Shore Power Connector Tester

The National Shipbuilding Research Program

2019 Electrical Technologies Panel Project

FINAL REPORT
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Preface

This final report summarizes research done, test methodology, laboratory test results, field test results, and technology transition path forward as well as implementation and safety aspects of this connector measurement technology. The final project report is releasable to the NSRP technical community and does not contain any restricted information.

Executive Summary

A history of shore power connector failures and an arc flash event on an active DDG prompted the issuance of a new Maintenance Requirements Card (MRC) mandating extensive insulation resistance testing of shore power receptacles prior to use. This panel project investigated whether an automated testing device could be used to perform these tests and so reduce the time involved and the susceptibility to human error.

A Commercial Off the Shelf (COTS) cable tester was identified that could perform the tests. It was programmed and tested first with a surrogate set of connectors and then with the actual shore power connectors used aboard ship. A laboratory demonstration successfully showed that the tester was capable of making the required measurements automatically and in a fraction of the time required for manual testing. The laboratory demonstration also showed the tester's ability to detect various simulated failures.

The COTS tester was prepared for a field demonstration by streamlining the interface and packing it in a rugged travel case. A demonstration on DDG 121 was performed at Ingalls Shipbuilding. The tester was unable to perform the shipboard tests. This was later determined to be due to capacitance and induced voltage on the shipboard cables behind the receptacle causing noise that was picked up by the high sensitivity settings of the tester. The tester performed correctly on the isolated ship receptacle used in the laboratory tests. Consultation with the tester manufacturer provided a path forward to mitigating these effects through adjustment of the tester settings.

The project showed that such a test can be automated with a significant benefit in time saved and accuracy over the manual testing currently performed. However, more development is needed to verify that it can be used in the shipboard environment and be repackaged into a practical easy to use unit.

1.0 Background

The DDG class of surface ship utilizes 450 VAC three phase electrical power. While in port, shore power is supplied from a dockside power source to the ship via cables with connectors. These connectors mate with receptacles on the superstructure of the ship. Each 450 V connector is capable of 400 Amperes of current and a ship may have up to 12 of these connectors. Due to the level of current, each connector has seven separate contact pins per phase. The male pins are in the shipboard receptacle while the female mating pins are in the cable plug. The body of the receptacle provides a ground connection to the ship's hull.

The shipboard receptacles have a cover with an environmental seal. However, they are still subject to corrosion at the connection pins themselves. Corrosion results in a high impedance contact and subsequent heating of the pins. This can lead to eventual failure and the possibility of a dangerous and destructive arc fault. A December 2014 NSWCCD-SSES report has noted a significant number of 450V 400A surface ship shore power connection plug and receptacle failures. Because of this possibility, there is a procedure in place that requires the testing of each connector prior to connecting the shore power cable. The test utilizes a MegOhm meter (commonly called a Megger) to verify that there is sufficient high impedance between any of the three phases or between any phase and ground. Anything less than the required impedance could result in catastrophic failure or arc flash.

In February, 2018, there was an arc flash event on DDG 62 that resulted in an explosion of one of the 450V 400A shore power connectors. This event was traced to a pin failure in the connector. See Figure 1. As a result of this incident, and due to similar issues within the fleet, a new Maintenance Requirement Card (MRC – test procedure) has been issued that requires Megger testing not just between phases but between each pin in each phase to every other pin in each other phase. Every pin is also to be tested to ground.

Figure 1 Healthy connector (left). Connector after arc flash event (right)

The number of permutations for the new tests results in a significant increase in the time and effort to perform these tests and also increases the opportunity for human error, since the meter readings are presently recorded manually.

The number of permutations involved is:

- Phase A (7 pins) to Phase B (7 pins) and to Phase C (7 pins) is 7 x 14 = 98 tests
- Phase B (7 pins) to Phase C (7 pins) is 7 x 7 = 49 tests
- All phases (21 pins) to ground = 21 tests
- Total number of tests per receptacle is 98 + 49 + 21 = 168 tests
- Total number of tests per ship = 168 tests x 12 receptacles = 2016 tests

This large number of manually performed tests is a concern due to the amount of time to perform each test and record the results. The potential for human error in missing a test or erroneously recording the results also increases significantly with this number of tests.

This project investigated the feasibility of developing a portable automated tester that can perform all the permutations of the tests with limited or no additional operator actions. The premise is to equip the tester with the mating connector to the shipboard receptacle. The operator will plug the test connector into the shipboard receptacle and initiate the test with a simple command or button push. The tester will automatically cycle through all the permutations and indicate a Pass/Fail result. The tester may also record or offload the impedance measurements. The operator will then disengage the tester and proceed to the next receptacle. All other parts of the MRC test requirements will be performed prior to and after the actual test. This includes disconnecting power from the receptacles and following lock out procedures, etc.

Integrated Project Team (IPT)

Project execution was guided by the Integrated Project Team which consists of all funded participants including the lead investigators, sponsoring shipyard and government stakeholder, plus the project technical representative (listed on the title page of this document), as well as representatives from NAVSEA 05Z (see section 6.1 Other Advisors / Stakeholders).

Stakeholder guidance and participation helped shape the requirements and conclusions of the demonstrations so that the evaluation is relevant to the Navy shipboard environment.

2.0 Project Tasks

The project was broken down into the tasks described in the subsections below. The tasks were ordered to provide progression from understanding the problem, to determining requirements, through a laboratory demonstration of the candidate equipment and culminating in a demonstration/experiment on board a ship with the shore power connectors in question.

This report is the final project deliverable.

2.1 Kickoff Meeting

The Project Kickoff meeting was held November 12, 2019 via teleconference. All members of the IPT were represented.

Project background, scope of work, deliverables and schedule were reviewed for the benefit of the IPT. The IPT reviewed the Maintenance Requirement Card (MRC) 65 2PN5 N which describes the required test, with particular emphasis on the sections regarding the insulation resistance measurements. This review produced the following points:

- Access to the cables behind the shipboard receptacle is not possible for these tests.
- The candidate CableEye tester is capable of testing all the permutations of pin to pin and pin to ground required for the tests.
- The mating connector for the receptacle will be connected to the tester. This connector is typically potted. As access to each individual pin is required for the test, an unpotted version of the connector must be obtained.
- The laboratory test should have both sides of the connector. It was decided to purchase both the plug and receptacle in time for the laboratory demonstration.

- The device typically tests a cable from end to end. As there is no access to the cable behind the shipboard receptacle, the tester must be re-programmed to take this into account by creating a loop back using the receptacle phase pins already connected to each other.
- Failures can be simulated by connecting a lower resistance value between conductors. The tester will report this as a failure.

The location and time of the shipboard demonstration had not been identified at that time.

2.2 Develop Requirements

The steps in the MRC relating to preparation (inspection, de-energizing, tagout/lockout, etc.) and restoration of the connector to service (cleaning, inspection, preventive maintenance, etc.) remain unchanged in this scenario. Only the actual measurement steps are affected. Note that preparation includes pulling the fuse for an indicator light at the connector. If this light is left in circuit, it can affect the readings.

The MRC requires testing of the receptacle conducting pins. A 500VDC MegOhm meter (Megger) is used to measure insulation resistance between every pin of every phase to ground and between every pin to every pin in the other phases. The minimum acceptable insulation resistance is 1 MegOhm. Figure 2 shows a typical hand held insulation resistance tester. Each reading is recorded manually. The automated tester must be able to make these same measurements.

Figure 2 MegOhm Insulation Resistance Tester (MIT300 Megger shown)

This MRC is required to be performed prior to each use of the shore power connectors and two months prior to the ship's return from deployment.

The scope of this project only included developing a proof of concept system. However, consideration was given to the eventual technology transition to a practical system for shipboard use. This included a path forward towards miniaturization and robustness and a simplified user interface (providing a Pass/Fail result).

2.3 Assess COTS Equipment for Feasibility

The candidate COTS device is the CableEye HVX High Voltage Cable Tester from CAMI Research (Acton, MA). This equipment is nominally a cable tester that tests a cable from end to end, but is reconfigurable to make the required measurements. It is a portable table top device with an interface to a laptop computer. It requires a 120 VAC power source and initiates the test by selection of a menu item on the user interface. All contacts are tested automatically in the course of a minute or so and a complete report is generated, recorded and displayed.

Refer to Figure 3. The tester has two banks of terminal blocks on the top. Normally, each conductor on one end of the cable under test would be connected to the left terminal block and the other end of the conductor connected to the right terminal block. When the test is initiated, the tester uses low voltage to verify that the cable connected to it matches a schematic stored in its memory. If there is an issue, a failure is reported and the test stops. If the cable matches the schematic, the high voltage test (500V) is initiated. Every pin is tested against every other pin against programmable criteria for current and insulation resistance. Any connection that does not meet these criteria causes a failed test. There are pass and fail lights on the front panel of the tester to the right.

In addition, if the tester is connected to a laptop computer, reports can be displayed and exported that indicate the pass/fail condition and also the location of any pin that did not meet the test criteria. The inset in the figure shows one such display.

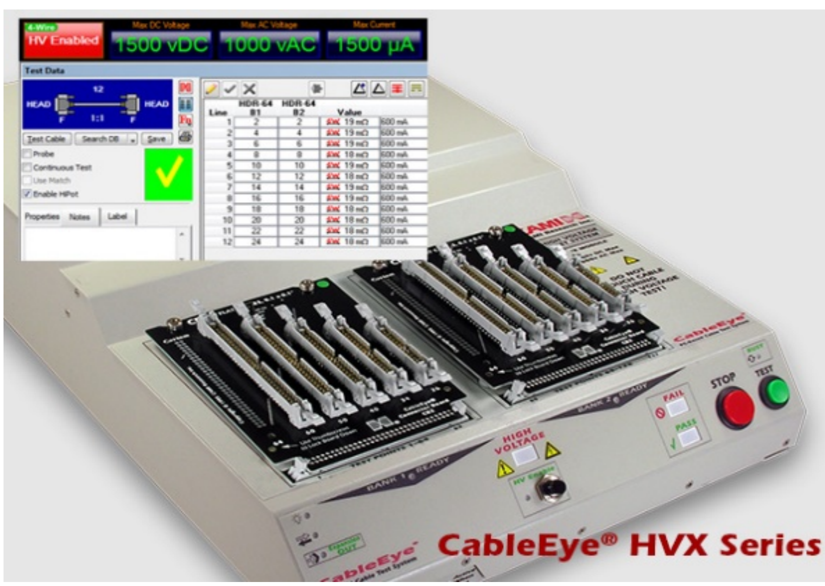

Figure 3 CableEye Cable Tester

D'Angelo Technologies (D5T) created a surrogate connector for evaluating the capabilities of the CableEye Tester. See Figure 4.

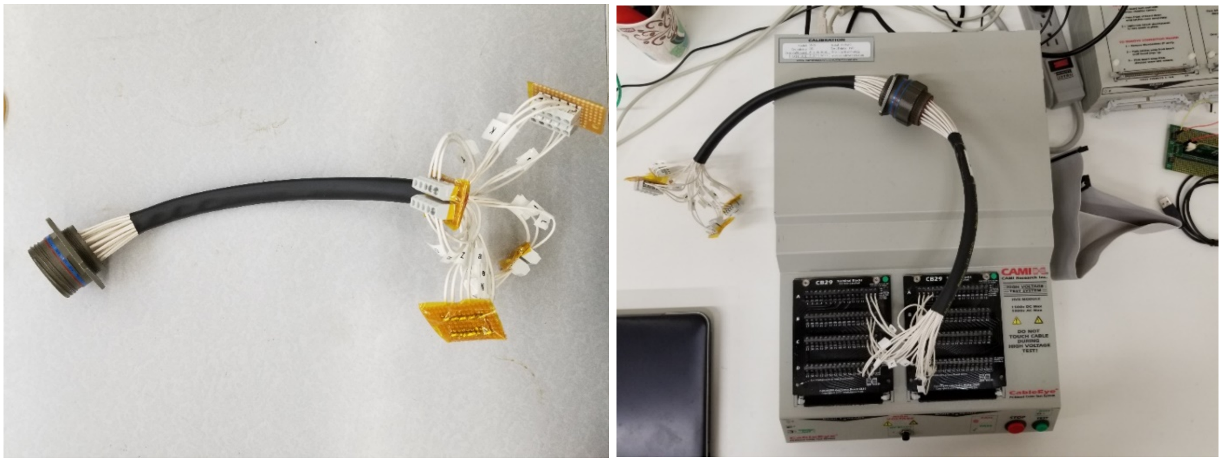

Figure 4 Surrogate shipboard shore power receptacle alone (Left) and connected to the surrogate plug, which is connected to the tester (Right)

The surrogate connector represents the shipboard shore power receptacle. It uses 28 pins. 7 of the pins were connected together via terminal blocks to represent the Phase A pins of the actual connector, which are connected together behind the receptacle. Likewise, 7 pins were connected together to represent the B phase and 7 pins for the C phase. The remaining 7 pins were connected together and represent the ground connection (ship's hull).

The mating connector represented the plug connected to the tester. Each of the 28 pins were brought back to the terminal blocks on the tester. See Figure 5.

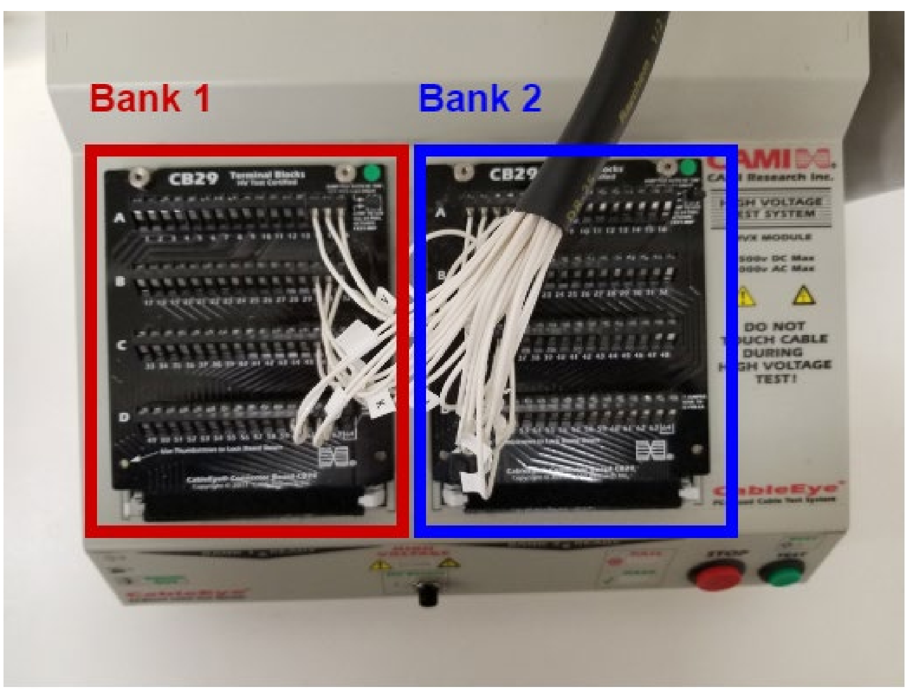

Figure 5 Surrogate connector attached to tester terminal blocks

Three of the wires representing the Phase A conductors were attached to the left terminal block (Bank 1). The other four wires from Phase A conductors were attached to the right terminal block (Bank 2). The conductors from the left loop back through the Phase A receptacle wires, which are connected to each other and return to the right. This looks like a normal end to end test to the tester as the conductors go from Bank 1 to Bank 2. The Phase B, Phase C and ground wires are connected similarly. This represents the baseline connections for a healthy connector on board the ship.

The tester then captured the schematic that represents this arrangement and was used as a reference for all other tests. Figure 6 shows the resulting schematic. Phase A is the first line crossing from the left bank to the right. Three of the Phase A wires are on pins 14, 15 and 16 of Bank 1 terminal blocks and the other four Phase A wires are on pins 1, 2, 3 and 4 of Bank 2 terminals. Phase B is the second line down, Phase C is the third and Ground is the bottom line.

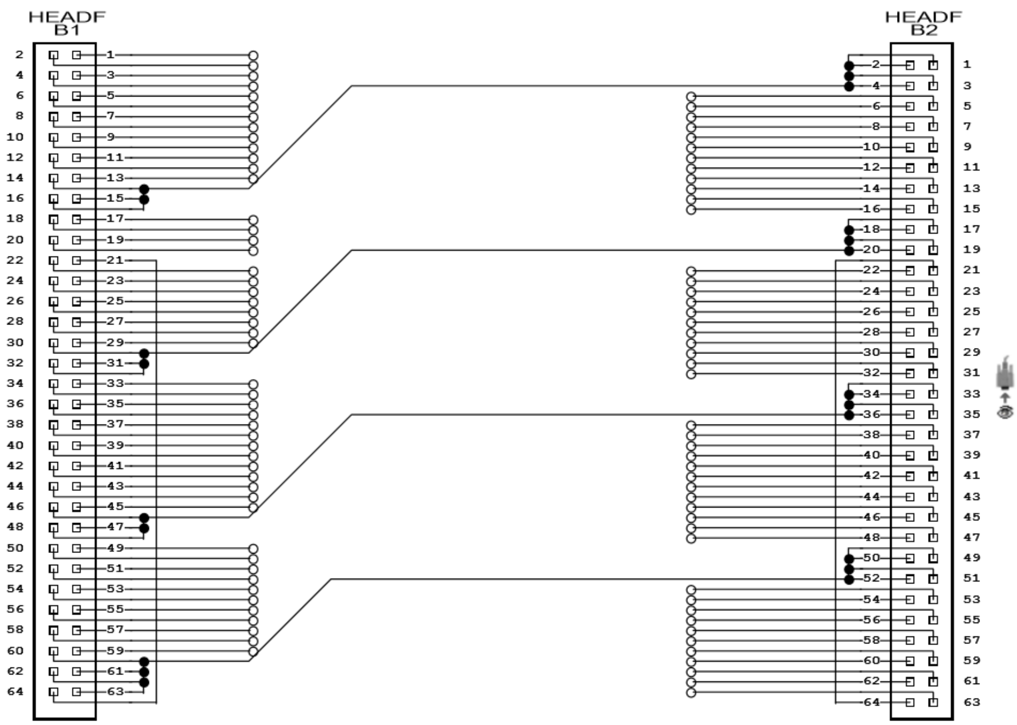

Figure 6 Schematic Representing a Correctly Wired Shore Power Receptacle

The tester first runs a low voltage continuity check of the Device Under Test (DUT) against the reference schematic. If there is a match, it provides a Pass indication. A netlist can be generated if desired. It notes any connections missing and any connections that should not be there. Figure 7 is an excerpt from the netlist of the surrogate cable showing that it matched the reference schematic. Every pin is tested and if it is a match to the reference, it gets a green check mark in the netlist. The figure shows that pins 14, 15 and 16 on the left are connected to pins 1, 2, 3, and 4, which matches the schematic. Similarly, pins 30 – 32 are shown connected to pins 17-20, also matching the schematic.

N E T L I S T (cont.)

Line	HDR-64 J1	HDR-64 J2	Value	HiPot
7	7			✓
8	8			✓
9	9			✓
10	10			✓
11	11			✓
12	12			✓
13	13			✓
14	14, 15, 16	1, 2, 3, 4		✓
15	17			✓
16	18			✓
17	19			✓
18	20			✓
19	21, 64		0.3 Ω	✓
20	22			✓
21	23			✓
22	24			✓
23	25			✓
24	26			✓
25	27			✓
26	28			✓
27	29			✓
28	30, 31, 32	17, 18, 19, 20		✓
29	33			✓
30	34			✓
31	35			✓
32	36			✓
33	37			✓
34	38			✓

Figure 7 Netlist for passing cable

To demonstrate a failure of the match test, a 76 Ohm resister was connected between pin 32 and pin 46 on bank 1. This resistor simulates the isolation breakdown between a pin on Phase B and a pin on Phase C. The netlist shown in Figure 8 shows the detection of the low impedance between the two phases.

EXTRA CONNECTIONS IN TEST CABLE

B1	B2	Value	HiPot
32, 46		76 Ω	

Figure 8 Netlist for a failed cable

If the cable passes the match test against the schematic, the high voltage insulation resistance test is run. If the isolation between any pin and any other pin not supposed to be connected exceeds the test parameters, the tester gives a failed indication and the report can pinpoint the location and nature of the problem.

These tests established that the CableEye tester is effective in classifying DC pin isolation as either within tolerance or out of tolerance at up to 1 MΩ. The tester is capable of isolation measurements up to 1 GΩ, but the parameter was set to match the MRC limits. The separate sequences of the test were written into a script so that a single action can initiate the match test, the high voltage insulation resistance test and the generating of reports.

2.4 Laboratory Demonstration

The project plan called for a demonstration of the Commercial Off the Shelf (COTS) cable tester in a laboratory setting. The demonstration took place at D'Angelo Technologies' offices in Beavercreek, OH. Due to schedule conflicts among the Integrated Project Team (IPT), the demo was actually run twice. The official demonstration for the project occurred on February 20, 2020. Clay Smith from Gulf Coast SUPSHIPS and Jason Farmer from HII-Ingalls Shipbuilding attended this demo. A preview demo took place on February 18, 2020 for Jeff Callen of the Penn State Electro-Optics Center. The preview demo served as a "dry run" for the official demonstration. Other members of the IPT were unable to attend either demonstration live due to travel or schedule restrictions. A summary report was prepared and sent to the IPT. This report is reproduced as Appendix A of this Final Report.

For the preview demonstration, D5T used the surrogate connector that they constructed for programming the tester. Penn State purchased the actual shipboard plug and receptacle and modified them for the test. This plug and receptacle were delivered to D5T at the preview demonstration, enabling D5T to install the actual connectors on the tester for the second demonstration.

Figure 9 shows the actual shipboard plug connected to the tester with the shipboard receptacle in the center. The seven pins of each phase are clearly seen. The ship electrical system uses a 3 Phase Delta configuration, which has no absolute ground connection. Note the green and yellow wire from the plug cable bundle to a clip attached to the receptacle. The test requires checking each pin to ground. On ship, the receptacle housing or the bolts securing it are used for a ground connection. For this test, a ground wire from both the plug and receptacle are clipped to the receptacle.

The laptop computer on top of the tester gives a sense of scale to indicate the size of the plug and receptacle used on board the ship.

Figure 9 Cable tester set up with the shipboard plug and receptacle.

Summary

For the first part of the demo, the machine tested a correctly wired cable to show a shore power receptacle with no problems. The test parameters are programmable, but for the demonstration, the voltage was set for 500 VDC and the fail criterion was any resistance isolation less than one MegOhm. These conditions duplicate the test from the MRC.

Simulated faults were then introduced in two ways. In the first, a resistor was added to the tester between connections representing two different phases of the three-phase wiring. This simulated a low impedance path between two of the phases. In the second, one of the wires was removed from the tester, and a resistor inserted in series with it before re-connecting it. This represented a corrosion effect in one pin that would isolate it from the other pins of the same phase.

Figure 10 is a screenshot from the tester laptop showing the simulated fault with the unexpected connection between Phase A and Phase B. The large X on the red background at left indicates a failure of the test. It lists the test parameters across the top. The schematic shows the differences between the stored schematic and the tested cable, highlighted in red. In this case, it shows a connection between the pins networked for Phase A and the pins networked for Phase B. Compare against the schematic shown in Figure 6.

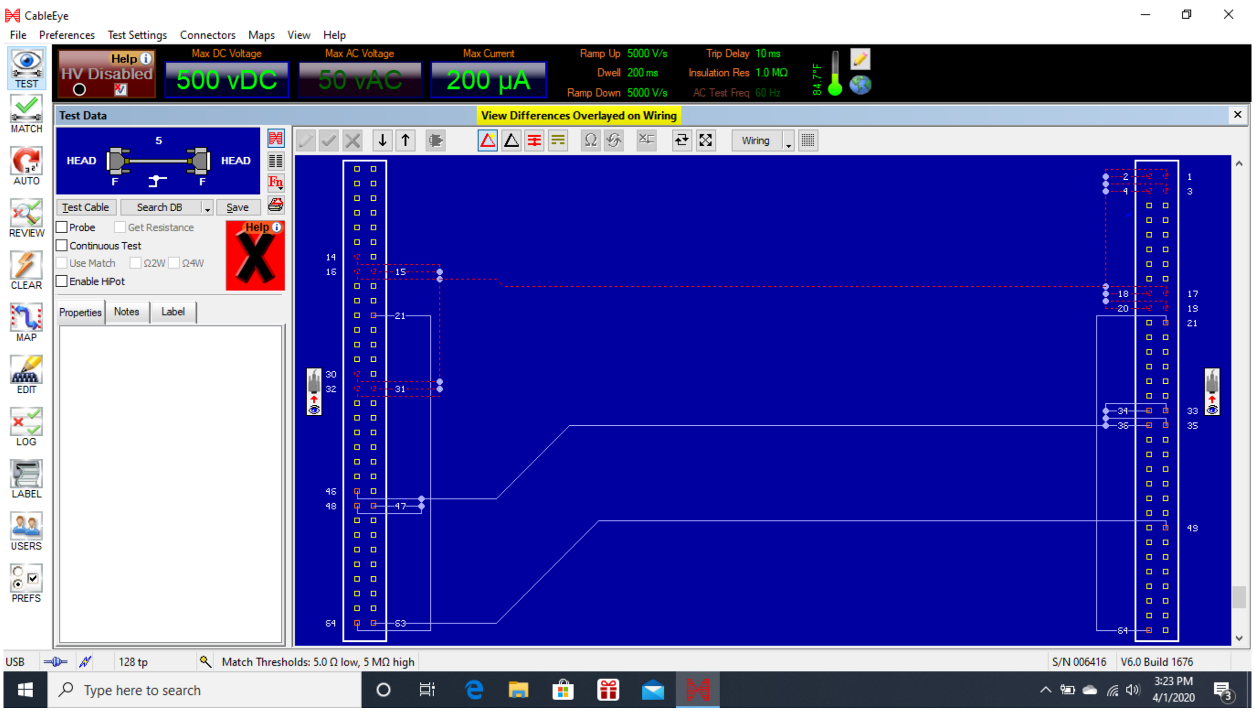

Figure 10 Tester screenshot showing fault between Phase A and Phase B

The tester recognized both faults during the low voltage test and reported the location of the resistor and its value. When the tester detects a faulty cable (different from the schematic stored in its memory), it does not run the high voltage test for safety reasons.

The full test of both low voltage and high voltage on a good connector takes about 51 seconds. If there is a fault, the tester detects it within a few seconds. See Appendix A for more details on the Laboratory Demonstration.

Conclusions

Feedback from the Navy and shipyard representatives indicated that this cable tester configured in this manner can perform the required inspections on board ship. The tester finding the faults during the low voltage test is not an issue.

The present test is a proof of concept demonstration. The test needs to be simplified for shipboard use. It will not be used if it is too complicated. The eventual tester is envisioned as a self-contained unit, packaged entirely or mostly within the connector plug itself. D5T is looking at packaging the tester in a Pelican type case with the remainder of the electronics inside the plug as an interim step. The test would be Pass/Fail.

The sophisticated reports generated by the tester are not required for the everyday use of the test. It would not be necessary for the tester to identify the bad pin, for example, since the crew would start to troubleshoot by hand regardless after a failed test. The Pass/Fail lights on the front of the tester would be sufficient feedback for normal use.

The proposed operation would be to plug the unit into the ship's receptacle, clip the ground wire to the receptacle bolt and press a button to start the test. A pass/fail indication (green light/red light perhaps) would result. The tester is capable of storing data from the tests. A data port (USB or other) or a removable SD card can provide a means to offload the data if desired.

At the time of the demo, D5T took an action to consult with the cable tester manufacturer to explore the repackaging idea. This repackaging is beyond the scope of this project, but a path forward will be identified.

2.5 Fabricate Items for Field Demonstration

D'Angelo Technologies repackaged the table top setup used in the laboratory demonstration for use in the shipboard demonstration.

The laptop user interface was replaced with an Intel W5 Pocket PC. This computer is more than powerful enough to run the CAMI Research software and has a package size of 4" x 1.5" x 0.5". User interface was provided by a 7" touchscreen manufactured by Lebula, utilizing an onscreen keyboard. A 3D printed case was constructed for the touchscreen and it was mounted to the top of the CableEye Tester. See Figure 11.

Figure 11 W5 Pocket PC (Left) and Lebula touchscreen installed on tester (Right)

To make the unit portable, D5T selected a Hardigg 472 Medical Chest as a case for its size and durability. D5T removed the drawers and shelving from the case and installed case foam, creating cutouts for the appropriate components and channels for ventilation. The Pocket PC and the touchscreen monitor were powered with a 5Vdc power supply, while the CAMI Research HVX tester was powered directly with 120V from a IEC C14 receptacle installed in the side of the Hardigg case. This allowed for a self-contained tester on wheels. The wires from the plug to the tester were replaced by a single multiconductor cable and 3D printed covers were installed over the tester terminal blocks to guard against unintended contact with high voltage during the test. Figure 12 shows the system packaged in the travel case.

Figure 12 Packaged tester, computer and plug

An isolation transformer was used for shipyard tests to power the tester. This was carried separately.

2.6 Field Demonstration

The Field Demonstration was a project deliverable. The Field Demo took place on October 6, 2020 at Huntington Ingalls shipyard in Pascagoula, MS. There were two portions to the demonstration. The first took place on board the DDG 121 which was in floating dry dock at the time. Members of the IPT, the Ingalls Electrical Test Team, and an Ingalls Industrial Engineer witnessed the tests. The second took place at the Ingalls Research and Development laboratory with the IPT members present. Additional IPT members and interested parties participated in a discussion via teleconference.

Testing was conducted on the receptacle at the starboard end of the shore power receiving station. There are twelve receptacles on this ship. See Figure 13. The ship was operating on generator power at the time, but the tested shore power receptacle circuit was secured and locked out, as per the MRC. The indicator light for the receptacle was first removed and then its fuse was pulled as per the MRC so that the light in the circuit did not influence the test. The tester was powered first from a shore power 120 VAC receptacle and later from ship's power (generator). Detailed notes about the test runs are included in Appendix B.

Figure 13 Two starboard most receptacles with indicator lights above

Summary – Shipboard Tests

Figure 14 Inserting tester plug (L) and reading results on computer display (R)

Figure 14 shows the tester being demonstrated on the DDG 121.

The tester was unable to perform any tests with the shipboard shore power receptacle. The issue manifested itself in two ways. During the initial low voltage test, where the tester was seeking to verify that the circuit connected matched the circuit stored in its memory, it was unable to complete this test and continually repeated it. After a few minutes (around 10,000 of these measurements), the operator terminated the test. This happened for every test attempted with the tester connected to the ship receptacle. This occurred under all of the following conditions:

- Tester connected to ship's 120 VAC power (generator) or shore power
- Isolation transformer for tester 120 VAC in or out of the circuit
- Receptacle light pulled from circuit or fuses removed.
- Tester ground wire connected or disconnected from ship hull.

The second symptom appeared when the tester was run in a "Learn Cable" test mode. Rather than compare the device under test against a saved schematic, the system runs a low voltage test and reports what it found. In this test the system returned the following:

- ~ 800 KOhm resistance between Phase B and Phase C
- ~ 9V discrepancy between Phase A and Phase B.

This happened consistently every time the learn cable test was run. The Ingalls Electrical Test Team repeated these measurements with handheld meters and saw between 1.5 and 2 V between phases and measured over 900 MegOhms isolation between all pins.

It was speculated that the 9V detected between phases was likely due to induced voltage on the line from powered cables running adjacent to the cables to the receptacle under test. Induced voltages under these circumstances are not uncommon. There is approximately 150 feet of cable between the shore power receptacles on deck and the breaker panels below deck. Half of the shore power receptacles were connected and powered during the test.

The tester was disconnected from the ship receptacle and connected to the receptacle that was used in the laboratory demonstration. This receptacle was free standing and not connected to the ship in any way. The tester was powered from ship's power but the isolation transformer was not used. Tester ground clip was connected to the receptacle housing. Five tests were run. Four of them were successful in good circuit connections and simulated faults of a short between phases and a missing wire. However, on one test, the system hung on what was later determined to be an intermittent connection on a jumper internal to the tester.

Summary – Lab Tests

Following the shipboard tests, the system was set up at the Ingalls R&D lab using house power for the tester and the lab demo receptacle as the test article.

With the test receptacle connected to the same earth ground as the tester power supply, the system would get stuck in the searching mode if the isolation transformer was not used between the power outlet and the tester. If the isolation transformer was used, then the system would operate correctly. This suggests that the tests on board the ship with the isolation transformer ought to have worked. There was some suspicion that the isolation transformer may have been damaged during transportation to the Ingalls shipyard. The isolation transformer was disassembled and examined but no obvious damage was found.

During these tests, the tester reported an isolation resistance failure between two pins that did not have anything connected to them. This happened on four separate tests, although it did not occur on one test in between the others. The Ingalls R&D laboratory has the same CAMI Research CableEye tester. The terminal boards from the shore power tester were transferred to the Ingalls tester and it did not exhibit the same fault on these pins.

While this issue would not have caused the problems encountered on the shipboard tests, it did indicate that the tester should be examined for potential failures.

Analysis and Conclusions from the Test Results

After the demo, D5T consulted with CAMI Research, the manufacturer of the CableEye tester. The manufacturer indicated that the failures on the shipboard tests to get past the low voltage test were due to electrical noise. If the noise on the line causes the tester to exceed the threshold parameters that are set, the tester will continue to take measurements indefinitely. In other words, the tester parameters were set up and tested in the relatively pristine environment of the laboratory using a test receptacle with very short cables behind it. Since the tester could not get past this first stage, it never ran the high voltage insulation resistance tests.

The readings taken during the "Learn Cable" test on the shipboard connector were attributed to the noise on the lines showing up as these measurements. It is likely that the exact numbers measured (800 KΩ and 9V) were not accurate. The tester parameters were set for very short dwell times to take the measurement and the capacitance of the line would affect the reading if it were not given sufficient time to take an accurate reading.

The anomaly seen during the lab tests (two unconnected pins reporting a failure) was determined to be an intermittent connector on an internal jumper. The tester has several options for terminating the cable under test. The terminal boards used in this test have a jumper that allows the tester to "auto-detect" the type of boards connected. With an intermittent connection on this jumper, the tester was sometimes confused as to whether it should see something on those pins or not. In post demonstration testing, self-diagnostics tests run by D5T with manufacturer guidance confirmed that the tester itself was working properly. It was recommended that the jumper be removed and the terminal board type set in software. The project team concluded that this anomaly was completely unrelated to the issues seen on the shipboard tests.

The manufacturer confirmed that the 120 VAC power source for the tester should be isolated from ground if any of the measurements also require a connection to ground. This can be done with an isolation transformer with the input and output grounds disconnected or with a three prong to two prong adapter. If the grounds are not isolated, the tester will get stuck in the searching mode and will never complete the test. This was verified in the lab tests and also consistent with the fact that on ship, the free standing test receptacle (not connected to the ship hull/ground) was tested correctly.

Path Forward

The manufacturer recommends an iterative process to reduce the tester sensitivity to electrical noise on the lines of the receptacle under test. The low voltage test threshold presently looks for any resistance between connections that is lower than 1 MΩ. This threshold can be incrementally reduced from 1 MΩ to 500 KΩ and below while also increasing the dwell time for measurements from the present 200 μsec to progressively larger values in conjunction with the lowering of the threshold until the device can complete the test. Extreme levels of noise or capacitance may still cause the tester to fail, even with this adjustment.

NOTE: this method only affects the low voltage test that is looking for proper connectivity between the pins. This does not affect the high voltage test, which tests for sufficient insulation resistance between the pins. The tester will still be able to perform the test required on the MRC at 500V and with a failure threshold of 1 MΩ.

D5T will also create a test setup using a metal plate that can be connected or disconnected to earth ground and can be connected to a test pin on the CableEye. This will verify the need for isolating the tester ground (isolation transformer, 3 prong to 2 prong power adapter, or completely isolated power supply such as battery) when one of the test pins is also connected to ground. This test bed will also be used to simulate the tuning of the dwell time and threshold settings if long cables are added to increase the capacitance of the unit under test.

3.0 Technology Transition

As the scope of the project limited the effort to producing a proof of concept demonstration, it was known that some maturation of the technology would be needed to transition the technology into a practical device for everyday use. The MRC requires these tests to be performed every time the shore power connectors are to be used and two months prior to return from deployment. That means the tester will need to be used not just after new construction or refurbishment, but dozens if not hundreds of times over the life cycle of the ship.

This section provides user perspective on the incorporation of such a device into shipbuilder and Navy service. These perspectives include some notions on what forms that maturation should take.

3.1 Navy Supervisor of Shipbuilding Gulf Coast Perspectives [Clay Smith - SSGC]

Background

In 2018, while overhauling the USS Fitzgerald (DDG 62) an arc flash occurred on the #5 Shore Power receptacle. See Figure 15. This damage was extensive not only to the shore power receptacle, but also to the cable and corresponding circuit breaker. After this failure occurred, the local Navy team learned similar failures were occurring in the fleet. NAVSEA 05 and others were investigating the root cause of this issue. This resulted in the development of a new MRC card to test (megger) each pin to each other pin and ground. This new test drastically increases the amount of time it takes to perform shore power receptacle checks.

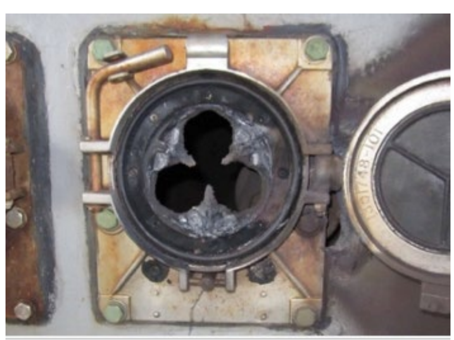

Figure 15 Damage from connector arc flash event

Concerns with current testing approach:

During and after construction a routine test is conducted before connecting shore power cables. This test measures the insulation resistance of the shore power receptacles to ensure that there are no shorts between each phase or between phase and the hull of the ship. By validating sufficient resistance between phases and the hull, we ensure a fault will not occur when power is applied to the ship. Before the 2018 MRC card was issued, this was a quick test that only took a few minutes since only 1 pin had to be tested to 1 pin on the other phase along with the hull. When the MRC card required pin to pin checks, this drastically increased the amount of time it takes to perform this test.

While NAVSEA 05 and ISEAs (In Service Engineering Agents) feel these additional measurements are necessary to prevent the casualty we experienced on DDG 62, local SUPSHIP engineers have the following concerns:

- How likely are shipbuilders to perform the same level of testing since the additional testing is currently not contractually required?
- Having to take 2000+ measurements will likely have numerous errors or missed measurements. Even a 1% error rate would mean that 20 pins were either missed or improperly measured.
- Cost and time associated with this increased testing.

Proposed NSRP Solution

The proposed solution by the NSRP team to quickly measure the insulation resistance of all pin to pin and pin to hull permutations using a Cable-eye tester is a reasonable solution. The tester is integrated using an umbilical cable to a standard shore power plug. By inserting the plug into the receptacle, a laptop can quickly activate the tester to perform all the necessary permutations. It has various methods and variables that can be programmed, but the real value is being able to quickly perform the test knowing a consistent method was utilized.

Concerns with Proposed Solution:

The team's solution shows the required receptacle testing can be performed quickly using this cable tester. While this is a great starting point for Navy crews and shipbuilders to minimize time, additional effort is required to make it practical. First, the tester has to be packaged into a smaller device that is robust and can be easily transported and stored. Second, recording the specific insulation resistance for 2000 plus measurements is not necessary. The system needs an indicator light to show when it passes and an indicator light to show when it fails. If it passes, move on to test the next receptacle. If it fails, then additional troubleshooting should occur in accordance with NSTM CH 300. Lastly, the tester needs its own power source. Attempting to find a power source especially having to run extension cables to power this unit is an unnecessary hassle that reduces the value and time-savings that this device could provide.

Conclusion:

The cost associated with the Arc Fault on DDG 62 Shore Power receptacle was extensive and the schedule impact required produced additional ramifications. Since this failure is not the only one in the fleet and the NAVSEA tech community now has yearly Shore Power meetings, a device/tester similar to the one developed by this team is needed. We cannot expect shipbuilders and/or Navy crews to continuously perform such a repetitious task without expecting errors and/or skipping test steps. This project was a great start to solving the issue of properly testing Shore Power receptacles and with a bit more effort a more viable solution can be fully developed which will benefit many of the US Navy ships, shipbuilders, and other US Government ships.

3.2 Shipyard Impacts [Jason Farmer, Ingalls Shipbuilding]

Background

A new approach to validate shore power connections is being evaluated through this NSRP Panel Project as discussed herein. The new method utilizes an automated circuit tester to verify proper connections (i.e., connector pinned out properly), absence of short circuits, and proper insulation resistance readings prior to energizing the circuit. The new approach has the ability to reduce time for the testing process, to provide documented test results, and to eliminate the potential of arc flash incidents associated with damaged connectors. The proof of concept system utilizes a Cami Research CableEye HVX circuit tester attached to a shore power connector through a wiring harness. A computer interface (laptop or tablet) is used to run the test program and display results. The prototype test system used in the laboratory demonstration utilized a laptop as illustrated in Figure 9.

Impacts to Current Testing Process

Shipyard facilities provide shore power to ships under construction through the shore power receiving stations. The electrical service provided may vary based on the ship class. Electrical service for an Arleigh Burke (DDG 51) Class Guided Missile Destroyer is 3 phase, 450 VAC. The shore power receiving station on a DDG 51 class ship includes twelve (12) receptacles as shown in Figure 16. Each receptacle is inspected and tested as per procedures given in MRC 65 2PN5 N. The shore power connector test includes verifying proper pin connections and insulation resistance for each of the twelve receptacles of the shore power receiving station. Insulation resistance readings are manually taken using a handheld meter similar to the Megger illustrated in Figure 2, above. Test results are noted for each of the pin to pin and pin to hull readings. This test is conducted each time the ship is transferred to shore power.

Figure 16: Shore Power Receiving Station (Two of twelve receptacles shown)

The proof of concept system was demonstrated at Ingalls Shipbuilding on October 6, 2020 aboard DDG 121. The shipboard demonstration system is shown in Figure 17. As illustrated, the system was packaged in a protective case for transport to the ship and a small computer interface (Figure 18) was added (replacing the laptop used in the lab demonstration). In addition to the test system, two additional pieces of hardware are shown; an isolation transformer was needed for the test set-up and a separate receptacle was provided to demonstrate simulated faults. The evaluation process included shipboard testing and laboratory testing. Testing conducted onboard DDG 121 included a test of shore power receptacle #12, followed by a demonstration of faults using a separate demonstration receptacle provided by the Project Team. The onsite testing and demonstration provided an overview of the proposed automated circuit testing approach. Additionally, this provided an opportunity to field test the system and identify any impacts of the shipboard environment that are not present in controlled laboratory testing. Additional detail is included in Section 2.6.

Ingalls Shipbuilding reviewed the testing approach and evaluated impacts to current shipyard processes. As noted previously, each of the twelve receptacles are tested prior to connection of shore power services. This process is conducted approximately four times during a ship construction cycle. The proposed process using an automated circuit tester has the potential to decrease test time and reduce or eliminate the need for manual transcription of test results in the field. The automated circuit tester conducts testing very rapidly (approximately 51 seconds per receptacle), reducing test time by over 90%. Results are stored automatically, thereby providing documentation of the receptacle health without manually writing down the test results in the field and later uploading data for contract deliverables.

Figure 17 Field Demonstration System

Figure 18 Shore Power Circuit Tester – Onboard Computer Interface and Test Results

Benefits and Cost Savings Opportunities

A business case analysis was conducted on the system concept to identify cost savings opportunities. The benefits identified include reduced test time and reduced damage associated with bad connections. Efficiency gains from reduced testing time alone would provide a 5-year savings potential of greater than $10,000. Additional cost savings are possible in the form of cost avoidance associated with damaged equipment, connector hardware, and cabling that can result from faulty connections. It should be noted that damage from bad connectors is not common in new construction; opportunities in this area would primarily be focused on post-delivery/life-cycle maintenance activities.

Recommendations for Successful Transition

The testing approach developed in this NSRP project provides potential benefit in the form of cost savings and process improvements. For successful transition, the unit will need to be further developed to address issues identified in the Field Trial at Ingalls Shipbuilding discussed in Section 2.6. Additionally, further development of the system should address the following items:

- Size
- Weight
- Portability
- Robustness

Testing operations during the construction cycle may require the test electrician to climb several flights of stairs to get to the work area. The ideal test system should be of similar size as other handheld test instruments. The weight and size of the packaged system should allow an individual to easily carry the unit to the work station. The ideal solution would be a simplified test unit packaged into the back shell of the shore power connector plug and would be internally powered. The unit will need to be ruggedized to facilitate typical shipyard conditions, including high temperatures and high humidity. The unit should be capable of withstanding drops in excess of 10 feet. A commercial rating of IP64 or higher as defined by International Electrotechnical Commission (IEC) Code 60529 is recommended to provide dust and water protection.

Conclusion and Recommendations

A proof of concept test system was developed and evaluated though this NSRP Panel Project. Evaluations of the test system were conducted through laboratory and field evaluations. The test system shows potential to reduce test time and associated costs with a fully developed system. Cost savings opportunities have been identified, including reducing testing time by over 90%. Further development is recommended to field a portable system that could be used in shipyard testing processes.

4.0 Conclusions

Maintenance Requirement Card 65 2PN5 N mandates over 2000 individual insulation resistance measurements to be made on a DDG class ship's shore power connectors prior to each use. There are concerns over the length of time to make these measurements and the potential for human error.

This project addressed these concerns by demonstrating the use of a COTS cable tester, the CAMI Research CableEye HVX connected to the mating plug for the receptacles to be tested. The tester was wired so as to use the common phase pins of the receptacle as a loop back test and programmed to verify continuity and also check for unwanted low impedance connections between phases and phase to ground. The tester then performed the insulation resistance test required by the MRC.

The system was tested in the laboratory using the actual shipboard connectors and aboard the DDG 121 at Ingalls shipyard.

The laboratory tests showed that the CableEye tester, properly configured, is capable of addressing both concerns with the required tests of MRC 65 2PN5 N. The tester can perform a complete shore power receptacle test in 51 seconds, a reduction in time of over 90%. The tester also eliminates human error in that the test is performed automatically and consistently each time, checking all pins to all other phase pins and all pins to ground. No pins are missed. The tester does also keep records so there would be no transcription errors as is possible with a manual test. This is useful for new construction and refurbishment, but less of an issue in operational use. In operations, procedures require troubleshooting after a failed insulation resistance test and this would reveal what the tester recorded.

The tester did have trouble making the required tests in the electrically noisy environment of the actual shipboard receptacles and cables. This has been attributed to the sensitivity of the settings on the tester preventing it from assessing the circuit correctly and therefore never getting to the stage where the insulation resistance was tested. A path forward has been identified to reduce the sensitivity of the tester to these initial conditions. Some experimentation is required to verify that the programming changes are sufficient.

It was known at the start of the project that using a COTS tester was a proof of concept effort. Some follow-on work will be needed to turn it into a practical system for everyday use, including ruggedizing and miniaturizing the equipment. Ideally, the tester electronics can be made to fit inside the mating plug for the connectors, which it required for ease of use. A sophisticated interface is not required, as the tester would be programmed ahead of time and would only need a switch to initiate the test and pass/fail indicator lights to report the results. This effort is beyond the scope of this project.

The use of an automated tester has great potential to save hundreds of hours of work, avoid costly and dangerous arc flash events and provide confidence that the receptacles are 100% inspected prior to each use.

5.0 Recommendations

It is recommended that follow-on work be performed to mature the technology into a practical device for everyday shipboard use.

The steps toward this goal primarily consist of two items: additional testing and miniaturization/robustness.

Additional Testing/Development

Additional testing is required for the following:

- Create a testbed to explore the tester behavior both with and without isolation and varying degrees of capacitance on the test cables and over extended length of cables.

- Explore the programming steps identified by the manufacturer to reduce the susceptibility of the tester to electrical noise. Determine the effectiveness of these steps.
- Develop a method to incorporate this into a practical test.
- Test the changes again on shipboard to verify that the changes will allow the tester to operate successfully in the shipboard environment.
- Test again during and after the miniaturization effort to verify that the necessary functionality has been retained.

Miniaturization and Robustness

D5T had contacted Cami Research about miniaturizing the tester. The company is not interested in doing it themselves, but are willing to support an external effort. This is beyond the scope of this project, but could be developed further with a follow-on effort. Some obvious places for reduction include:

- Number of connections – the COTS tester has 64 connections each side and only 22 are required (3x7 for the phases and 1 for ground).
- Relays – the unit has internal relays that switch between all the combinations of pins. Fewer pins means fewer relays.
- There are internal transformers to generate the high voltages needed for the insulation resistance test. The MRC requires 500 V and the tester is capable of 1000 V. The transformers could be downsized.
- The tester can also run tests with AC voltage which is not needed. There might be some opportunity to strip out some AC conditioning circuits.
- Component substitution might save space.
- Repackaging will save additional space. It may be necessary to redesign circuit boards to eliminate unneeded circuitry and fit a different form factor. The connector housing may also be redone.
- The internal software might need to be modified to accommodate the changes.

There was also discussion about making the unit completely isolated and more portable by using battery power. There will be some tradeoffs in size and weight that have to be explored, but given that the tests can run quite quickly, the battery capacity need not be too large to accomplish even all 12 receptacles on a single charge.

The ideal package would have all of the electronics contained within the plug itself or within a box that protrudes out the rear of the plug. This would put everything in one package that would be attached to the receptacle, powered on and the test initiated with a single button push. A pass/fail indicator light is the only feedback required. If the test fails, the electrician will check pins with a hand held meter to locate the problem. The tester is capable of offloading the reports. This could be accomplished by means of an accessible USB port or an SD card or similar memory slot.

It will not be known if this is possible until it is seen how much of the COTS components must be retained. An alternative would be to put what doesn't fit into the plug housing into a separate box connected by cable to the plug. This separate box would be as small and lightweight as possible, perhaps containing the required power supplies and conversions. These tend to be the heavier components, so this power unit could be set on the deck with enough cable to reach the receptacle with the plug.

During this process, the construction of the new packaging would take the shipboard environment into account, allowing for rugged construction and protection against weather and temperature extremes. Human factors will need to be taken into account as the finished tester will need to be maneuvered through narrow openings and carried up and down ladders and so must be of manageable size and weight.

6.0 References

6.1 Other Advisors / Stakeholders

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6.2 Reference Documents

Issues with these types of shore power connector have been documented since 2014. The following documents provide a framework of the issues and the background of this project. Most of these documents are referenced Distribution D (DoD and DoD contractors only) or Proprietary and therefore are not reproduced here, only referenced.

1. Maintenance Reference Card (MRC) 65 2PN5 N is Distro D – Describes the manual measurement technique addressed by this project
2. DDG 62 Shore Power Casualty Customer Critique, March 1, 2018 – an Ingalls document describing the arc fault incident on the DDG 62
3. Surface Ship 450V Shore Power Connections Ser. 936-045 December 15, 2014 – a summary of the 2014 Shore Power Working Group Meeting outlining a number of shore power connector failures.
4. Ship Change Document 22714, February 7, 2017 – a ship change document recommending a design change to the connector pins to reduce the pin failure rate.

7.0 Appendix A Laboratory Demonstration Report

This section is a reproduction of the summary report written after the laboratory demonstration. Double click on the first page image below to bring up the PDF.

D'ANGELO TECHNOLOGIES, LLC

PennState Applied Research Laboratory

Shore Power Connector Tester

The National Shipbuilding Research Program
2019 Electrical Technologies Panel Project

Laboratory Demonstration Summary Report

April 14 2020

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Shore Power Connector Tester (2019 NSRP ETP Panel Project)
Laboratory Demonstration Summary Report (March 2020)
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8.0 Appendix B – Summary of Shipboard Testing

This section is a copy of the notes written after the shipboard demonstration. Double click on the first page image below to bring up the PDF.

A summary of the tests ran on October 6, 2020 at Huntington Ingalls shipyard in Pascagoula, MS is as follows:

Shipboard Test 1
- Test configuration
  - Tester plugged into ship's shorepower receptacle (Starboard)
  - Tester powered by shore facility temp power
  - Power isolated through D5T's isolation transformer with grounds disconnected.
  - Ground clip from tester pin # 63 connected to receptacle frame
- System repeated low-voltage measurements indefinitely. User terminated test after >10,000 measurements
- Note: Fuse to indicator light was likely in place

Shipboard Test 2
- Test configuration
  - Tester plugged into ship's shorepower receptacle (Starboard)
  - Tester powered by shore facility temp power
  - Power isolated through D5T's isolation transformer with grounds disconnected
  - Ground clip from tester pin # 63 *disconnected* from receptacle frame
- System repeated low-voltage measurements indefinitely. User terminated test after >10,000 measurements
- Note: Fuse to indicator light was likely in place
- Conducted a "learn cable" operation to see what the tester would indicate on each pin. System found the following:
  - ~9v from Phase A to B
  - 800kOhm from Phase B to C

Shipboard Test 3
- Test configuration
  - Tester plugged into ship's shorepower receptacle (Starboard)
  - Tester powered by ship's power (generator)
  - Power isolated through D5T's isolation transformer with grounds disconnected
  - Ground clip from tester pin # 63 connected to receptacle frame
  - Indicator light fuse removed
- System repeated low-voltage measurements indefinitely. User terminated test after >5,000 measurements
- Ingalls Electrical Test Team tested receptacle with handheld meters
  - ~1.5V was measured with handheld meter
  - Insulation Resistance test showed >900MOhm between all phases with MIT300 series Megger.

Shipboard Test 4
- Test configuration
  - Tester plugged into ship's shorepower receptacle
  - Tester powered by ship's power (generator)
  - Isolation transformer removed from the system

1