Ensuring Error-Free Performance of Communications Equipment

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Published in
SEL *Journal of Reliable Power*, Volume 3, Number 2, August 2012

Originally presented at the
11th Annual Western Power Delivery Automation Conference, April 2009

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Abstract—**Modern substations employ extensive data communications equipment, including automation controllers, radios, Ethernet switches, routers, encryption devices, and modems. Widespread use of Ethernet and communications technology in substations continues and may involve mission-critical applications, such as protection functions with Generic Object-Oriented Substation Event (GOOSE) and sampled measured values. Data errors or interruptions in any of this equipment can result in an incorrect operation or false trip.**

IEEE 1613-2003, Standard Environmental and Testing Requirements for Communications Networking Devices in Electric Power Substations, initially approved and published in 2003 and updated in 2009, specifies service conditions, ratings, and environmental performance and testing requirements for communications devices used in the harsh substation environment.

In this paper, we describe specific requirements of IEEE 1613 along with illustrations of test equipment and fixtures. We provide testing pictures to illustrate testing methods that ensure communications equipment meets these requirements and provides error-free performance. We provide testing results and correlate successful margin testing with observed field reliability.

I. Introduction

A. The Development of IEEE 1613

Prior to 2003, some utilities installed commercial-grade Ethernet devices (hubs and switches) in substations. These devices were designed for a more benign office environment, so it was not a surprise that operators experienced intermittent failures. In 2003, IEEE Power Engineering Society (PES) members began work to address the need for a design requirements standard for communications equipment.

A working group (C2) in the Substation Committee developed a standard (IEEE 1613 [1]) for communications networking devices (not just Ethernet), modeled primarily after four IEEE standards developed by the Power System Relaying Committee (PSRC): IEEE C37.90, IEEE C37.90.1, IEEE C37.90.2, and IEEE C37.90.3. Sections of these standards are found verbatim in IEEE 1613; thus, this paper references IEEE 1613 almost exclusively, rather than these individual standards.

1) Environmental Requirements

Because IEEE 1613 devices would be used in protective relaying applications, they would need the same environmental requirements listed in IEEE C37.90-2005, Standard for Relays and Relay Systems Associated With Electric Power Apparatus [2]. These include temperature, humidity, and input voltage ratings; contact make, carry, and interrupt ratings; dielectric withstand; and factory impulse voltage testing. IEEE 1613 also includes a requirement that fans or any other types of forced air movement are not allowed in devices that meet IEEE 1613.

2) Oscillatory and Fast Transient Tests

In the early 1970s, there were a number of false operations and solid-state relay failures in extra-high-voltage (EHV) substations. These often occurred not during fault conditions, but rather when the EHV air disconnect switches were opened. Because these switch contacts opened relatively slowly, there were repeated restrikes across the opening contacts until sufficient dielectric strength built up and the restrikes ended. These restrikes repeatedly energized an L-C circuit (comprised of the buswork inductance and the capacitance to ground of the bus, the transformer and circuit breaker bushings, the voltage transformers (VTs) or capacitive coupling voltage transformers (CCVTs), and the current transformers (CTs) connected to that bus section) and thus induced an oscillation at that L-C circuit's natural frequency. Field measurements showed it ranged from 300 kHz to 1.5 MHz. The electromagnetic field (emf) created by that oscillation was coupled to the VT, CT, and control circuit cabling (which was usually parallel to, and often essentially under, the EHV buswork). The induced voltage from this emf coupling caused incidents of solid-state relay misoperation and failure. The oscillatory surge withstand capability (SWC) test was designed to replicate the field condition of a damped cosine wave that occurs in bursts (see Fig. 1). It first became an IEEE standard in IEEE C37.90a in 1974 (now IEEE C37.90.1-2002, Surge Withstand Capability (SWC) Tests for Relays and Relay Systems Associated With Electric Power Apparatus [3]). The comparable IEC test waveform has a shorter duration and lower total energy.

During the next few years, there were instances of relays that had passed the oscillatory SWC test that occasionally misoperated or were damaged by transients originating in the dc control circuits. Detailed research showed that these transients had an extremely fast rise time and short duration (typically a 5 kV peak, 10 ns initial rise, and 50 to 100 ns total duration). The fast transient SWC test was designed to replicate these transients (see Fig. 2). It was added to IEEE C37.90.1 in 1978.

IEEE C37.90.1 includes both the oscillatory and fast transient SWC tests. Relays are required to be energized during the transient tests with rated voltage and current equal to 75 percent of nominal rating. This is intended to simulate relay operating conditions close to a transition state when the transient is applied.

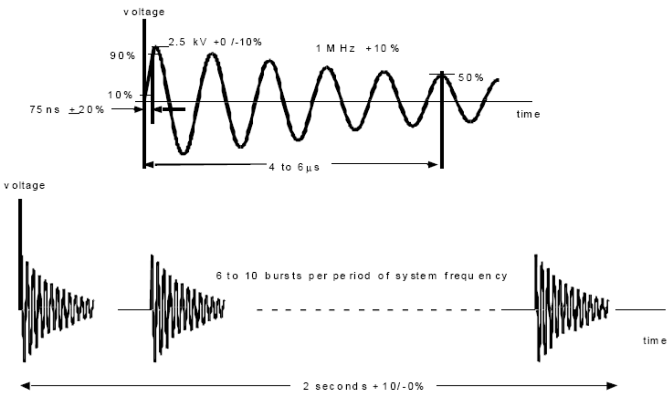

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Fig. 1. Oscillatory SWC Test Parameters and Waveform

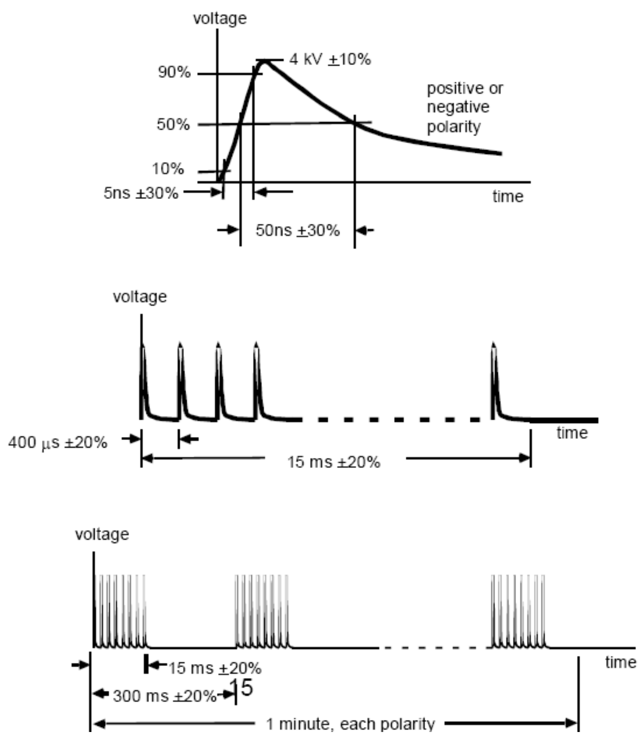

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Fig. 2. Fast Transient SWC Test Parameters and Waveform

3) False Trips From Walkie-Talkie Radios

Another hazard to the proper operation of protective relays in the substation environment is the common handheld transceiver. In the early 1970s, 5 W transceivers were known to have caused relay misoperations. This led to the development of IEEE C37.90.2-2004, Withstand Capability of Relay Systems to Radiated Electromagnetic Interference From Transceivers [4]. Its test includes the same requirements as IEEE C37.90.1; i.e., the relay must be energized with prescribed currents and voltages during the radio frequency (RF) tests. Because the RF field strength varies as the inverse square of the distance between the antenna and the test object, IEEE C37.90.2 needed to define the equivalent separation distance for a 5 W transceiver's antenna during the tests. Table I shows the relationship for 5 W, 150 MHz and 450 MHz transceivers.

TABLE I
RF FIELD STRENGTH VS SEPARATION DISTANCE TESTING DATA

Distance (cm)	Field Strength (V/m)
7.5	100
10	60
15	35
22	20
100	5

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The IEC Standard 60255-22-3, Electrical Relays [5] adopted 10 V/m as the requirement. However, based on field experience, the 1995 working group for IEEE C37.90.2 determined that immunity to a field strength of 10 V/m was inadequate and adopted a 35 V/m requirement (corresponding to a separation of 15 cm). In 1995, IEEE C37.90.2 was approved with this 35 V/m field strength requirement. This is still the requirement today. The IEC standard still only requires 10 V/m [5].

4) Static Electric Discharges

The fourth IEEE standard of interest is IEEE C37.90.3-2001, Electrostatic Discharge (ESD) Tests for Protective Relays [6]. This standard was developed in response to another threat to relays—the electrostatic discharge from a human to a relay. The following from [1] is taken from the Informative Annex to IEEE C37.90.3:

> *"Electrostatic charges are easily generated in an environment with dry atmosphere and synthetic fabrics [or dissimilar materials]…The effect of discharge from the operator may be a malfunction of the equipment or damage of electronic components."*

IEEE C37.90.3 requires testing at 8 kV to 15 kV because many installations in North America have relative humidity less than 50 percent. The comparable IEC standard (IEC Standard 61000-4-2, Electromagnetic Compatibility [7]) only requires testing in the 4 kV to 8 kV range, presuming that the humidity will never be less than 50 percent near the relay.

5) Operational Immunity Note

It is important to note that the tests specified in the PSRC standards IEEE C37.90.1 (SWC), IEEE C37.90.2 (RF), and IEEE C37.90.3 (ESD) are not simple bench tests to see if any damage occurs. They are operational immunity tests to determine immunity to false operation when these transients are applied. During these tests, the relays are operational. They are energized with rated voltage, and the current is very close to the set point.

B. Additional Requirements for Communications Equipment

IEEE 1613 was built on these four PSRC standards. The requirements of IEEE C37.90 were incorporated into IEEE 1613 without changes. The requirements in the other three PSRC standards were added along with acceptance criteria (defined in Section III of this paper) and a description of the communications that shall take place during these design tests while the transients are applied.

IEEE 1613 defines two performance classes. Performance Class 1 "is for communications devices used for general-purpose substation communications where temporary loss of communications and/or communication errors can be tolerated during the occurrence of [SWC, RF, or ESD] transients." Performance Class 2 "is for communication devices used for substation communications where it is desired to have error-free, uninterrupted communications during the occurrence of [those three] transients."

IEEE 1613 also defines two communications categories. For serial devices (equipment without a specified range of frame sizes), the conditions in Table II apply.

TABLE II
PROFILE CONDITIONS FOR SERIAL DEVICES

Profile	Bit Rate	Comments
1	0	Idle conditions (no communications)
2	30% of Max	Simulate lower bandwidth communications
3	Max	Simulate higher bandwidth communications

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For equipment with specified ranges of frame sizes (Ethernet), the conditions in Table III apply.

TABLE III
PROFILE CONDITIONS FOR ETHERNET DEVICES

Profile	Bit Rate	Frame Size	Frame Rate	Comments
1	0	0	0	Idle conditions (no communications)
2	Max	Max	30	Simulate typical loading
3	Max	Max	90	Simulate heavy loading

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II. TEST PARAMETERS AND TESTING

Manufacturers perform equipment type (design) tests prior to initial product release or prior to changes in design, but not on every device manufactured. Many large power utilities in the past had the equipment and facilities required to perform these type tests and used this capability to verify product compliance. Over time, utilities with these test and verification capabilities have become very rare. This is due in part to a lack of the testing equipment. In addition, many consumers of compliant products may not have had an opportunity to study or understand the test requirements; and, although the standards development groups intend to create clear, concise documents, there are sometimes differences in interpretation, as with many such documents. Today, most users of products that comply with IEEE 1613 have never witnessed or run this product-compliance testing. Utilities specify that compliance to the standard is required; however, over time, the understanding of why or how we test is slowly being lost. Compliance to IEEE standards is voluntary; therefore, unlike UL or FCC compliance, there are no mandatory third-party compliance authorities. In this industry we rely on trust between the manufacturer and user. IEEE 1613 includes many figures to describe the testing. In this section we highlight specific requirements and include pictures of the actual test setup and equipment for comparison and perspective.

A. Temperature and Humidity

IEEE 1613 calls out several classes of operational temperature range. They are as follows:

- –40° to +70°C.
- –30° to +65°C.
- –20° to +55°C (the default range if no other range is specified).
- Range defined by the manufacturer.

These temperature ranges are specified for altitudes of 1500 m or less with a derating factor for higher altitudes.

Testing for compliance to IEEE 1613 includes temperature soaking at the extremes with the equipment unpowered to ensure hot and cold start capabilities. A 96-hour humidity test cycle is included as well. The humidity extreme is 95 percent noncondensing. The temperature and humidity cycles are performed in specialized environmental test chambers, such as the one shown in Fig. 3.

IEEE 1613 prohibits the use of fans to achieve specified temperature performance because fans are limited life components whose failures would result in premature communications equipment failure.

Fig. 3. Typical Environmental Test Chamber

B. Dielectric Withstand and Impulse

The purpose of this test is to prove that the insulation of the device is sufficient to meet the specified ratings. This is the only test in the standard that is specified as both a type and production test. This is also the only nonoperational test in the standard. A successful test results in no flashover or component damage. Although this test is performed on nonenergized devices, the equipment is required to work as specified after testing. Typical dielectric test values are 500 and 2000 Vrms.

In addition to the dielectric tests, IEEE 1613 requires impulse tests, which are intended to test the ability of the equipment to withstand overvoltages and electrical stress without damage. This stress is a very high voltage (5 kV) with a very short duration (50 μs), as shown in Fig. 4. This test is considered a type test.

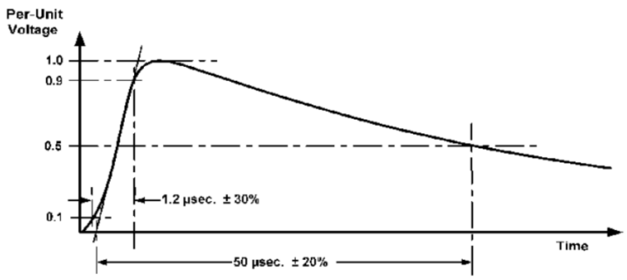

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Fig. 4. Impulse Waveform Specified in IEEE 1613

C. Surge Withstand Capability

These are considered immunity tests. They differ from the dielectric tests because they are run on devices that are operating. A successful test is one in which the equipment is operational before, during, and after the test voltage is applied. In addition, there are two acceptance classes (Class 1 and Class 2). Class 1 allows disruption of communications during the application of the test surge voltage, but if disrupted, it requires that communications automatically restore after the test without human intervention. Class 2 states that communications are not disrupted during the application of the test surge voltage. Fig. 1 shows the oscillatory waveform, and Fig. 2 shows the fast transient waveform.

To ensure repeatability, IEEE 1613 specifies that these tests be performed over a reference ground plane. Fig. 5 illustrates the construction. Because these tests are performed on live equipment, care must be taken to isolate the test equipment from the transient voltage. In Fig. 5, a coupling/decoupling device is shown between the generator and the equipment under test. Not shown are the isolating reactors and coupling capacitors required to isolate the equipment not intended to be tested.

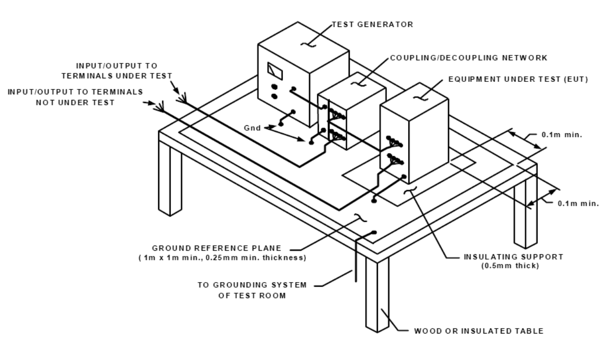

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Fig. 5. Reference Ground Plane

In addition to direct coupling of the transient waveform to the equipment terminals, capacitive coupling is allowed for circuits that are normally shielded or require galvanic isolation. These are limited by the standard to data communications and signal circuits.

Fig. 6 describes the coupling clamp design. Fig. 7 is a picture of a commercially available coupling clamp made specifically for this test.

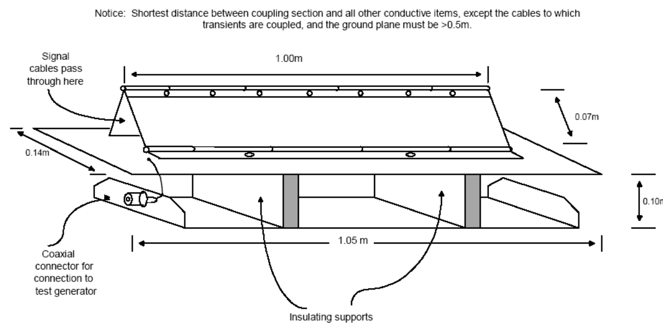

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Fig. 6. Surge Withstand Capacitive Coupling Clamp

Fig. 7. Commercially Available Capacitive Coupling Clamp

Isolating the test and verification equipment can be challenging. In Fig. 8, a commercially available Ethernet switch is being tested. In this setup, the Ethernet switch under test is at one end of the coupling clamp with the Ethernet cables passing through the clamp. These cables then pass through two large ferrite chokes to attenuate the effects of the transient on the downstream equipment. Two battery-powered media converters further isolate the Ethernet test equipment. The connection between the test set and the equipment under test is a pair of fiber-optic cables. This setup ensures complete isolation of the equipment under test from the test and measurement equipment. The blocks of wood keep the cabling 0.1 m above the ground plane, as specified in the standard.

Only a few manufacturers of waveform generators provide a compliant signal. The test generator used here is designed to automatically run both the IEEE and IEC fast transient waveforms. A different generator runs the oscillatory test.

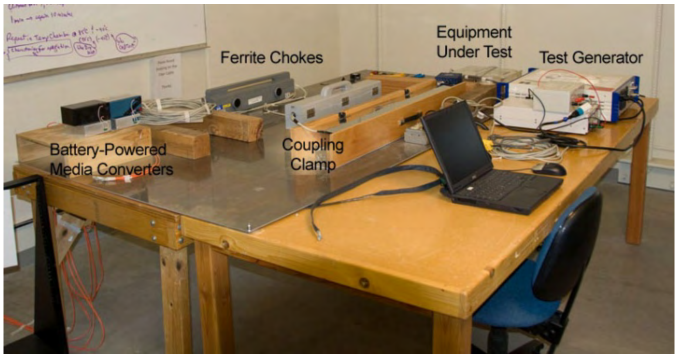

Fig. 8. Typical Fast Transient Test Setup

D. Radio Frequency Susceptibility

As stated in Section I of this paper, the RF susceptibility test has evolved from the need to prevent equipment misoperations due to RF signals from common transceivers such as the 5 W handheld radio. Also from Section I, the 35 V/m is derived from the signal strength 15 cm away from the antenna of a 5 W transceiver.

Fig. 9 shows an example test setup. Based on the dimensions given, it would appear relatively easy to perform the susceptibility test; however, near field effects can make it difficult to use this setup. The intent of the specification is to expose the front and rear surfaces to the RF energy as different test conditions.

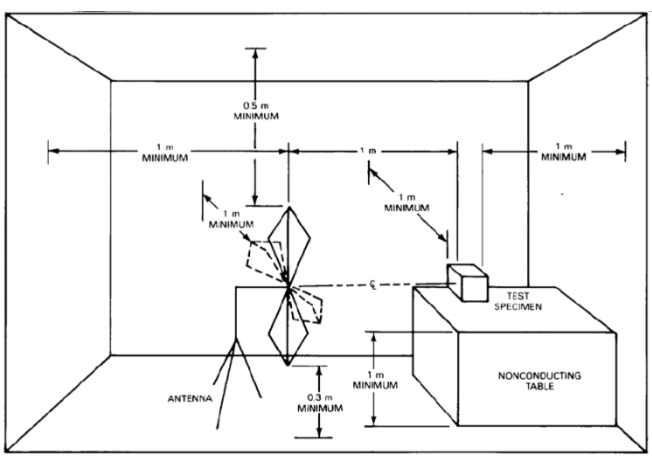

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Fig. 9. RF Susceptibility Test Setup

This test consists of three different exposure conditions:

1. Frequency sweep from 80 to 1000 MHz.
2. Keying test from 80 to 1000 MHz.
3. Spot frequency test from 80 to 900 MHz.

The frequency sweep test, as the name implies, sweeps through the stated frequency range with the signal 80 percent modulated with a 1 kHz sine wave.

The keying test turns the transmitter on and off during the test sweep to simulate a handheld radio being keyed up (push to talk).

The spot frequency test is used to test known frequencies that are commonly used by handheld devices. Table IV lists the frequencies required by IEEE 1613.

TABLE IV
SPOT FREQUENCY TEST REQUIREMENTS

Test	Spot Frequency MHz	Tolerance	Amplitude Modulation	Duty Cycle
1	80	±0.5%	80%	100%
2	160	±0.5%	80%	100%
3	450	±0.5%	80%	100%
4	900	±5 MHz	80%	100%
5	900	±5 MHz	Pulse*	50%

* Keying frequency of 200 Hz

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Equipment users may have additional frequencies that are of concern. Testing these can be done per separate agreement. In Test 5 of Table IV, the unmodulated signal is repeatedly switched on for 2.5 ms and off for 2.5 ms. This is a pulse-modulated signal with 200 Hz to simulate the use of portable digital telephones.

An anechoic chamber is preferred for this test, such as the one shown in Fig. 10. In this environment, it is important that the only metallic object above the ground plane be the equipment under test. Blue foam peaks in the shape of pyramids absorb the RF signals that are not directed at the equipment under test. Ferrite material covers the walls of the chamber, which helps prevent the RF signals from reflecting off the walls and thus exposing more than one surface at a time to the test signal. The white panels are there only to reflect light because the black ferrite material creates a dark environment.

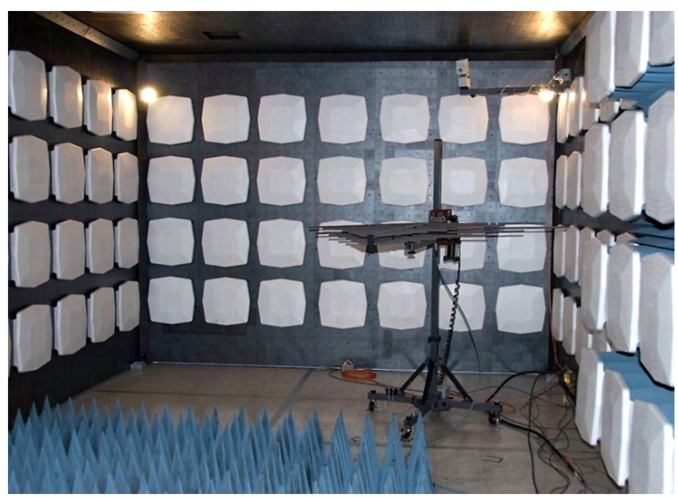

Fig. 10. Anechoic Testing Chamber

The antenna shown in Fig. 10 is a linearly polarized antenna. Other allowed antennas are biconical (as illustrated in Fig. 9) and conical logarithmic spiral. The test is run with the antenna in horizontal polarization and then again with vertical polarization. The antenna stand is made of nonconductive material and has an air actuator to change the antenna polarization automatically. Notice the camera mounted on the roof of the chamber behind the antenna (Fig. 10). This allows the test operator to observe the equipment during the test. Fig. 11 and Fig. 12 show the amplifiers and frequency generators required to run the test.

Fig. 11. High-Power Amplifier

Fig. 12. Frequency Generators

E. Electrostatic Discharge

ESD is one of the most recent tests added to the IEEE C37 series. With modern electronic equipment, care must be taken in the design to protect the equipment from an ESD event. Personnel working on or with electronic equipment should note the ESD warnings in the instruction manuals and warning labels on the equipment and also be aware of grounding and wrist strap requirements while working on or with exposed circuit boards. ESD events are not a problem for electromechanical equipment.

This ESD test is intended to prove that the equipment will not misoperate or be damaged during the event. Significant ESD stress may induce immediate component failure or it may be latent, where component damage may occur but not become a hard failure until months or years later.

From [1], the test states that:

> *"The points selected for the application of the test shall be those which are accessible under normal in-service conditions. Test points shall include case, knobs, pushbuttons, switches, terminals, data ports, keypads, target resets, etc. The application of discharge to any point of the equipment which is accessed only for repair and maintenance purposes is outside the scope of this standard.*
>
> *Examples:*
>
> *a) Terminals normally wired at installation;*
> *b) Setting adjustments that are not accessed during normal service conditions."*

Fig. 13 shows an example of an air discharge to an open communications port.

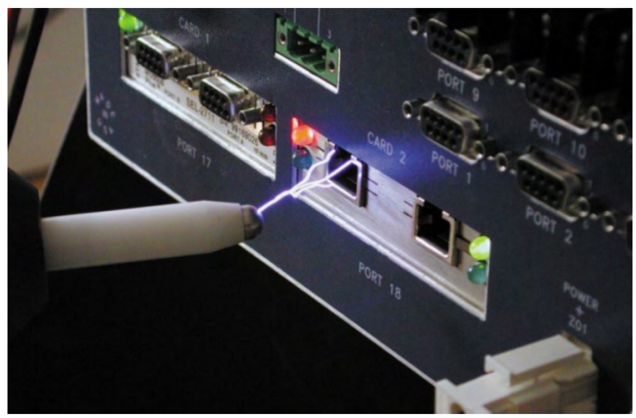

Fig. 13. Air Discharge ESD Event

III. Test Results and Interpretation

A. Test Results and Acceptance Criteria

IEEE 1613 states that the following are required test results for SWC, RF, and ESD [1].

a) No hardware damage occurs.
b) No loss or corruption of stored memory or data, including active or stored settings, occurs.
c) Device resets do not occur, and manual resetting is not required.
d) No changes in the states of the electrical, mechanical, or communication status outputs occur. These outputs include alarms, status outputs, or targets.
e) No erroneous, permanent change of state of the visual, audio, or message outputs results. Momentary changes of these outputs during the tests are permitted.
f) No error outside normal tolerances of the data communication signals (e.g., SCADA analogs) occurs.

B. *Additional Conditions*

For devices claiming compliance to Class 1, these additional conditions are to be met:

"Established communications [as defined]…may be disrupted or sustain errors during the period the [SWC, RF, ESD] tests are applied. If disrupted, the communications recovers within the manufacturer's specified time period."

For devices claiming compliance to Class 2, these additional conditions are to be met:

"Established communications [as defined]…shall NOT be disrupted or sustain errors during the period the [SWC, RF, ESD] tests are applied."

A final Equipment Functioning requirement must be met for each test set: "During and after the tests, the equipment shall be completely and accurately functional as designed, unless otherwise stated by the manufacturer, for the equipment to be considered as having passed the [SWC, RF, ESD] tests."

IV. How Testing to Standards Impacts Product Reliability

A. *Testing and Failure Models*

Testing to standards such as IEEE 1613 is part of engineering the product hardware. Such testing verifies that products operate reliably in harsh locations, including the environmental extremes of temperature, humidity, and emf transients. Other industries such as automotive and aerospace have embraced testing to recognized standards to ensure product robustness. They find that fewer "No Problem Found" failures occur on products made robust to environmental conditions.

The testing can also give the product designer feedback for future design enhancements for more product robustness. The more designers understand where and why products fail, the more robust future products will become.

To better understand the positive reliability performance impact of standards testing, it is helpful to understand why products fail in field use. The following is summarized from [8] and lists various reasons for product failures:

1. Product design may be inherently incapable of meeting specified requirements.
2. Item may be overstressed. If the applied stress (also called load) exceeds the strength, then failure will occur. An electronic component will fail if the applied stress (for example, voltage or current) exceeds the ability to withstand that stress.
3. Variation of component strength or load. If the known strength always exceeds load, as shown in Fig. 14, failure will not occur. Generally, there will be some uncertainty (distribution of component strength and load) as in Fig. 15. Failure will not occur as long as the load distribution does not exceed the strength. However, if there is an overlap in the tails of the distributions, as in Fig. 16, and a load value in the high tail of the load distribution is applied to an item in the weak tail of the strength distribution, then failure will occur.
4. Wear out failures may occur when an item, which was sufficiently strong at the start of its service life, becomes weaker with age. Fig. 17 illustrates this situation.
5. Errors in design, assembly, test, or application can also cause failures.

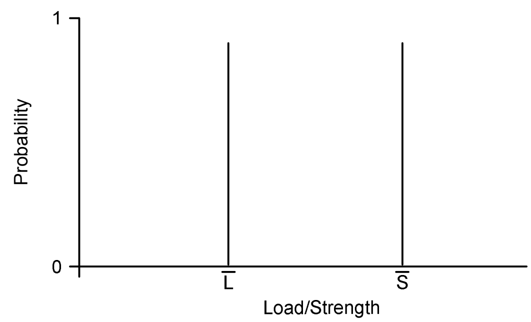

Fig. 14. Load/Strength—Discrete Values

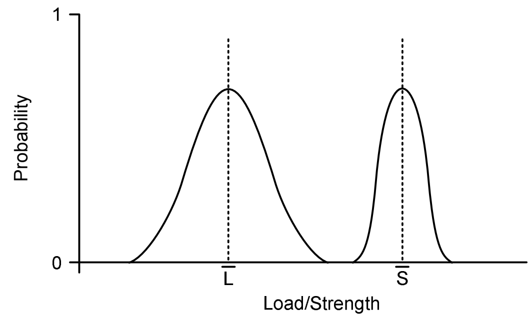

Fig. 15. Load/Strength—Distributed Values

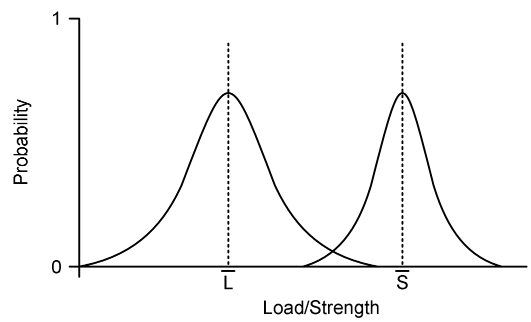

Fig. 16. Load/Strength—Interfering Distributions

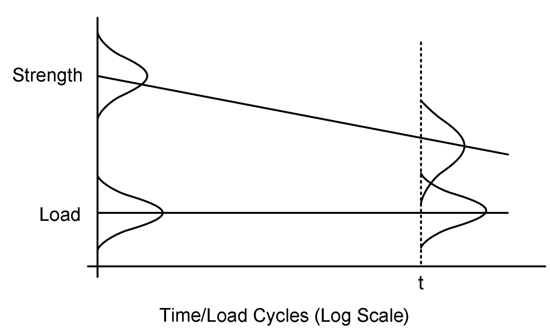

Fig. 17. Time-Dependent Load and Strength Variation

B. *Testing Beyond Standards Improves Reliability Results*

Industry best practices are for product designers to test beyond the published standard limits to ensure that, even with production variation, all products meet the standard test requirements. This practice is called margin testing. Designers reduce the chance of field failures by making the product robust to those higher test levels, typically 10 to 50 percent beyond the standard test requirements. Designing beyond the standard requirements increases the separation between the mean of the strength distribution and the mean of the load distribution and lessens the probability of failure due to degradation of strength or extreme variation of load. An illustration of margin testing is shown in Fig. 18. In this example, if we extend our test stress from T_1 to T_2, then the result is that the strength distribution moves up from S to S’ with respect to the load. The practice of margin testing accrues benefit when you find a failure mode and change the design to provide operation well beyond that failure level.

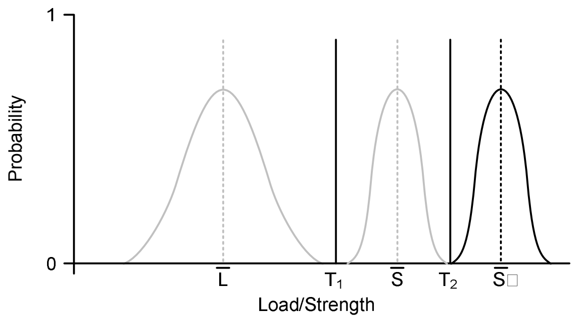

Fig. 18. Effects of Margin Testing

How much do testing to standards, margin testing, and design robustness affect field reliability? We have observed, in a field population of over 50,000 communications devices, a failure rate of 0.1 to 0.2 percent per year, with very few No Problem Found instances. These observed failure rates are approximately an order of magnitude lower than published field reliability figures for communications equipment not known to be tested at the higher margin level.

V. Conclusion

Field experience gained by applying communications devices in substations has taught us that the substation environment is not benign. Utility industry representatives to standards bodies have captured those lessons learned as test requirements in standards such as IEEE 1613. These standards, when properly applied to the communications devices in design and validated by testing, ensure product robustness in the application environment.

Understanding the IEEE 1613 standard and its origins will help users select the correct product for the intended application.

VI. References

[1] IEEE Standard 1613-2003, IEEE Standard Environmental and Testing Requirements for Communications Networking Devices in Electric Power Substations, 2003.

[2] IEEE Standard C37.90-2005, IEEE Standard for Relays and Relay Systems Associated With Electric Power Apparatus, 2006.

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VII. Biographies

John T. Tengdin was born in South Bend, Indiana. He graduated from Purdue University, West Lafayette, Indiana, in 1949 with a BSEE degree. His employment experience includes Dayton Power and Light Company, General Electric Company, Honeywell Information Systems, and the Tech Division of American Diversified Bank. He began work as an independent consultant in 1986, and formed OPUS Consulting Group as a two-man partnership specializing in substation automation and cybersecurity in 1999. He has received numerous awards from the PES Substations Committee and the PES Power System Relaying Committee for his work on technical papers and standards, and from the IEEE SA for rapid standard development. He chaired the PES Substations Working Group C2 that created IEEE 1613 and is Vice Chair of the 2008-2009 update working group. His 2007 Fellow citation was “for leadership in Ethernet local area network-based protective relaying and control in electric power substations.”

Ronald A. Schwartz earned a Bachelor of Electrical Engineering from Ohio State University in 1968 and a Master of Science in Electrical Engineering from the University of Maryland in 1970. He has served in the Oregon Quality Award Program as Senior Examiner. In addition, Schwartz has served on the board of directors for Schweitzer Engineering Laboratories, Inc. (SEL) since February 1994. He founded and served as principal for International Quality Associates, Inc. of Beaverton, Oregon, a consulting and training firm helping companies develop and implement effective management systems. Prior to founding International Quality Associates, Schwartz was employed for eight years by Sequent Computer Systems, also of Beaverton, as Component Engineering Manager as well as a Reliability Engineer. At SEL since October 1998, Schwartz has served as Senior Vice President of Quality.

Ken Fodero is currently an R&D manager for the time and communications product lines at Schweitzer Engineering Laboratories, Inc. in Pullman, Washington. Before coming to SEL, he was a product manager at Pulsar Technology for four years in Coral Springs, Florida. Prior to Pulsar Technology, Ken worked at RFL Electronics for 15 years, and his last position there was Director of Product Planning.

20120501 • TP6349-01