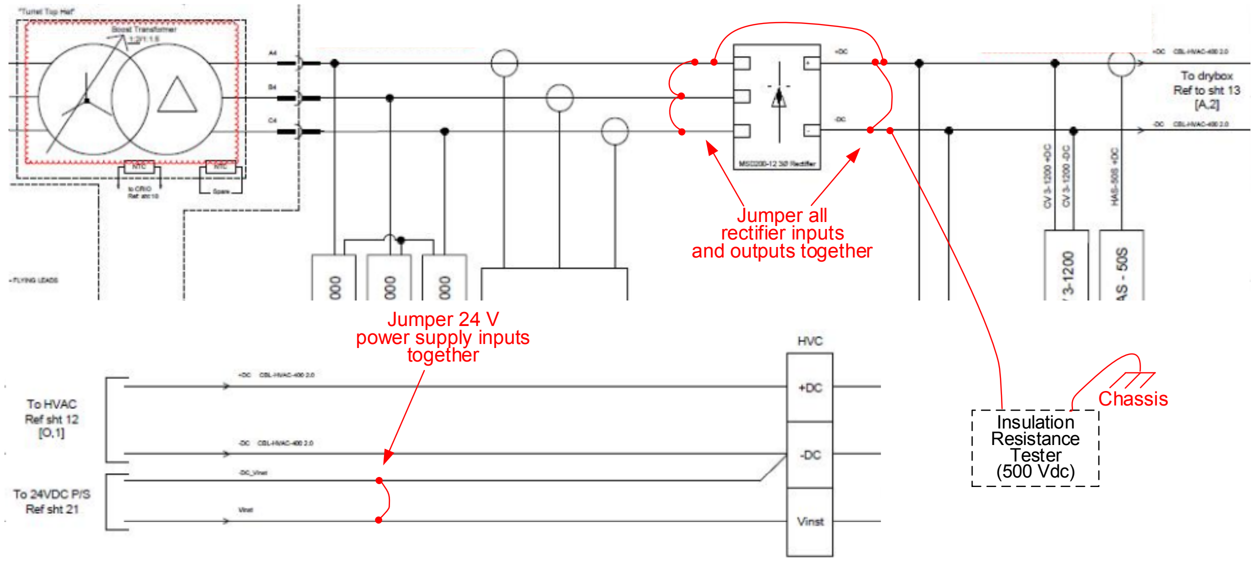


Figure 3 Setup for insulation resistance test of boost transformer to dry box

Table 1 Required equipment for insulation resistance tests

Item	Manufacturer	Model Number	Notes
Megohmmeter	Kyoritsu	KEW 6016	Or equivalent

4.2. Electrical Setup for 24V Power Supply Pre-test

This setup, shown in Figure 5, will be used to initially test the 24 V power supply circuitry with a fixed 220 Vdc input voltage. The details of this setup are as follows:

- The float will not be rotated, and electrical power outputs from the PowerPod will be disconnected
- Input power supplies will consist of two, 110 Vdc Acopian power supplies that will ultimately be installed on shore in HI.
- The CompactRIO data acquisition and control system will not be installed during these tests.
- Two digital voltmeters (DVMs) will be used to monitor the input and output voltages of the power supply. If two meters are not available, the test can be performed with a single meter that is moved between the two positions.
- Initially, all 24 Vdc fuses will be disconnected so that the 24 V supply operates at no load. Fuses will then be added in one by one to verify proper voltages throughout the instrumentation system.

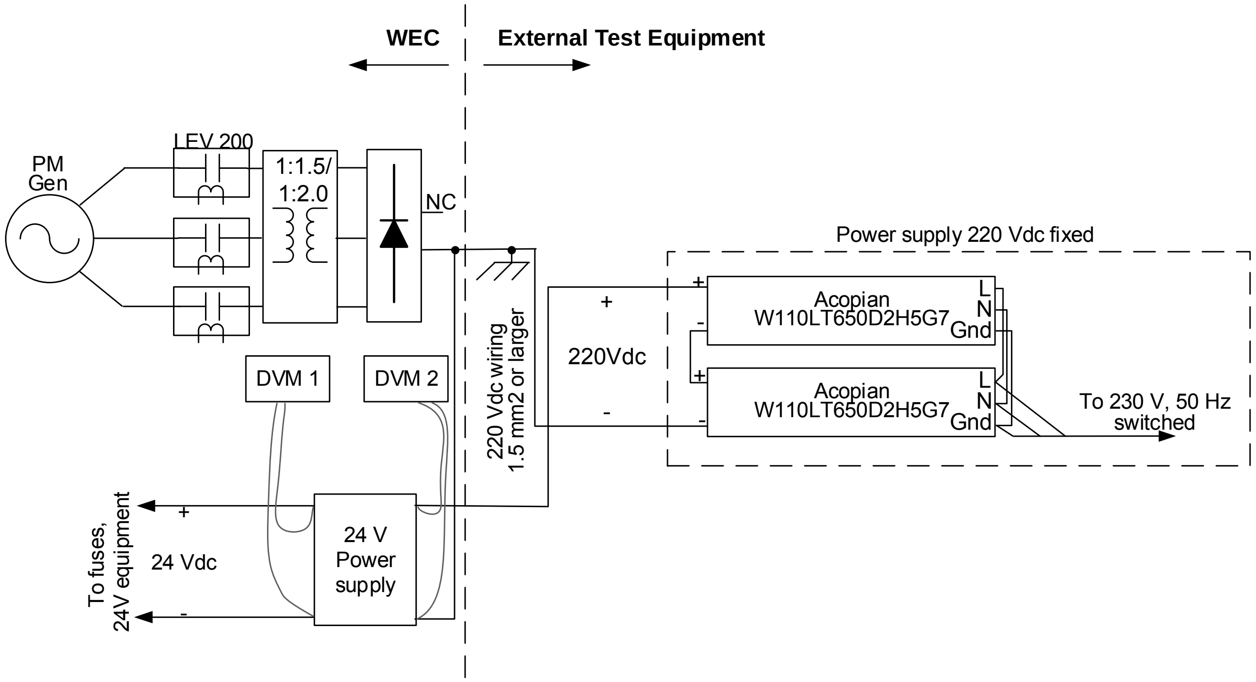


Figure 4 Electrical Setup for 24V Power Supply Pre-test

Table 2 Required components for 24V power supply pre-test

Item	Manufacturer	Model Number	Notes
110 Vdc power supplies	Acopian	W110LT650D2H5G7	NWEI to provide (Qty 2)
Digital volt meter (DVM)	APPA	79	

4.3. Electrical Setup for 24V Power Supply Testing

This setup, shown in Figure 5, will be used to test the 24 V power supply onboard the PowerPod with an input voltage that can be switched between 220 Vdc and 300 Vdc, and with a switched load that increases output current by 24 A above that provided by normal equipment. This setup will simulate variations in input voltage that will occur during the Hawaii deployment due to the resistance of the subsea cable. The details of this setup are as follows:

- The float will not be rotated, and electrical power outputs from the PowerPod will be disconnected
- Input power supplies will consist of two, 110 Vdc Acopian power supplies that will be installed on shore in Hawaii and used for normal operation of the device at 220 Vdc, and an additional 0-110 Vdc adjustable power supply set for 80 Vdc added in series to give 300 Vdc total capability. An external shorting switch will be connected to the output of the 80 Vdc supply (these supplies are current limited so will not be damaged if their output is shorted) to switch output voltage of the series connected supplies between 220 Vdc and 300 Vdc.
- A 1 mHy inductor will be wired in series with the output of the onshore power supplies to simulate inductance of the subsea cable. Input inductance has a tendency to destabilize operation of the 24 Vdc power supplies.
- An external, 1 Ω, 1.5 kW resistor will be wired to the output of the onboard 24 Vdc supply that is being tested through an external switch. When switched in during testing, this resistor will provide an additional 24 A of load to the 24 Vdc supplies.
- Two digital voltmeters (DVMs) and an oscilloscope with two isolated channels will be used to monitor the input and output voltages of the power supply while input voltages and output loads are switched.
- During some testing, the normal 24 V equipment connected to the onboard 24 Vdc supply will be disconnected so that the load can be switched between no load and the load provided by the external 1 Ω resistor.

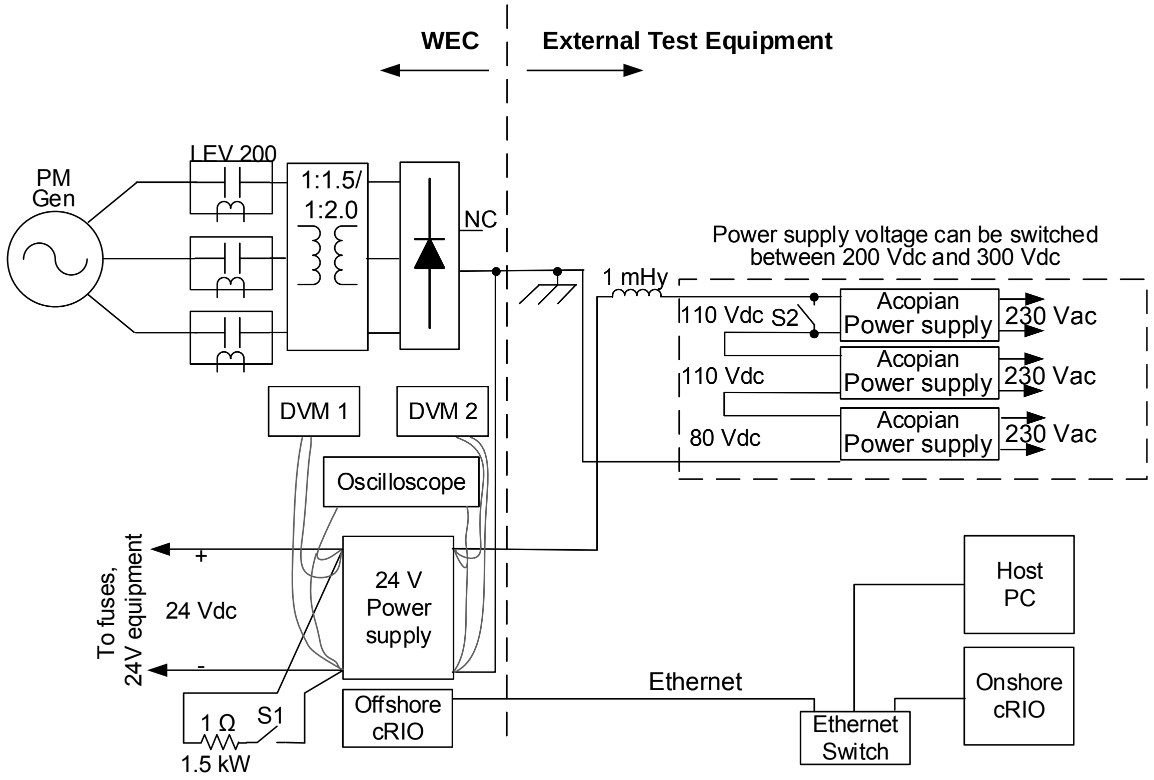


Figure 5 Electrical Setup for 24V Power Supply Testing

Table 3 Required components for 24V power supply test setup

Item	Manufacturer	Model Number	Notes
110 Vdc power supplies	Acopian	W110LT650D2H5G7	NWEI to provide (Qty 2)
0-110 Vdc power supply	Acopian	Y0110LX650D2H5G7	NWEI to provide (Qty 1)
Ethernet switch (shore)	TP-LINK	TL-SG10050	NWEI to provide
Host PC	Dell	Optiplex 9020	NWEI to provide
Monitor for host PC	TBD	TBD	EHL to provide
Switch – input	Altech	KUE340	NWEI to provide
Switch – output	Altech	KUE340	NWEI to provide
1 Ω, 1.5 kW resistor	TE Connectivity	TE1500B1R0J	NWEI to provide
Line inductor	Hammond	157D	1 mHy, 10A; stock at Mouser Electronics (US)
Digital volt meters (DVM)	Fluke APPA	15B 79	NWEI can provide one EHL to provide one
Oscilloscope	Tektronix	THS710A	NWEI to provide
K Thermocouple wire/connector	TBD	TBD	NWEI to provide
Thermocouple meters	Fluke	80TK	NWEI to provide 2

4.4. Cylinder and Float Drive Test Rig

See Figure 7 for a photo of the test rig at EHL that will be used to drive the PowerPod cylinders outside of the PowerPod structure. See Figure 7 for the test rig that will drive float movement during the dry tests after final PowerPod assembly.

Figure 6 Hydraulic Rig Used to Drive Cylinders out of Power Pod Structure

Figure 7 Test Rig for Driving Float

4.5. Electrical Setup for No Load Testing

This setup, shown in Figure 8, will be used to for the following purposes:

- With no float movement or generator rotation: Initial checkout of the cRIO system and some sensors.
- With float movement and no load generator rotation:
    - Further sensor checks for cRIO system.
    - Verification of correct power system voltages at no load.
    - Measurement of no load power supplied to the float.

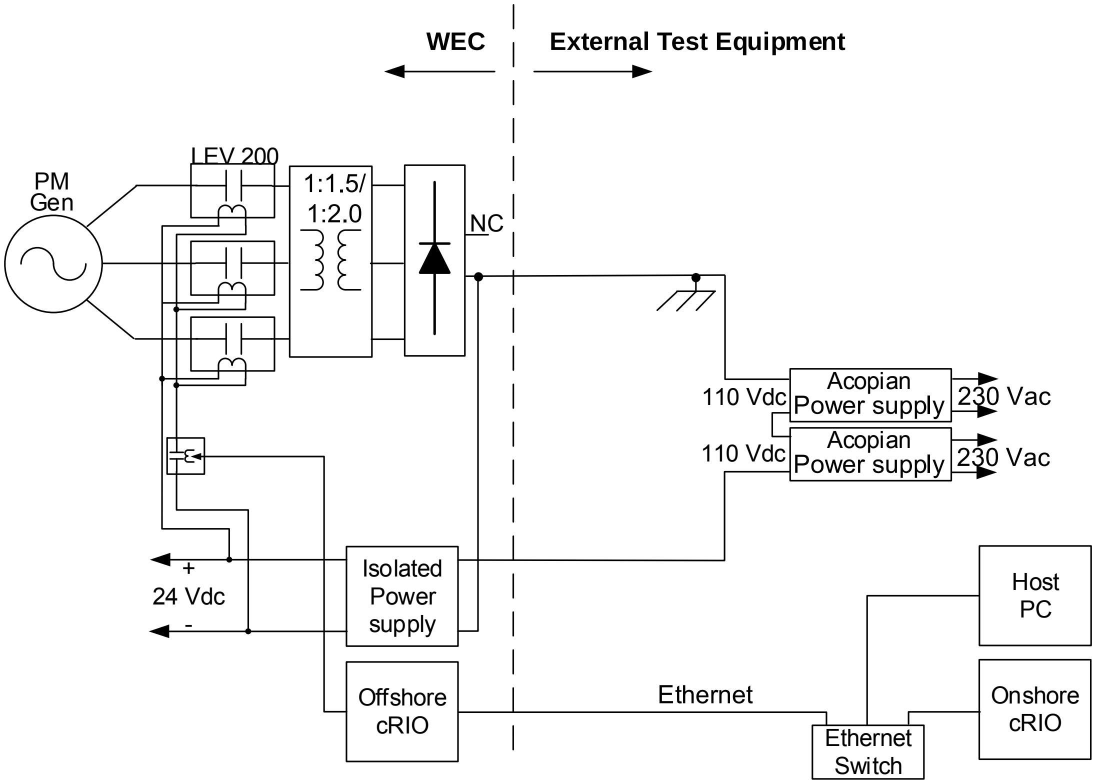


Figure 8 Electrical Setup for No Load Testing

No components are required for this test setup that are not also required for the 24V power supply test setup described in Section 4.3.

4.6. Electrical Test Setup for 50 Hz Power Measurement Calibration

This setup, shown in Figure 9, will be used to calibrate the two sets of three phase power measurements made by the cRIO controller. This calibration will be done using 50 Hz, three phase utility power and a load bank rather than using the electrical generator in the device for the following reasons:

- This setup provides constant power measurement which simplifies the power measurements; power always varies with the oscillating float movement of other test setups.
- The three phase power meter needed to provide a secondary, calibrated power measurement is not available for the variable frequency generator output that occurs during normal operation.

The details of this setup are as follows:

- There will be no float movement or generator rotation.
- The output of the electrical generator will be disconnected and a 50 Hz, three phase utility voltage will be connected into the circuit as shown in Figure 9.
- The boost transformer can either be disconnected, as shown in Figure 9, or connected in place as either a step-up or step-down transformer to give appropriate loading from the load bank.
- The three phase bridge that normally converts the ac generator output to dc for connection to the subsea cable will be disconnected and a three phase resistive load bank will be connected in its place.
- A calibrated three phase, clamp-on type hand-held power meter will be used to measure power and check the two power measurements made by the offshore cRIO.

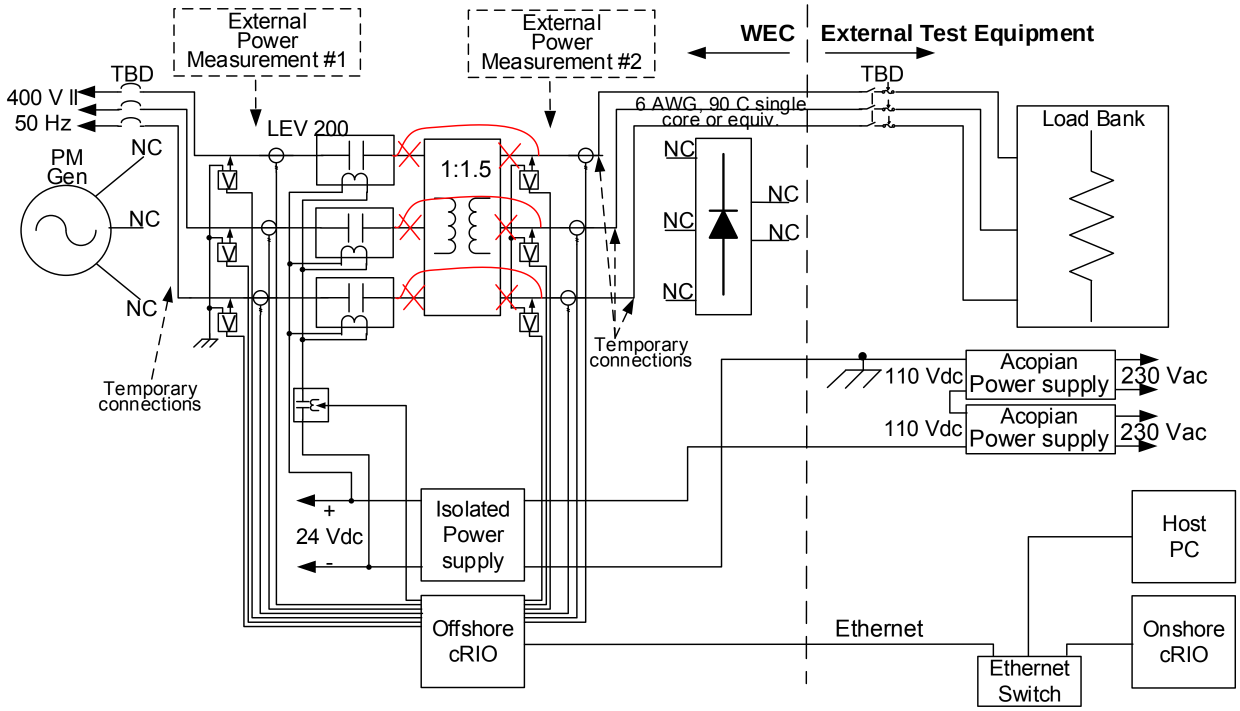


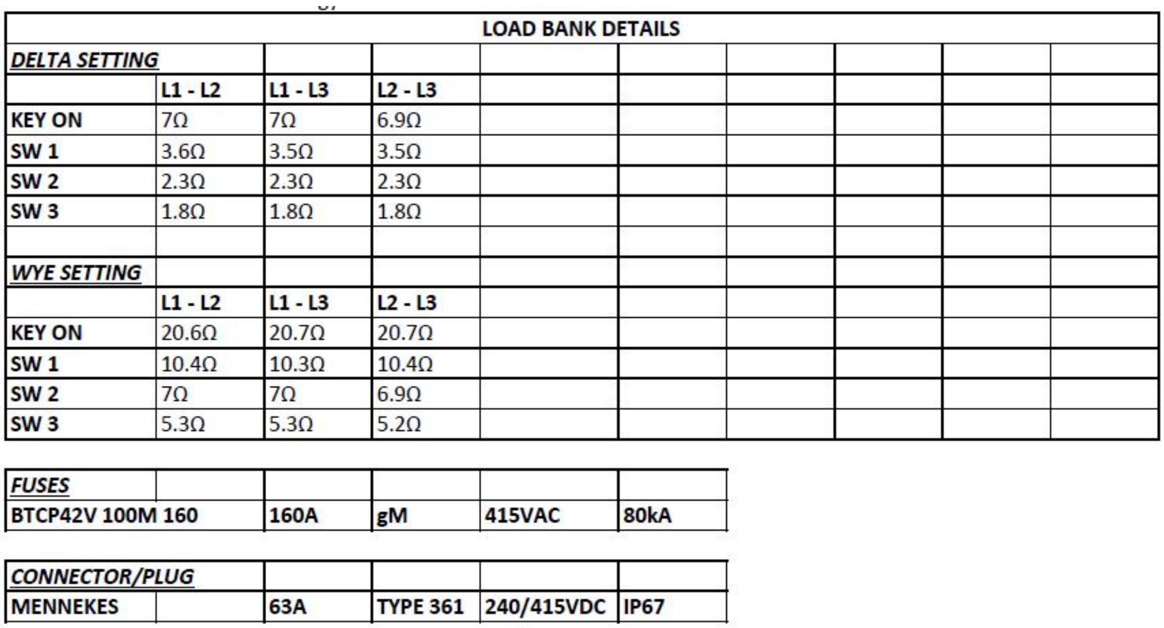
Figure 9 Electrical Test Setup for 50 Hz Power Measurement Calibration

Table 4 Required components for 50 Hz Power Measurement Calibration Test Setup

Item	Manufacturer	Model Number	Notes
3 Phase power meter	Hioki	3169-20	Or equivalent; need 0.5% V/I accuracy and 1% power accuracy; available from http://www.techrentals.co.nz
3 Phase power source	NA	NA	230V 50 Hz, 3-phase grid connection with 65 A circuit breaker to be provided by EHL.
Load bank			See Table 5

Items used in test set setups described in previous sections not included

Table 5 Load Bank Information



LOAD BANK DETAILS									
DELTA SETTING									
	L1 - L2	**L1 - L3**	**L2 - L3**						
KEY ON	7Ω	7Ω	6.9Ω						
SW 1	3.6Ω	3.5Ω	3.5Ω						
SW 2	2.3Ω	2.3Ω	2.3Ω						
SW 3	1.8Ω	1.8Ω	1.8Ω						
WYE SETTING									
	L1 - L2	**L1 - L3**	**L2 - L3**						
KEY ON	20.6Ω	20.7Ω	20.7Ω						
SW 1	10.4Ω	10.3Ω	10.4Ω						
SW 2	7Ω	7Ω	6.9Ω						
SW 3	5.3Ω	5.3Ω	5.2Ω						

FUSES					
BTCP42V 100M 160		**160A**	**gM**	**415VAC**	**80kA**

CONNECTOR/PLUG					
MENNEKES		**63A**	**TYPE 361**	**240/415VDC**	**IP67**

4.7. Electrical Setup for Resistive Load bank Testing

This setup, shown in Figure 10, will be used to 1) perform thermal testing of power components at full 18 kW output power, and 2) test the functionality of the cRIO to control hydraulic motor displacement separate from the inverter control.

The details of this setup are as follows:

- The load bank will be connected to the dc outputs of the device. The load bank, designed for three phase, will be configured for a wye load. Two of the phases will be connected to the device output and the third phase will be left open.
- The remainder of the device electrical system will be in its final configuration.

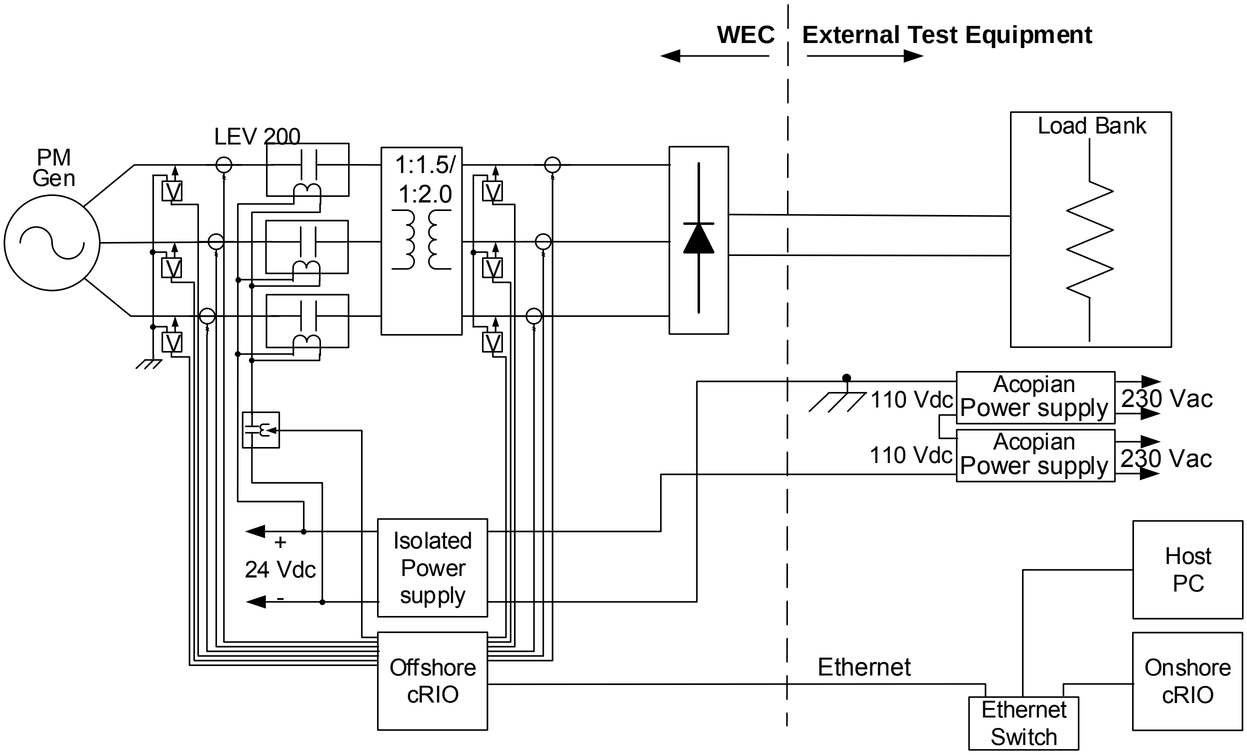


Figure 10 Electrical Setup for Resistive Load bank Testing

No components are required for this test setup are not required for the 50 Hz power measurement calibration setup described in Section 4.6.

4.8. Electrical Setup for System Testing with PowerOne Inverter

This setup, shown in Figure 11, operates the PowerPod similar to the way it will be operated after deployment in Hawaii and will be used to verify operation of the entire system together.

The details of this setup are as follows:

- This test setup will use a single, 50 Hz version of the 60 Hz, 6 kW PowerOne inverters used in Hawaii. Note that three, parallel 6 kW inverters will be used in Hawaii so dry testing will be done at reduced power.
- The setup otherwise reproduces the Hawaii onshore electrical system with a 230V:230V isolation transformer connecting the inverter to the grid, a 3300 µF capacitor bank at the dc input to the inverter, and a soft-start circuit consisting of a LEV200 with parallel 330 Ω resistor driven by a time delay relay that limits inrush current when the dc disconnect switch is closed.

- Four wire wound power resistors will be used to simulate the 2 Ω per conductor resistance of the subsea cable connecting the device to the onshore electrical equipment in Hawaii.
- The inverter will be controlled by a pulse command from the onshore cRIO controller through a voltage isolation module.

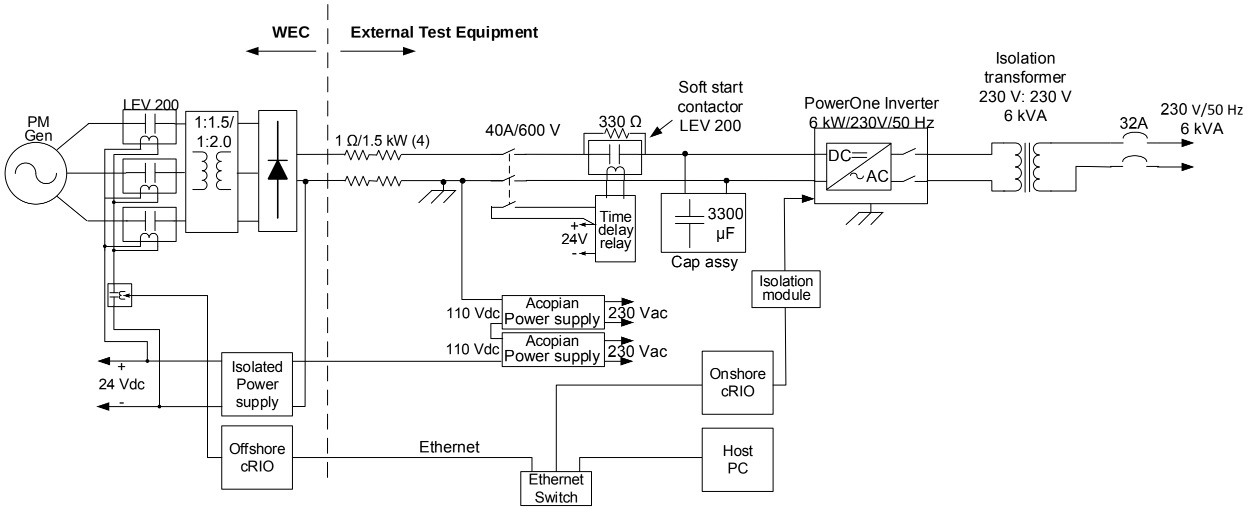


Figure 11 Electrical Setup for System Testing with PowerOne Inverter

Table 6 Required components for PowerOne Inverter Test Setup

Item	Manufacturer	Model Number	Notes
50 Hz PowerOne Inverter	PowerOne	PVI-6000-OUTD-W-AU	NWEI having shipped to EHL
Transformer 230V : 230V, 50 Hz	Victron	ITR000702000	NWEI to provide
CB/disconnect 230V 1 Ph 30A or equivalent	TBD	TBD	EHL to provide with 230V single phase grid connection
1 Ω, 1.5 kW resistor	TE Connectivity	TE1500B1R0J	NWEI to provide
330 Ω resistor	Vishay Dale	RH050330R0FE02	NWEI to provide
LEV 200 contactor	TE Connectivity	LEV 200	NWEI to provide
Time delay relay	Schneider	821TD10H-UNI	NWEI to provide
Capacitor bank	Kemet	ALS31A332NF400 (four series-parallel)	NWEI to provide
Onshore cRIO	National Instruments	cRIO-9074	NWEI to provide
Isolation module	Power-IO	IO-ODC-60-LL	NWEI to provide

Items used in test set setups described in previous sections not included

5. TEST PROCEDURES

The following test procedures will all be performed initially with the PowerPod hydraulics, electrical generator, and all electrical equipment external to the PowerPod structure. During these tests, the EHL test rig shown in Figure 6 will directly drive the PowerPod hydraulic cylinders with cyclical motion to simulate movement of the float.

After initial testing is complete, all equipment will be installed inside the PowerPod structure. This installation will take approximately 2 days. After this final assembly, a subset of the tests described in this section will be performed on the assembled PowerPod. For those tests, the EHL test rig shown in Figure 7 will drive the float mount of the PowerPod. The specific subset of tests to be performed on the final PowerPod assembly will be determined after the completion of initial testing.

5.1. Insulation Resistance Tests

See Section 4.1 for the three different test setups used to perform these tests.

First test the generator using the setup shown in Figure 1 with a voltage of 1000 Vdc. Apply the test voltage for a one minute period then record the insulation resistance reading. A reading of 100 MΩ is expected; if the reading is lower the generator manufacturer will be consulted.

Following the generator test, perform the tests on the equipment on the primary and secondary sides of the boost transformer using the setups shown in Figure 2 and Figure 3, respectively, with a test voltage of 500 Vdc. Apply the test voltage for one minute then record the measurement. A lower resistance measurement is expected for these tests than the generator test. If the measurement is less than 10 MΩ for either test, determine the source of the low resistance by disconnecting components from the circuit one by one and repeating the tests.

Note: for safety, following insulation resistance testing, before touching any electrical conductors in the system the insulation tester should be disconnected and the dc voltage should be measured with a meter with respect to chassis. This will verify that capacitances in the system are discharged. While capacitances in this system are low and voltages are expected to drop immediately following the tests, this measurement is prudent.

5.2. 24V Power Supply Pre-test

This test will verify the basic functionality of the 24 V powers supply prior to installation of the CompactRIO data acquisition and control system and other tests.

Use the test setup described in Section 4.2 for this test.

Procedure:

1. Disconnect the inputs to the 24 V supply. Apply power to the Acopian power supplies and verify an output of approximately 220 Vdc. Remove power from the Acopian supplies and connect their output to the input of the 24 V power supply.
2. Remove fuses F1-F23 in the side hatch area so that the 24 V supply will operate at no load.
3. Apply power to the Acopian power supplies. Record the input and output voltage for the 24 V power supplies. Verify that with a 220 Vdc input, the output is 24 ± 0.5 Vdc. Note that the output will likely be near the high end at no load.
4. One by one install fuses F1-F23. Verify the output of the 24 V supply remains in the range 24 ± 0.5 Vdc after each fuse is installed, and verify that fuses do not blow when installed. To the extent possible, verify proper function of transducers and other equipment powered by the 24 V supply including lower power 5V, 12 V, and ±15 V supplies.

5.3. 24V Power Supply Tests

Use the test setup described in Section 4.3 for these tests

Procedure:

1. Disconnect all equipment from the 24 V power supplies and switch in the external 1 Ω load, so all loading is provided by the external load.
2. Turn on input power supplies with shorting switch open so that 300 Vdc is applied.
3. Verify with the two DVMs that the input voltage is approximately 300 Vdc and the output voltage is 24 Vdc ± 0.5 Vdc.
4. Verify with the oscilloscope that no significant high frequency voltage oscillations exist in the 24 Vdc output.
5. Measure the voltage across the input 5 Ω resistors (not shown in Figure 5) for each of the Synqor modules internal to the power supply with a DVM and verify that input currents to each module are equal within ± 5%.
6. Switch input voltage to 200 Vdc and repeat steps 3-5 for 200 Vdc input.
7. Turn input voltages on and off and observe the output voltage of the power supply.
8. Short the output of the power supply and observe the input and output voltage of the power supply as the short is applied and removed with the oscilloscope.
9. Short the output of one of the three Synqor power supply modules (anode side of Schottky diode) and observe the input and output voltage of the power supply.
10. Switch open the 1 Ω output load so that the power supply operates at no load, and repeat steps 3 and 4 for both 200 Vdc and 300 Vdc input voltages.

11. Connect in all onboard equipment normally powered by the 24 Vdc power supplies.
12. Repeat steps 3, 4, and 5 for all combinations of 200 Vdc and 300 Vdc inputs, and with the 1 Ω external load connected and not connected (two load settings; one normal equipment and the other normal equipment plus external load).
13. With the 1 Ω external load disconnected, observe output voltage with the oscilloscope while switching input voltage between 200 Vdc and 300 Vdc by triggering the oscilloscope on input voltage. Verify that no high frequency voltage oscillations in output voltage occur when input voltage is increased or decreased between the two settings. Repeat with 1 Ω external load removed.
14. Conduct a thermal test. Locate thermocouples as follows: 1) on aluminum heatsink near Synqor modules, 2) measuring internal ambient near future location of fiber converter, and 3) exterior metal of PowerPod a long distance from dry box. Operate the power supply with 200 Vdc input and normal loading plus 1 Ω external resistor with the cover of the drybox closed. Record temperatures at 10 minute intervals until they stabilize. Estimate worst case operating temperature by extrapolating stabilize temperature measurements to a maximum ambient temperature and check against component ratings.

5.4. No load testing

Use the no load test setup described in Section 4.5.

Procedure for tests performed prior to rotation:

1. Commission the offshore cRIO controller and verify communication and proper operation with the host computer.
2. Verify correct operation of the sensors that can be checked at no load and no rotation. These sensors are designated as “no rotation” in the “Test Condition” column of Table 7. Use the method listed Table 7 to verify that each sensor operates correctly. Sensor data can be monitored on the cRIO host computer or in cRIO data files.

Procedure for tests performed with rotation:

The boost transformer should be configured for a 1:1.5 ratio for these tests so that the generator can be rotated at a higher speed.

1. LEV200 contactor control functionality
    a. Prior to rotation, set the AL1 overvoltage setting of the ac overvoltage relay shown on sheet 3 of the electrical schematics for the device to 25%. This will limit generator voltage output to 150 V line-line rms. Set the AL1 overvoltage setting of the ac overvoltage relay shown on sheet 3 of the electrical schematics for the device to 75% (450 Vdc). Set hydraulic motor displacement to maximum with the cRIO in manual control mode. The boost transformer may be configured with either 1:1.5 or 1:2 ratio.

   b. At zero speed, verify that the LEV200 contactors shown on Sheet 12 of the PowerPod electrical and control drawings open and close as commanded by the cRIO control (verify indication of command on host computer and listen for clicking of relays if possible).
   c. Cycle the PowerPod float to slowly rotate the electrical generator with a peak speed of about 500 rpm (for example a hydraulic cylinder half-stroke of 50 mm and a 7.5 s period will give approximately 500 rpm). Initial line-line rms generator voltage should be approximately 40 V.
   d. Command the LEV200 contactors open. After a short time, command the LEV200 contactors closed. Use voltage data recorded with the cRIO on both sides of the LEV200 contactors to verify that they did not close while any of the three phase line-line rms voltages at the generator output were greater than 10V (the cRIO should delay contact closure until this condition is met to limit inrush current to dc capacitors).
2. Sensor checks with low speed rotation:
   a. Cycle the PowerPod float to slowly rotate the electrical generator with a peak speed of about 500 rpm (for example a hydraulic cylinder half-stroke of 50 mm and a 7.5 s period will give approximately 500 rpm). Initial line-line rms generator voltage should be approximately 40 V.
   b. Measure voltages throughout the electrical system with a DVM including generator output, boost transformer output, and dc voltage at three phase rectifier output and verify that these are consistent with cRIO voltage measurements.
   c. Measure motor speed with a hand held stroboscope, and verify that cRIO motor speed measurement is consistent.
   d. Calculate expected hydraulic flow from motor speed and displacement with pressure less than the accumulator pre-charge pressure and compare to cRIO flow readings.
3. Overvoltage relay tests

   Note: normal overvoltage relay settings for AL1 will be 88% (525V) for dc relay and 259V (43%) for ac relay. Both are expected to switch at approximately 2500-2900 rpm depending on load and relay tolerance.

   a. Set the AL1 setting for the ac overvoltage relay at 20 % (120 V line-line rms) and the AL1 setting for the dc overvoltage relay at 88% (450 Vdc). Slowly increase generator speed by either increasing hydraulic cylinder stroke or reducing motor displacement. Verify that generator speed is limited so that maximum generator voltage does not exceed 150 V line-line rms.
   b. Repeat the preceding test for the dc overvoltage relay with AL1 for the ac relay set to 43% (259V). Reduce the AL1 setting for the dc overvoltage relay to 30% (180 Vdc). Slowly increase generator speed by either increasing hydraulic cylinder stroke or reducing motor displacement. Verify that generator speed is limited so that maximum dc voltage at the three phase rectifier output does not exceed 180 Vdc.
   c. Set both overvoltage relays to their normal settings.
4. Verify cRIO adjustment of hydraulic motor displacement

   a. Cycle the float with a low stroke such as 50 mm/7.5 s. Manually control motor displacement with the cRIO. Verify that as motor displacement is reduced speed is increased; collect data for displacement command versus maximum motor speed and analyze data to verify that the results match expectations.

5. Sensor checks with high speed rotation

   Operate the device with higher peak generator speed (giving approximate voltage of approximately 400 Vdc at three phase rectifier output; this will occur at about 2100 rpm) initially by reducing motor displacement with a small cylinder stroke. Repeat the sensor checks described in Step 1 to verify correct correlation between maximum generator frequency, motor speed, generator speed, hydraulic flow, and change in float position. Repeat these measurements with the same motor speed achieved with a maximum motor displacement and higher cylinder stroke.

5.5. Calibration of cRIO Power Measurements

Use the test setup described in Section 4.6.

Procedure:

1. Connect the hand-held power meter near the LV25-1200 voltage transducers and HAS-50S current transducers shown on page 3 of the PowerPod electrical and control drawings. These transducers have accuracies of approximately 1%.
2. Apply 50 Hz, 3-phase power with the load bank open (zero load). Record the three phase voltages, three phase currents, and power measured by the power meter and record the same measurements made by the cRIO.
3. Repeat the preceding measurements with the load bank adjusted to 20.7 Ω (wye), which will give approximate output power of 15 kW.
4. Verify that the cRIO generator voltage and current measurements match the power meter voltage and current measurements within 1% and the cRIO power measurements match the power meter measurements within 2%.
5. Repeat steps 1-4 for the cRIO transformer output measurements using CV3-1000 current transducers and Dranetz 3003-XL current transducers. These transducers have accuracies of 0.5% or better for the voltage and current measurements, and a power measurement accuracy of 1% or better is expected.

5.6. System Testing with Resistive Load Bank

Use the resistive load bank test setup described in Section 4.7. Set the cRIO for manual control of motor displacement, with displacement set to maximum.

Thermal test procedure:

1. Use thermocouples to measure temperature at the following locations: 1) base of three phase diode rectifier, 2) dry box internal ambient, 3) HVAC enclosure metal near individual entry of generator phases.
2. Measure the following temperatures with the cRIO data system: 1) generator windings, 2) boost transformer windings, and 3) cRIO controller.
3. Connect taps of the boost transformer for a ratio of 1:1.5.
4. Operate the PowerPod with the sinusoidal cylinder cycling movements that gives once per cycle, maximum dc output from the three phase rectifier of about 400 V. If necessary, motor displacement can also be adjusted to adjust motor speed and voltage.
5. Adjust the resistive load bank for a total load of about 18 kW at the peak generator speed.
6. Record temperatures at 15 minute intervals until temperatures stabilize. Estimate worst case operating temperature by extrapolating stabilize temperature measurements to a maximum ambient temperature and check against component ratings.
7. Verify that high current electrical terminals did not overheat during the test by visual inspection.

Test procedure for hydraulic motor control:

The hydraulic motor control that has been implemented in the offshore cRIO in advance of the dry tests is shown in Figure 12. This control has the following settings:

- Damping constant (bar/lpm). This constant will be adjusted to different values during the ocean testing as performance of the device is evaluated.
- Time (seconds) of the moving average filter applied to hydraulic flow.
- PI proportional gain.
- PI integral gain.

In addition, the offshore cRIO also controls generator current with the inverter(s) as described in Section 5.7. During load bank testing, however, the resistance setting of the load bank will determine the generator load current and the cRIO inverter controls will not be used.

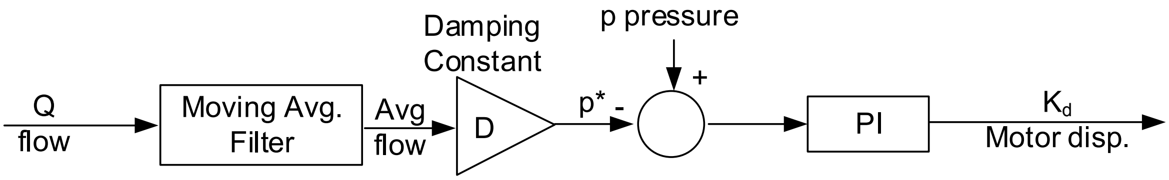


Figure 12 cRIO Hydraulic Motor Control

The procedure below will be used when testing the cRIO hydraulic motor control.

1. Verify manual control of motor displacement with the cRIO (no-load testing, Section 5.4).
2. Set damping constant for hydraulic pressure/hydraulic flow to 3. Initially set the flow averaging time to a high value (perhaps 30 s), so that the pressure setpoint p* (referring to Figure 12) changes slowly.
3. Set load bank resistance to 20 Ω.
4. Begin operating with increasing sinusoidal float movement. Experiment with different load resistance settings until the measured pressure follows the setpoint p* when float movement is slowly changed.
5. Decrease the flow averaging time so that it fluctuates with float movement. Observe the pressure response with respect to changes in the setpoint p*; use this information to tune the cRIO PID control. Also use random wave inputs as necessary.
6. Experiment further with different damping constants; adjust load bank settings as necessary for the PID control to stay in range. Verify that PI controller has adequate response and is stable.

5.7. System Testing with PowerOne Inverter

Use the test setup described in Section 4.8.

The inverter current control that has been implemented in the offshore cRIO in advance of the dry tests is shown in Figure 13. This control has the following settings:

- R_{dc} constant
- Max current limit (A)
- Overvoltage setting (V)
- Overvoltage gain (A/V)

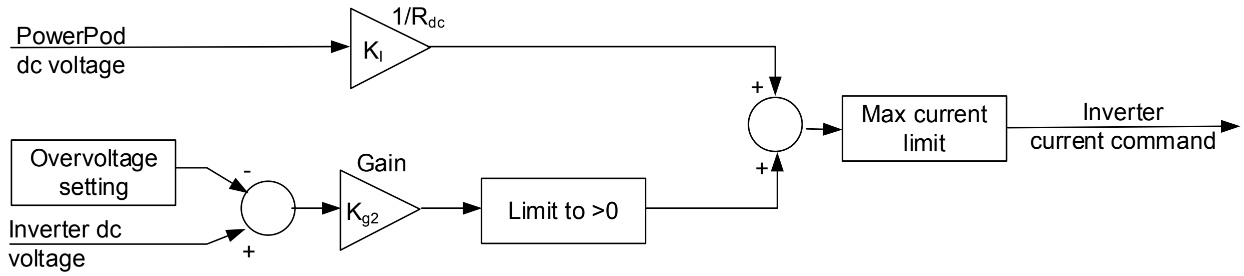


Figure 13 cRIO Inverter Current Control

Procedure:

1. Set the cRIO for manual control of motor displacement, with displacement set to maximum.
2. Close the dc disconnect switch to connect the inverter to the device.
3. With no ac power connected to the PowerOne inverter, provide sinusoidal cycling float movement to the device that gives approximately 100 Vdc maximum to the inverter input. Configure the PowerOne inverter with proper settings for the 50 Hz three phase ac connection via the host PC.
4. Adjust the R_{dc} constant to a high value in the cRIO control.
5. Connect three phase ac power to the PowerOne inverter.
6. Slowly decrease the R_{dc} constant in the cRIO software and verify that inverter current increases and is consistent with the setting.
7. Set the cRIO for PI control of pressure; use the best control settings determined during Section 5.6 load bank tests.
8. Test with the same float movements and damping constants successfully used during the load bank tests to the extent possible. Set the cRIO inverter R_{dc} constant to values equivalent to the load bank resistance setting used for each damping constant.
9. Review cRIO data and verify that inverter current follows the inverter current command. Experiment with settings as necessary to optimize performance.

5.8. Final safety and abnormal operating condition checks

1. With large float movement (200 mm/7.5 s), remove 230 V power from both Acopian 100V power supplies, so that 24 Vdc ancillary power on board the PowerPod is lost. Verify that the LEV200 contactors open and that none of the electrical circuitry is damaged.
2. During normal operation, disconnect the Ethernet cable between the offshore cRIO and the "onshore" Ethernet switch. Verify that 1) inverter power command is reduced to zero, and 2) the LEV 200 contactors on board the device open.

Table 7 CompactRIO Sensor Check Methods

Ref	Sensor	Test Condition	Sensor Check Method
	GPS time	NA	Check GPS reception using device antenna.
	Xfmr line A, B, C volts	50 Hz load bank testing	Calibrated power meter
	Xfmr line A, B, C current		
	Dc volts	Inverter testing	Voltmeter
	Dc current	Inverter testing	Clamp on current meter
HZ01	Generator rpm	No load rotation	Check against hand held strobe
	Motor disp. command	No rotation	Check against calculation using flow and motor speed measurements
	LEV 200 relay drive	No load rotation	Voltmeter
	Gen line A, B, C volts	50 Hz load bank testing	Calibrated power meter
	Gen line A, B, C current		
	24 Vdc	No rotation	Voltmeter
	Subsea J-box oil level	Hawaii pre-test	TBD
LT01	Hydraulic tank level switch	No rotation	Change level around threshold
TT02	Hydraulic tank temp switch	No load rotation	Observe switching at threshold
AS01	Float Angle 1	No rotation	Static float position measurement
PT09	Water Pressure 1	TBD	TBD
PT08	Gen Side Cyl (Closed)	50 Hz load bank testing	Rough check against secondary sensor while float rotating
PT07	Gen Side Cyl (Rod)	50 Hz load bank testing	
PT05	Motor Inlet	50 Hz load bank testing	
PT06	Motor Outlet	50 Hz load bank testing	
TT01	Gen Temp	No rotation	Room temperature check
	Xfmr winding temp	No rotation	Room temperature check
AS02	Float Angle 2	No rotation	Static float position measurement
PT10	Water Pressure 2	TBD	TBD
PT01	Filter side extension	50 Hz load bank testing	Rough check against secondary sensor while float rotating
PT02	Filter side retraction	50 Hz load bank testing	
PT04	TTP pressure	50 Hz load bank testing	
PT03	TP1 pressure	50 Hz load bank testing	
FT01	Hydraulic flow	No load rotation	Check against motor speed and motor displacement setting

Appendix A - PowerPod Dry Test Plan

Offshore NWEI CompactRIO Channel List

Ref	Measurement	Type	cRIO module	Sensor PN	Sensor Mfr	Notes	Scaling	Offset	Units
	GPS time		NI-9467	NA	NA	Using Spartan Antenna 3in1 MA.600	NA	NA	NA
	Xfmr line A volts	0-10 V (analog in)	NI 9239	CV3-1000	LEM	Voltage sensor connected line-neutral	100	0 or cal	V
	Xfmr line A current	0-10 V (analog in)		3003-XL	Dranetz		50.00	0 or cal	A
	Xfmr line B volts	0-10 V (analog in)		CV3-1000	LEM	Voltage sensor connected line-neutral	100	0 or cal	V
	Xfmr line B current	0-10 V (analog in)		3003-XL	Dranetz		50.00	0 or cal	A
	Xfmr line C volts	0-10 V (analog in)	NI 9239	CV3-1000	LEM	Voltage sensor connected line-neutral	100	0 or cal	V
	Xfmr line C current	0-10 V (analog in)		3003-XL	Dranetz		50.00	0 or cal	A
	Dc volts	0-10 V (analog in)		CV3-1200	LEM		120	0 or cal	V
	Dc current	0-10 V (analog in)		HAS-50S	LEM		12.5	0 or cal	A
HZ01	Motor rpm	Pulse	NI 9411	V12 spd sensor	Parker	36 pulses per rev.	1	0	rpm
HZ02	Generator rpm	Pulse		Gen integrated	UQM	9 pulses per rev.	1	0	rpm
	Motor displacement (command)	4-20 mA (analog out)	NI 9265	PWD 00A-400	Parker	Parker driver module with 4-20 mA input used Set up for 4 mA: min disp (16); 20 mA: max disp (80)	4000	0	cm^3/rev
	LEV 200 relay drive (command)	0-5V (switching out)		DC60S5 driver	Crydom	250 Ω burdon resistor converts 0/20 mA to 0/5V	NA	NA	NA
VT01	Gen line A volts	0-10 V (analog in)	NI 9205; (16) differential 0-10V channels	LV25-1200	LEM	Voltage sensors connected line-ground	137.14	0 or cal	V
VT02	Gen line B volts	0-10 V (analog in)					137.14	0 or cal	V
VT03	Gen line C volts	0-10 V (analog in)					137.14	0 or cal	V
IT01	Gen line A current	0-10 V (analog in)		HAS-50S	LEM		12.5	0 or cal	A
IT02	Gen line B current	0-10 V (analog in)					12.5	0 or cal	A
IT03	Gen line C current	0-10 V (analog in)					12.5	0 or cal	A
	24 Vdc	0-24 V (analog in)				Use 4:1 resistor divider	4.01	0 or cal	V
LS02	Comp oil level sensor Subsea J-box	4-20mA (analog in)			DOER	250 Ω burdon resistor converts 0-20 mA to 0-5V	62.5	0.25	0 empty 1 full
LT01	Hydraulic tank level switch	0/24V (switching in)		SCLTSD-370-00-07	Parker	Use 4:1 resistor divider	NA	NA	NA
TT02	Hydraulic tank temp switch	0/24V (switching in)		SCLTSD-370-00-07	Parker	Use 4:1 resistor divider	NA	NA	NA
AS01	Float Angle 1	4-20mA (analog in)	NI 9203 #1 8 4-20 mA channels.	AR63G360FL.92A4F	Hengstler	0 deg: 4 mA; 360 deg: 20 mA	22500	90	Deg
PT09	Water Pressure 1	4-20mA (analog in)		MLH100PGL01B	Honeywell	0 psi/0m: 4 mA; 100 psi/68.57m: 20 mA	4286	17.1425	m
PT08	Gen Side Cyl (Closed)	4-20mA (analog in)				P (bar) = 21.56 × (reading in mA – 4) According to IRL document "Recommendations for integration of NREL system (MOISyt) and WET-NZ SCADA system" (5000 psi sensor?)	22049	87.51	Bar
PT07	Gen Side Cyl (Rod)	4-20mA (analog in)					21783	84.02	Bar
PT05	Motor Inlet	4-20mA (analog in)					21858	80.67	Bar
PT06	Motor Outlet	4-20mA (analog in)					21902	84.65	Bar
TT01	Gen Temp	mA (analog in)		GE	GE9.7A	Non-linear; degC = 7.55e-5 mA5 - 0.0063 mA4 + 0.1979 mA3 - 2.9292 mA2 + 23.921 mA - 1.9795	NA	NA	C
TT03	Xfmr winding temp	mA (analog in)		GE	GE9.7A		NA	NA	C
AS02	Float Angle 2	4-20mA (analog in)	NI 9203 #2 8 4-20 mA channels.		IRL custom	0 deg: expect 6.9mA, 180 deg: expect 19.3mA	14516	100.1613	Deg
PT10	Water Pressure 2	4-20mA (analog in)		MLH100PGL01B	Honeywell	0 psi/0m: 4 mA; 100 psi/68.57m: 20 mA	4286	17.1425	m
PT01	Filter side extension	4-20mA (analog in)					22775	90.94	Bar
PT02	Filter side retraction	4-20mA (analog in)					21716	84.53	Bar
PT04	TTP pressure	4-20mA (analog in)					21888	82.19	Bar
PT03	TP1 pressure	4-20mA (analog in)					22439	87.44	Bar
FT01	Hydraulic flow	4-20mA analog in)		SCFT-300-22-07	Parker	0 l/min: 4 mA; 300 l/min: 20 mA	18750	75	l/min

Appendix II

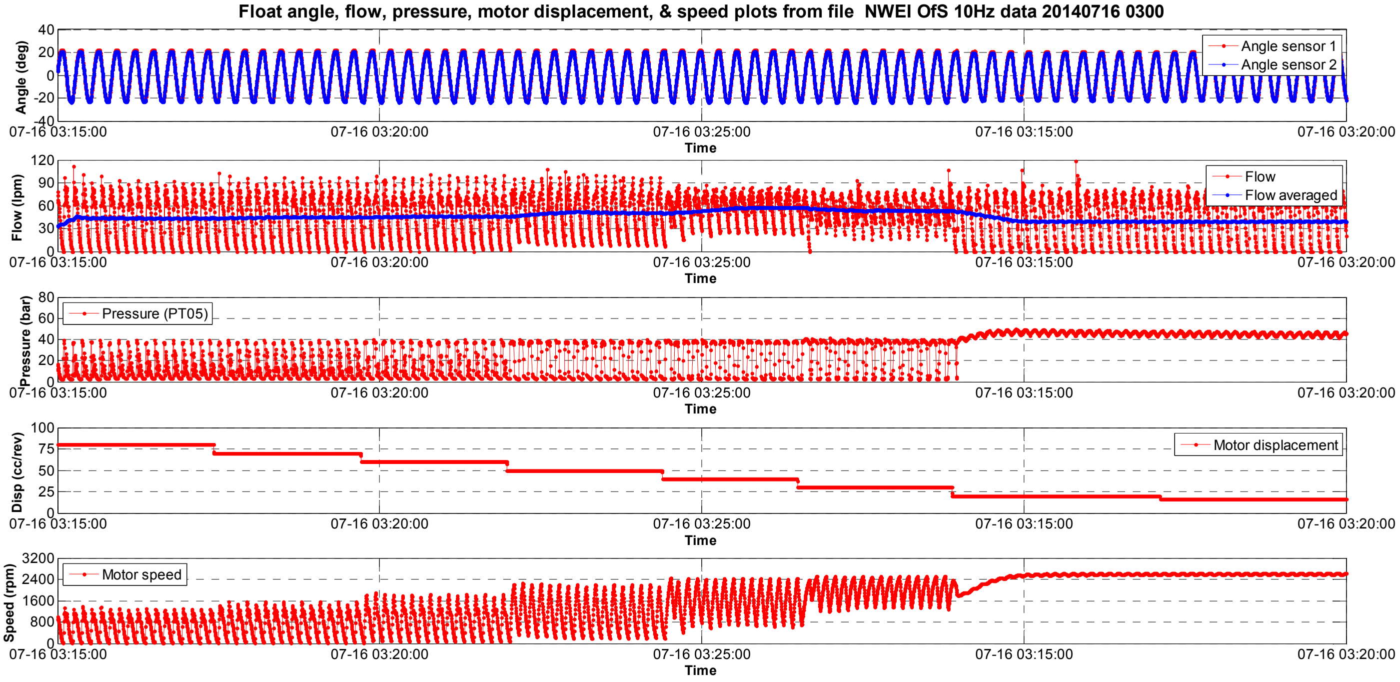
24V Power Supply Voltage Measurements

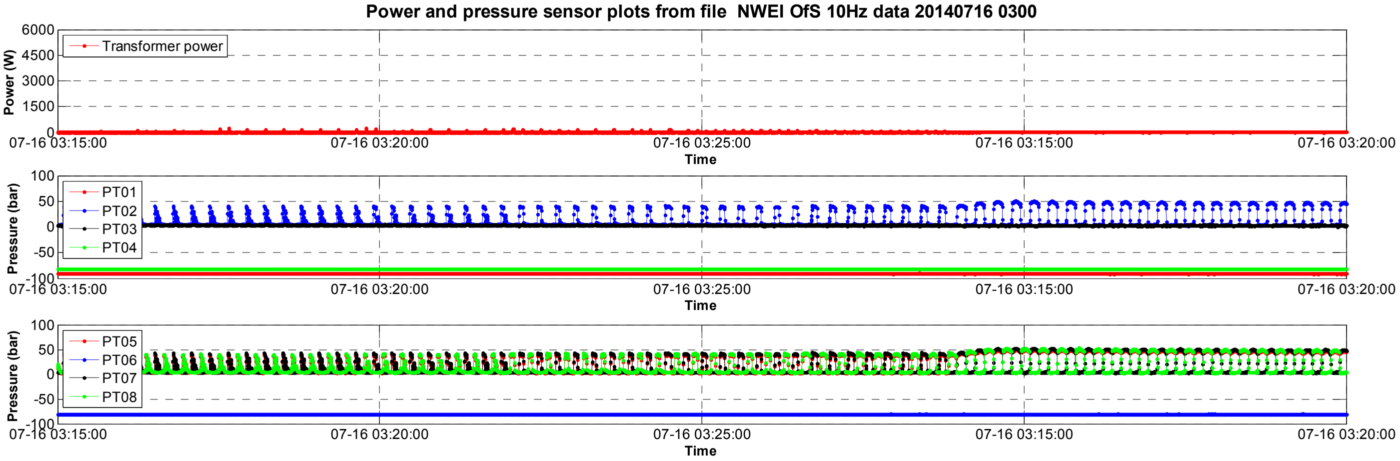
Step		Test	Recorded Measurement
3	300 Vin; 1Ω & 0.5Ω external load	Input voltage	299
3		Output voltage	24.1
5		Voltage across 5 Ω resistor #1 1/0.5 Ω load	2.9/6.5
5		Voltage across 5 Ω resistor #2 1/0.5 Ω load	3.3/6.9
5		Voltage across 5 Ω resistor #3 1/0.5 Ω load	4.5/8.3
6	220 Vin; 1Ω external load	Input voltage	219
6		Output voltage	24.1
6		Voltage across 5 Ω resistor #1	4.05
6		Voltage across 5 Ω resistor #2	4.45
6		Voltage across 5 Ω resistor #3	6.36
10	220V in; open load	Input voltage	219
10		Output voltage	26.6
10	300V in; open load	Input voltage - shorting switch open	299
10		Output voltage - shorting switch open	25.2
12	300 Vin; normal load only	Input voltage	299
12		Output voltage	24.2
12		Voltage across 5 Ω resistor #1	0.58
12		Voltage across 5 Ω resistor #2	0.26
12		Voltage across 5 Ω resistor #3	0.88
12	300 Vin; normal load + 1Ω	Input voltage	299
12		Output voltage	24.1
12		Voltage across 5 Ω resistor #1	3.3
12		Voltage across 5 Ω resistor #2	3.7
12		Voltage across 5 Ω resistor #3	5.0
12	220 Vin; normal load only	Input voltage	219
12		Output voltage	24.2
12		Voltage across 5 Ω resistor #1	0.72
12		Voltage across 5 Ω resistor #2	0.35
12		Voltage across 5 Ω resistor #3	1.2
12	220 Vin; normal load + 1Ω	Input voltage	219
12		Output voltage	24.1
12		Voltage across 5 Ω resistor #1	4.6
12		Voltage across 5 Ω resistor #2	5.1
12		Voltage across 5 Ω resistor #3	7.0

Appendix III

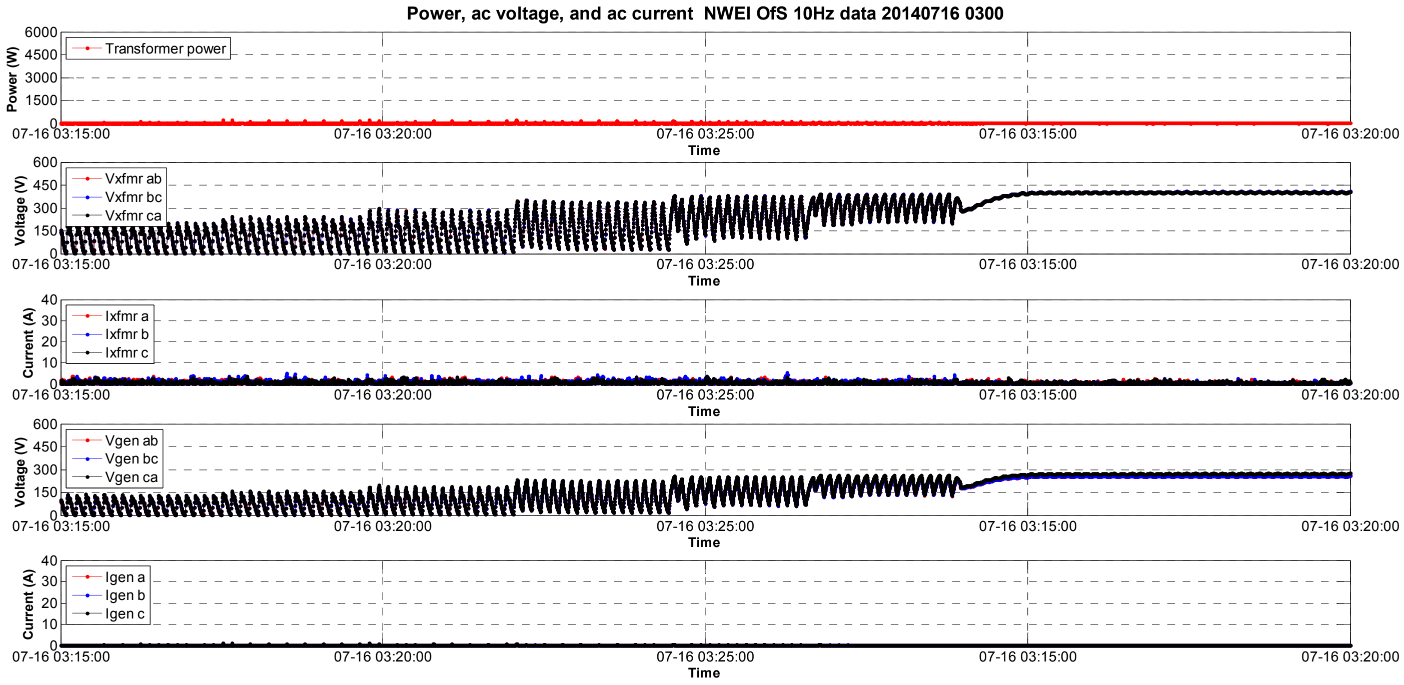
Characterization Data Plots for No Load Tests

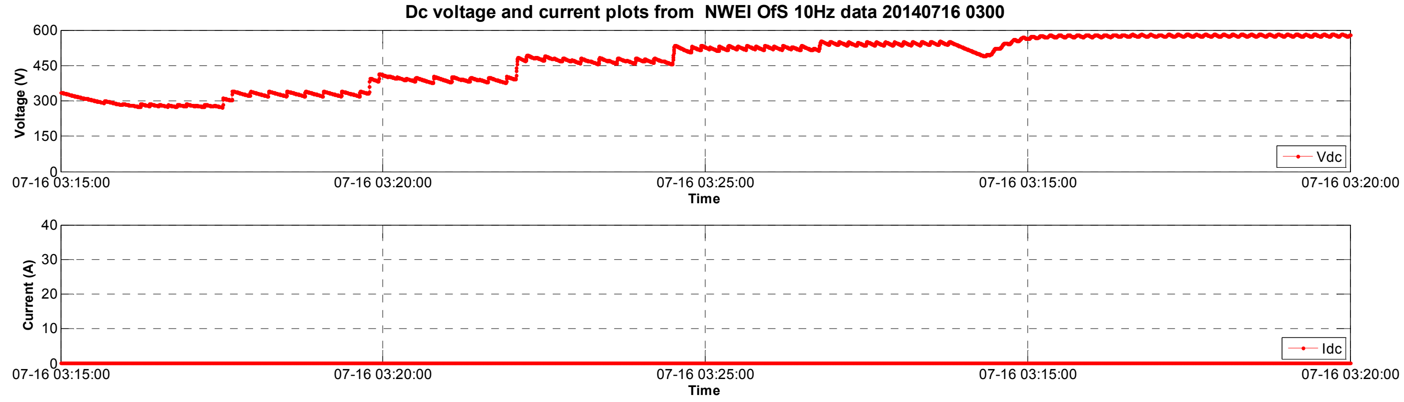
July 16, 2014 no load data
PowerPod testing 125 mm test rig stroke and 7.5 s period
Note: boost transformer ratio was 1:1.5 when this data was recorded


Float angle, flow, pressure, motor displacement, & speed plots from file NWEI OfS 10Hz data 20140716 0300


Power and pressure sensor plots from file NWEI OfS 10Hz data 20140716 0300

July 16, 2014 no load data
PowerPod testing with 125 mm test rig stroke and 7.5 s period (continued)
Note: boost transformer ratio was 1:1.5 when this data was recorded



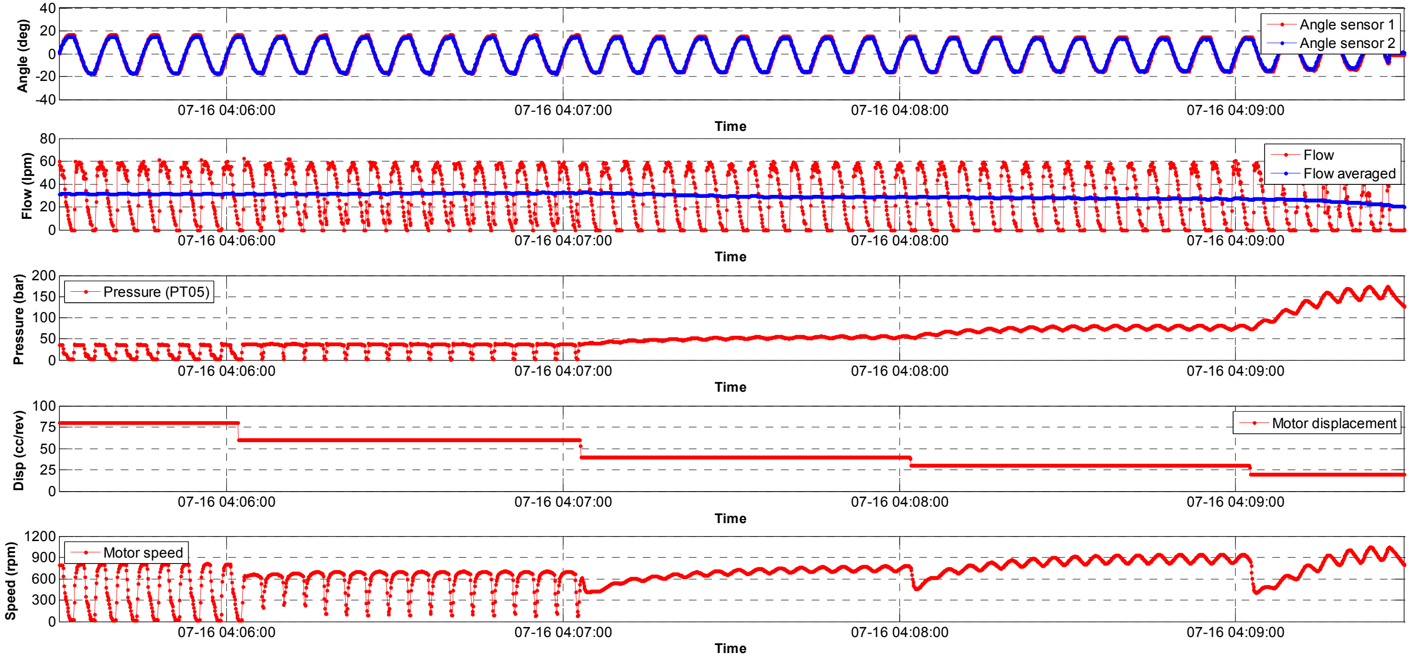


Appendix IV

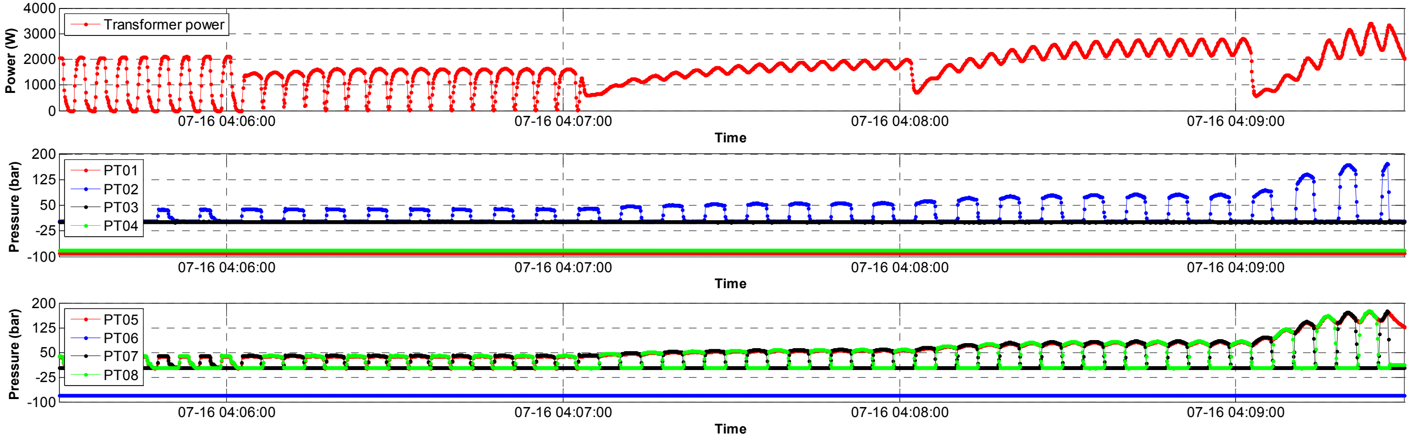
Characterization Data Plots for Load Bank Tests

July 16, 2014 data set 1
Load bank setting key only
PowerPod testing with 75 mm test rig stroke and 7.5 s period
Note: boost transformer ratio was 1:1.5 when this data was recorded

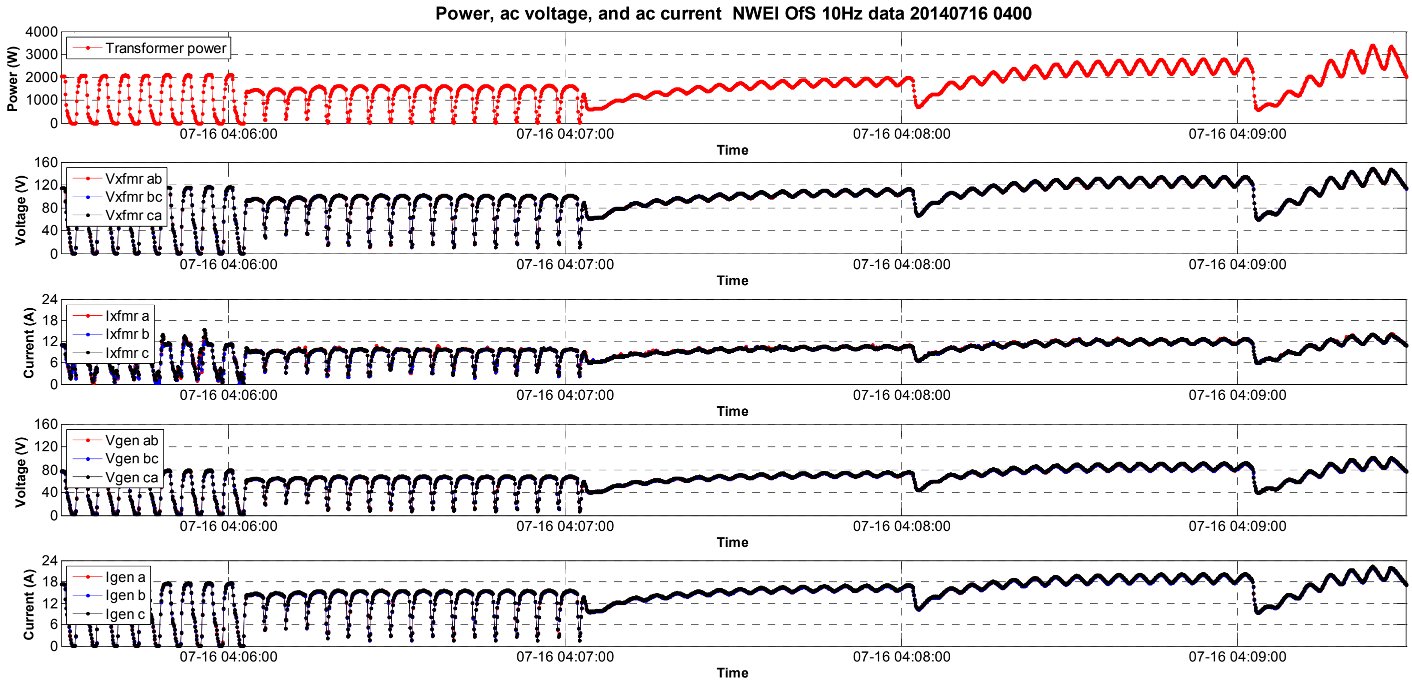
Float angle, flow, pressure, motor displacement, & speed plots from file NWEI OfS 10Hz data 20140716 0400

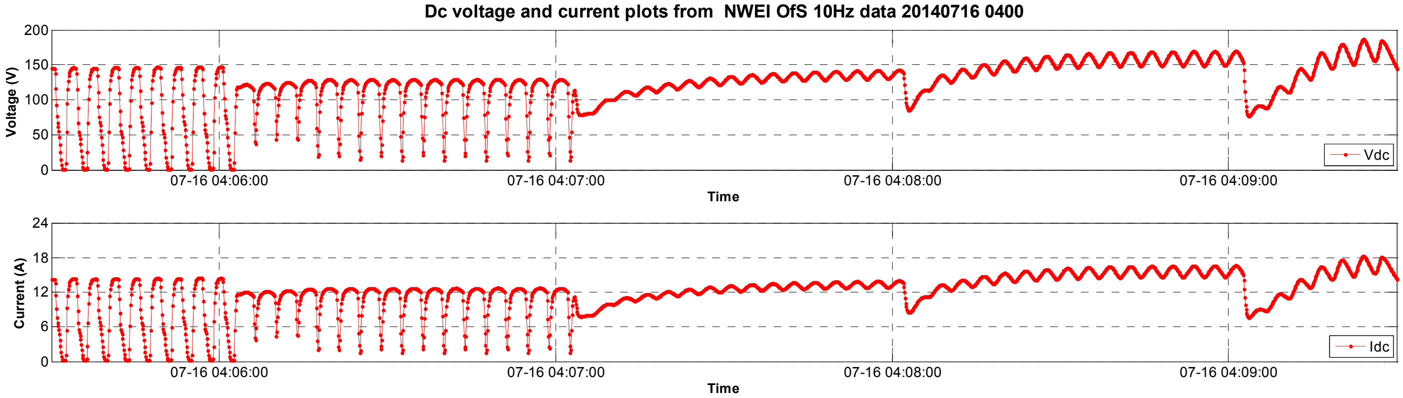


Power and pressure sensor plots from file NWEI OfS 10Hz data 20140716 0400

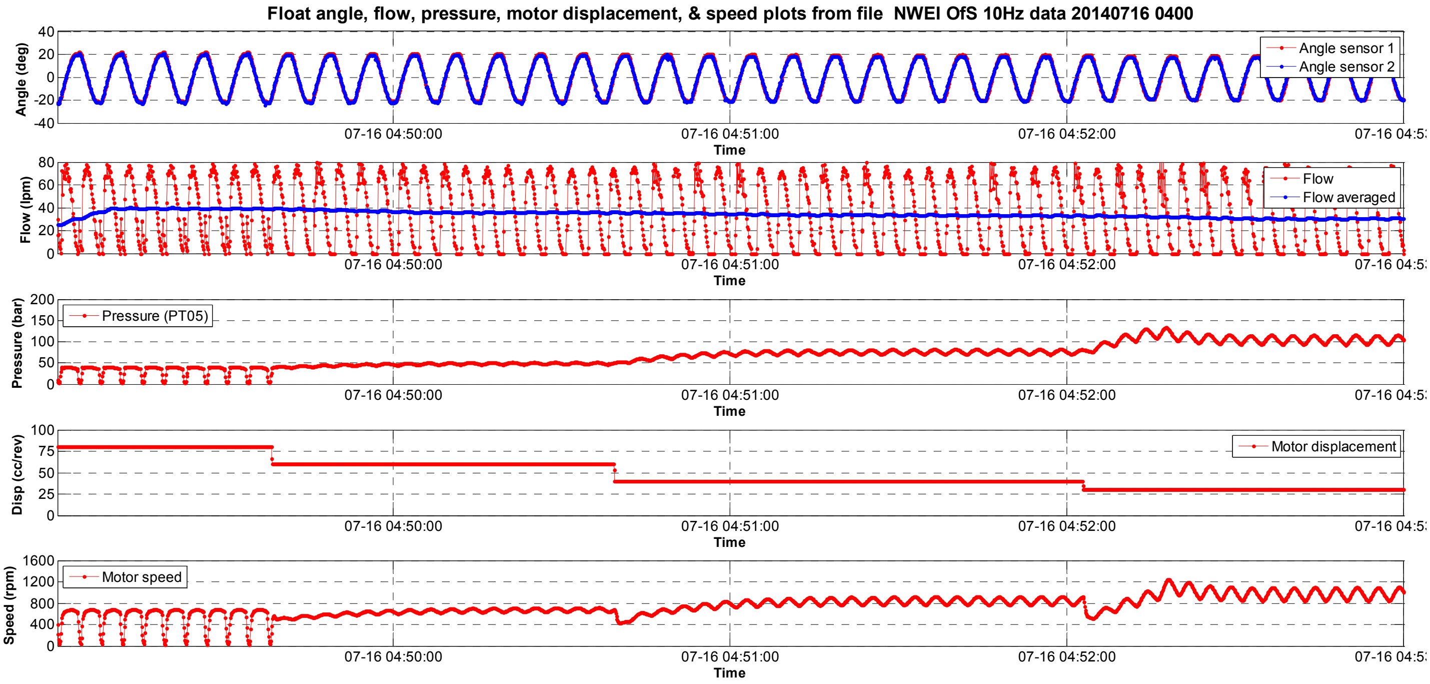


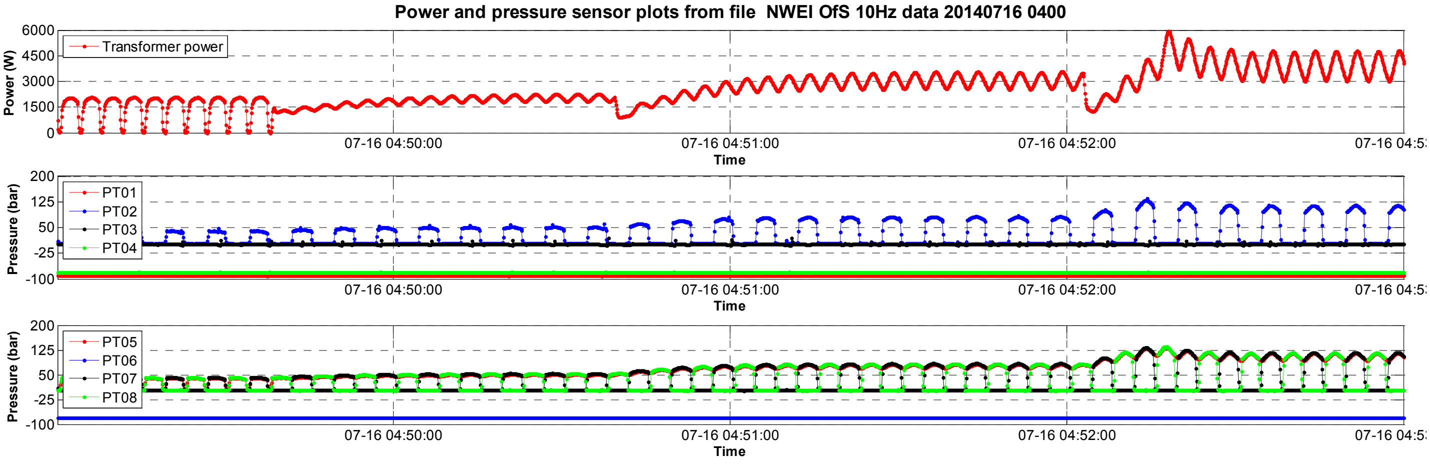
July 16, 2014 data set 1 (continued)
Load bank setting key only
PowerPod testing with 75 mm test rig stroke and 7.5 s period
Note: boost transformer ratio was 1:1.5 when this data was recorded



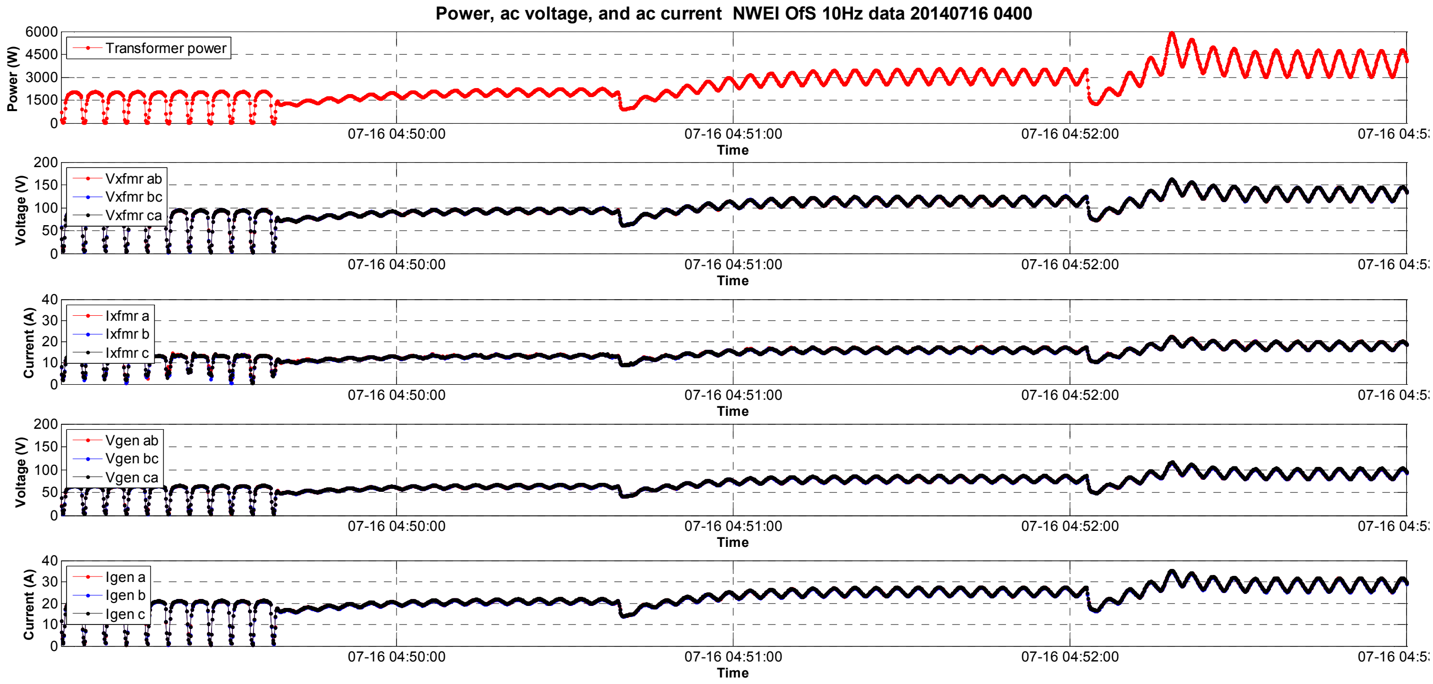


July 16, 2014 data set 2
Load bank setting key plus two star
PowerPod testing with 125 mm test rig stroke and 7.5 s period
Note: boost transformer ratio was 1:1.5 when this data was recorded

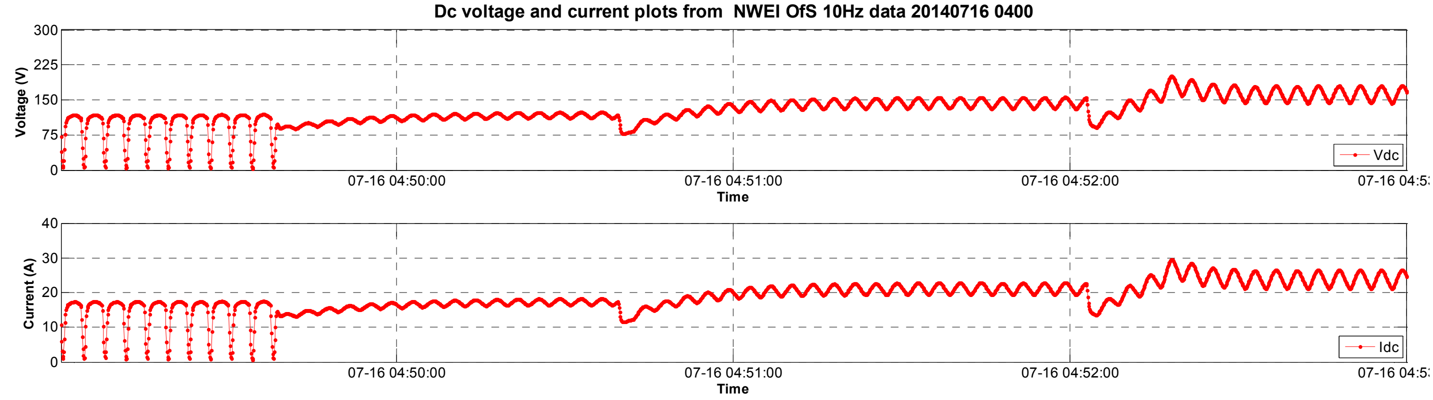

Float angle, flow, pressure, motor displacement, & speed plots from file NWEI OfS 10Hz data 20140716 0400


Power and pressure sensor plots from file NWEI OfS 10Hz data 20140716 0400

July 16, 2014 data set 2 (continued)
Load bank setting key plus two star
PowerPod testing with 125 mm test rig stroke and 7.5 s period
Note: boost transformer ratio was 1:1.5 when this data was recorded



Power, ac voltage, and ac current NWEI OfS 10Hz data 20140716 0400

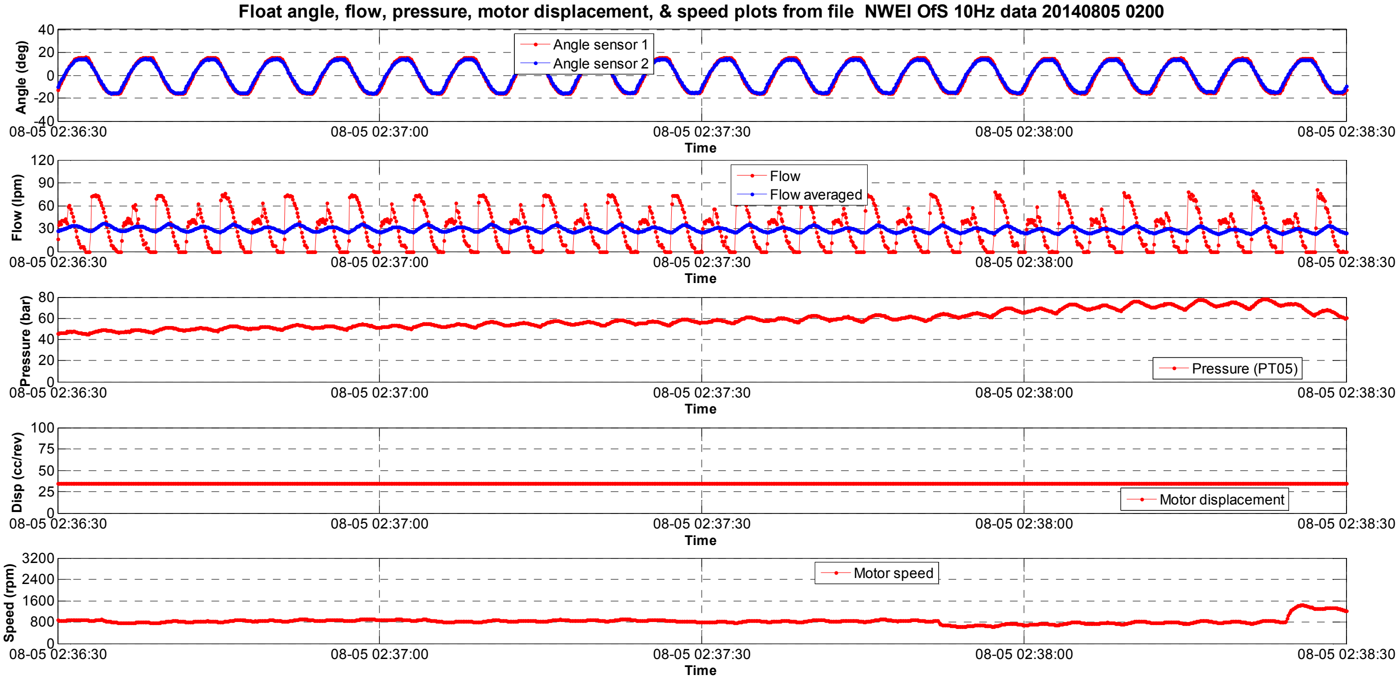


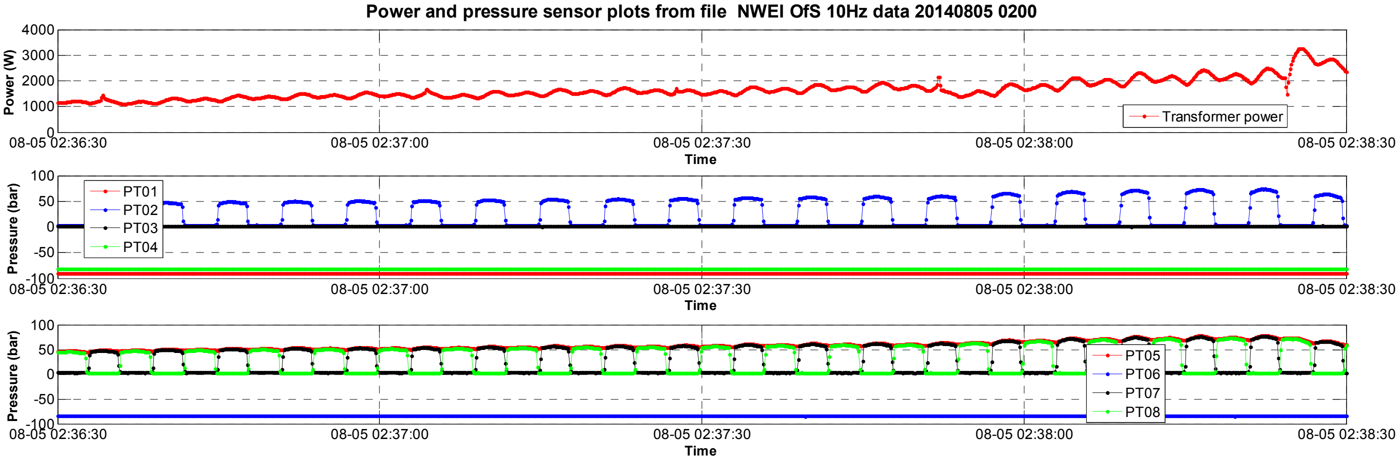
Dc voltage and current plots from NWEI OfS 10Hz data 20140716 0400

Appendix V

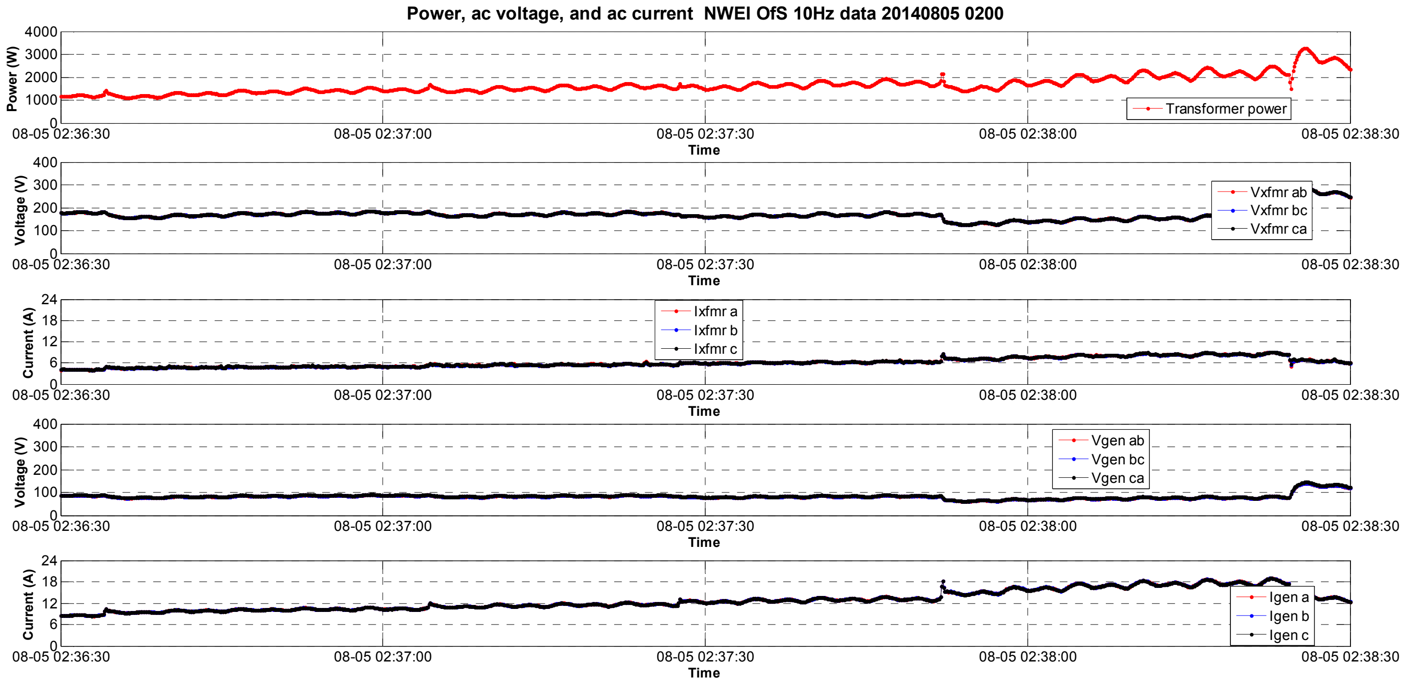
Characterization Data Plots for Inverter Tests

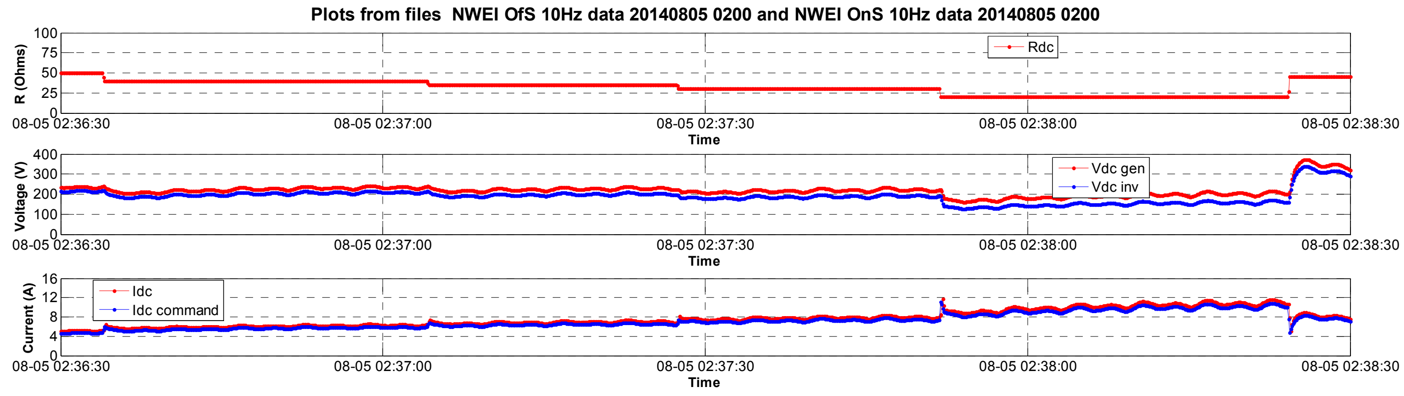
August 5, 2014 data set 1
PowerPod testing with 100 mm test rig stroke and 6 s period
30 cc/rev constant motor displacement and different Rdc settings
Note: data recorded after boost transformer ratio changed to 1:2



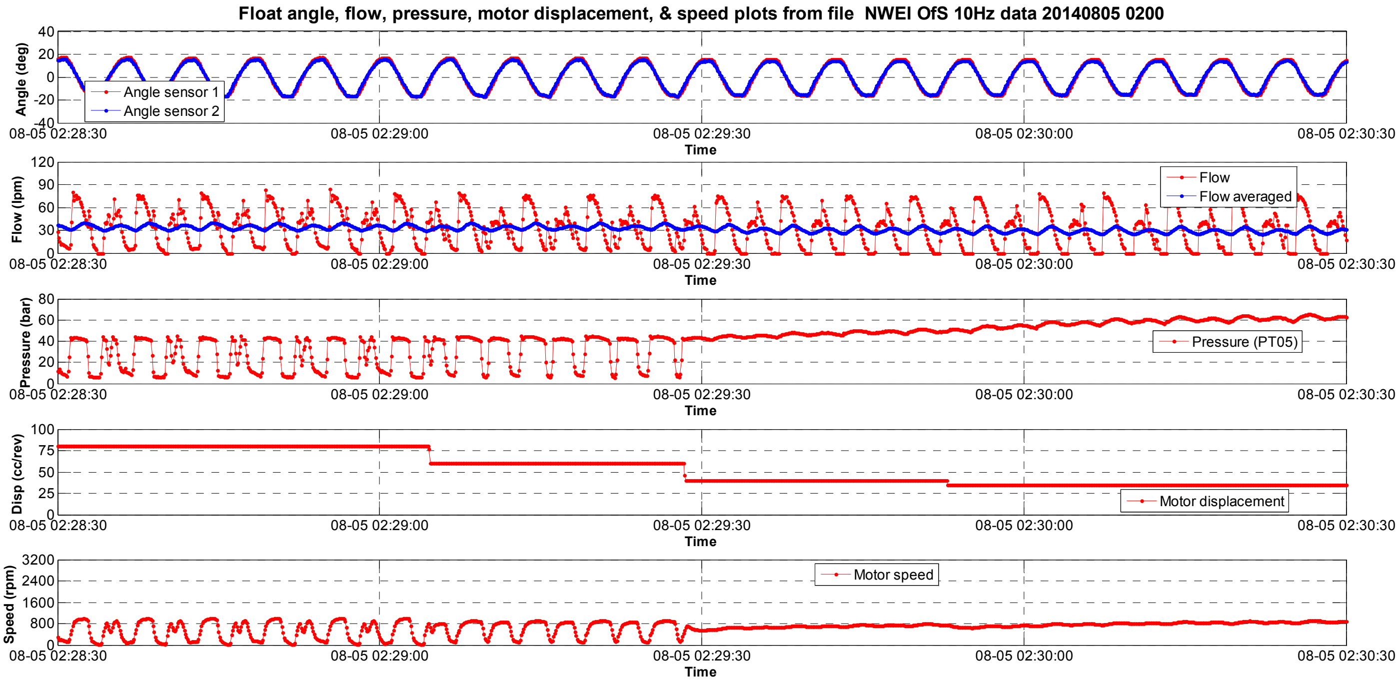


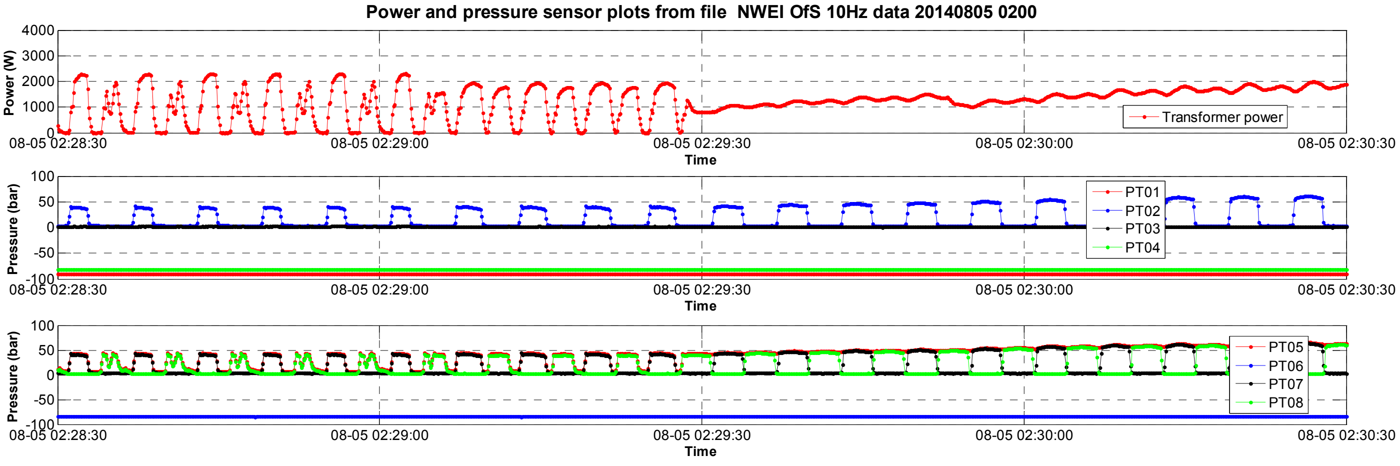
August 5, 2014 data set 1 (continued)
PowerPod testing with 100 mm test rig stroke and 6 s period
30 cc/rev constant motor displacement and different Rdc settings
Note: data recorded after boost transformer ratio changed to 1:2



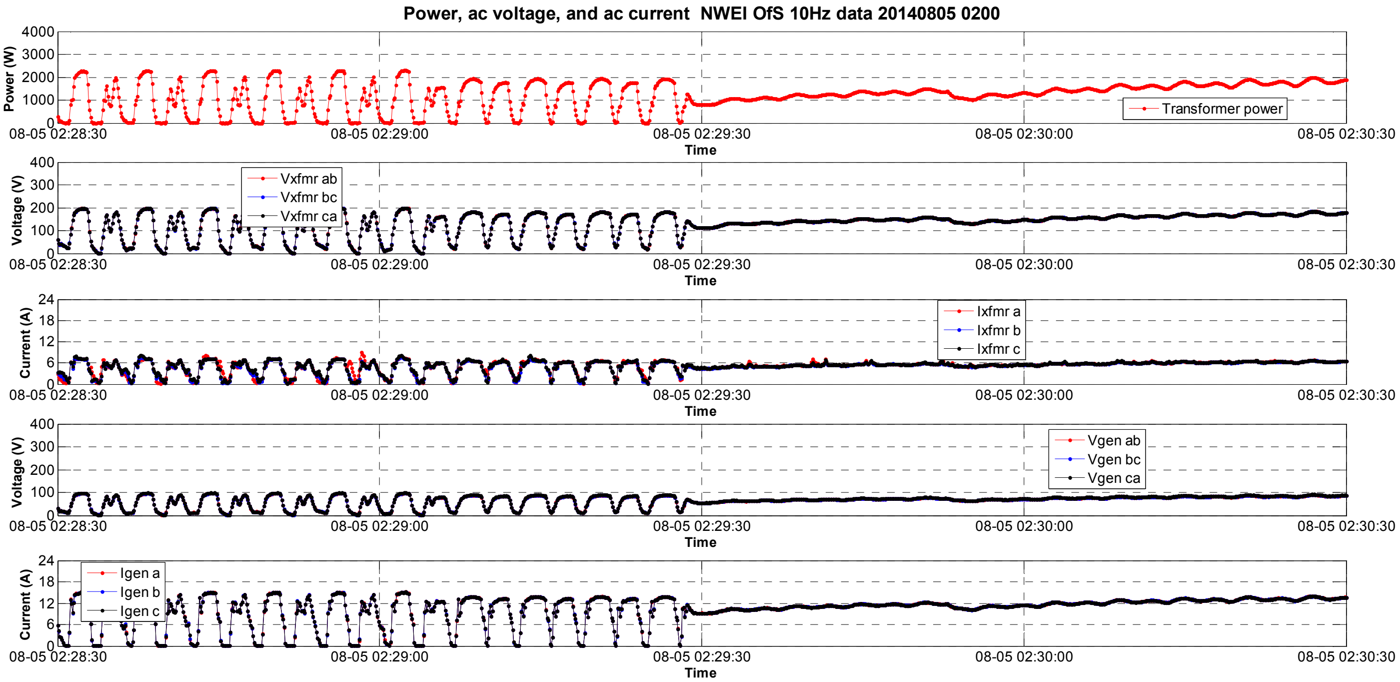


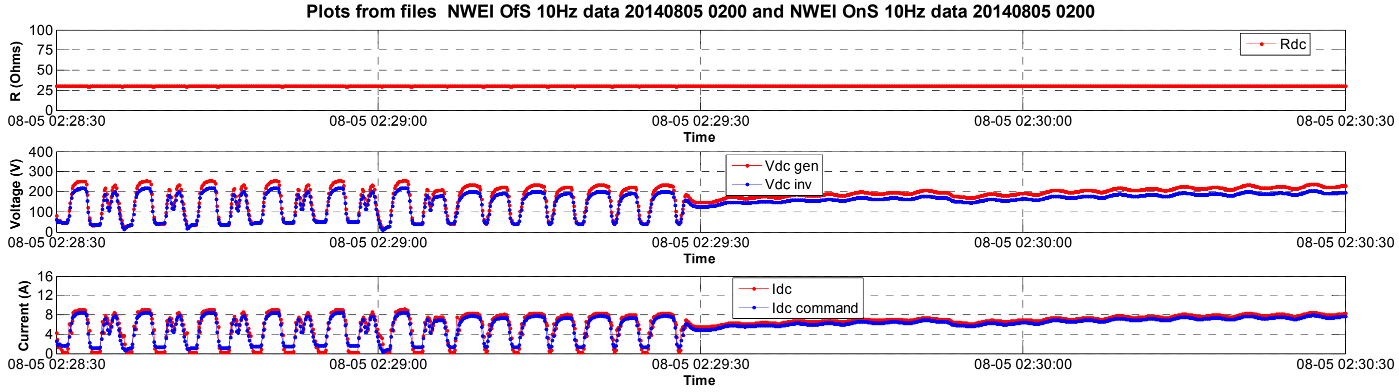
August 5, 2014 data set 2
PowerPod testing with 100 mm test rig stroke and 6 s period
Rdc fixed at 30 Ω and different motor displacement settings
Note: data recorded after boost transformer ratio changed to 1:2





August 5, 2014 data set 2 (continued)
PowerPod testing with 100 mm test rig stroke and 6 s period
Rdc fixed at 30 Ω and different motor displacement settings
Note: data recorded after boost transformer ratio changed to 1:2


Power, ac voltage, and ac current NWEI OfS 10Hz data 20140805 0200


Plots from files NWEI OfS 10Hz data 20140805 0200 and NWEI OnS 10Hz data 20140805 0200