Sensing and Characterization of EMI During Intermittent Connector Anomalies

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Abstract—**This paper presents a new on-line methodology for detecting intermittent disconnection failures. The detection principle operates on the fundamental Lorentz Law that states that sudden changes in flux create a large voltage, resulting in an arc. This arc propagates as a traveling wave through the circuit until all the energy associated with it is dissipated. It is possible to detect that traveling wave as an indication of an intermittent disconnection failure. A test bench was implemented to test and validate the theory. Preliminary results presented in this paper show the feasibility of detecting disconnection failures and the possibility of locating the failing connector based on distance.**

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1. INTRODUCTION

As "more electrical" technologies become prevalent in aerospace systems[1], the need to develop innovative monitoring, diagnostic, and fault tolerant techniques for electrical systems is becoming more important. One of the most common and critical failures in electrical systems is the intermittent disconnection in connectors [2]. Despite the extreme care in the design and quality control in manufacturing and installation of these connectors in avionics and military equipment, there is an increasing number of problems associated with the physical connectivity that ranges from intermittent discontinuities, sparks, and loss of controllability due to their increasing use. Also of interest, from the diagnostic perspective, is the determination of approximate location of the faulty connector or identification of a malfunctioning component within the power system. Exploring a non-traditional use of differential current sensors, this paper studies the feasibility of detection of intermittent disconnection problems. These intermittent discontinuities, which generate arcing because of the inductive nature of the circuit, result in a traveling electromagnetic wave and electromagnetic interference (EMI). A differential current sensor is evaluated to capture the imbalance caused by the traveling wave or electromagnetic induction. This paper studies online monitoring of the critical problems of intermittent disconnection in aircraft power systems using an actuator connector test bed. This novel sensing application has a potential to improve the safety margins for civilian aviation and enable greater utilization of new electrical systems for flight critical applications - such as power delivery and control surface actuation. This application can also be integrated with prognostic and health management system that are based on condition monitoring and system health assessment paradigms. The test bench system includes military standard connector with the capability of disconnecting the connector at varying speeds to generate the arc resulting in a signal imbalance. When the connector is connected properly, the current would flow in the DC bus and return resulting in zero leakage current. However, if the connection is suddenly disturbed, an arc will be produced based on the Lorentz Law. The traveling arc wave will propagate through the wires and the measured leakage current will no longer be zero indicating the detection of an arc anomaly in the electrical system. The main stress factors that a connector is subject to are discussed in this work, including the two main ones: vibration and differences in thermal expansion of the contact materials. The paper provides a brief theoretical introduction to arc generation and propagation. Next the paper describes the experimental test bench system along and shows the experimental results for detecting intermittent disconnection.

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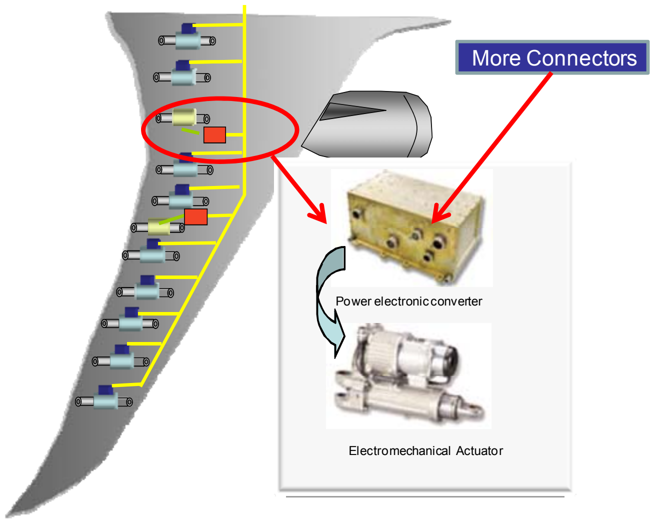

Figure 1 - "More electrical aircraft" with more connectors significantly increasing possible failures

2. INTRODUCTION TO THE ARC GENERATION AND DETECTION PRINCIPLE

Failure Mechanism

The percentile distribution of failure modes associated with connectors is shown in Table 1. It is clear that most failures are either open contact points or intermittent connections.

Table 1 - Connector Failure Modes

Failure Mode	Failure Mode Probability
Open	61%
Poor contact	23%
Short	16%

The dominant stress factors in a well-designed connector are due to the phenomenon occurring at the contact's interface. The two main stress factors, as shown in Figure 2, are vibration and differences in thermal expansion of the contact materials. Other physical factors contribute to the stresses, such as temperature, air pressure, and humidity.

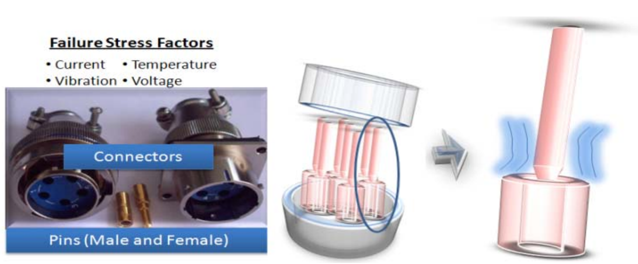

Figure 2 - Failure stress factors in connectors

When a connector pin is exposed to the combined stress of thermal cycling and vibration, it deteriorates until a contact void is created, resulting in decrease of capabilities, as shown in Figure 3.

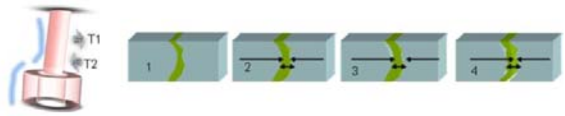

Figure 3 - Process of connection failures induced from thermal cycling

One of the most common anomalies in electrical systems is generated from bad or loose connections between cables, connectors, and components. This type of problem is difficult to detect because of its intermittent nature. The increasing number of cables and connections in the next generation systems (such as aircraft, ships, and automobiles) pose a significant challenge to detect and mitigate the problems associated with loose connection and solutions are highly desirable for innovative sensing capabilities that will lead to better design and operation of electrical power systems.

Arc Generation Theory

The focus of the work presented in this paper is on the events of interruption of current due to, for example, sudden disconnection of connectors in an inductive circuit. Lorentz Law states that sudden changes in trap flux create a large voltage resulting in the production of an arc, which is characterized as a travelling wave, and an RF emission (EMI) that propagates through the system until it is dissipated due to losses in the circuit. When the perturbation reaches the end of the line, it may bounce back, creating an imbalance in the current that can be detected with a sensing device. According to the Lorentz Law (shown in Equation (1)) an instantaneous change in the current, signified by a small Δt, would lead to a change in the magnetic flux, resulting in generation of a large voltage.

$$V = -\frac{\partial \lambda}{\partial t} = -L\frac{\partial I(t)}{\partial t} \quad (1)$$

where:
V is the voltage
λ is the magnetic flux
t is the time
L is the inductance

An arc is conventionally defined in industry as "an unintentional electrical discharge" due to bad cables and loose connections. As a connector disconnection occurs intermittently, the instantaneous conduction loss results in a large voltage at the terminals which gets manifested as an arc across the terminals where the connection is broken. Since arcs are generated through intermittent loss of connection, the signature that is observed in the current is similar to that of an impulse.
This phenomenon of arc impulse propagation in the system can be modeled similar to a wave propagation phenomenon studied in transmission lines. Equations (2) and (3) (please see [4]) describe the current and voltage propagation

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through the system's transmission lines in terms of the circuit quantities. ℓ represents the inductance per unit length (Henry/meter) and ς represents the capacitance per unit length (Farad/meter). These constants are the characteristic values of the transmission lines of an electrical system and can be evaluated based on the material properties of the cables and the load.

$$\frac{\partial V}{\partial z} = -\ell \frac{\partial I}{\partial t} \tag{2}$$

$$\frac{\partial I}{\partial z} = -\varsigma \frac{\partial V}{\partial t} \tag{3}$$

Using the relationship described in the partial differential equations above and solving for the voltage and current propagating along the +z and –z directions, Equations (4) and (5) are derived [4]. It should be noted that z represents the transmission direction along which the waves propagate. The functions *f* and *g* represent the traveling waves in the +z and –z directions and $Z_0 = \ell / \varsigma$ is the characteristic impedance of the transmission line.

$$V(z,t) = Af\left(t - \frac{z}{vp}\right) + Bg\left(t + \frac{z}{vp}\right) \tag{4}$$

$$I(z,t) = \frac{1}{Zo}\left[Af\left(t - \frac{z}{vp}\right) + Bg\left(t + \frac{z}{vp}\right)\right] \tag{5}$$

where:
t is the time
A,B are the constants
f, g are functions representing traveling waves in the +z and –z directions
vp is the velocity of propagation
Z_o is the characteristic impedance of the transmission line

Based on Maxwell's electromagnetic wave propagation, Figure 4 shows the orthogonal interaction of the electric and magnetic fields as the wave propagates in a certain direction. A sudden change in the flow of current due to an electrical disconnection will generate an arc traveling wave which will perturb the electromagnetic wave propagation compared to normal conditions and this perturbation can be detected.

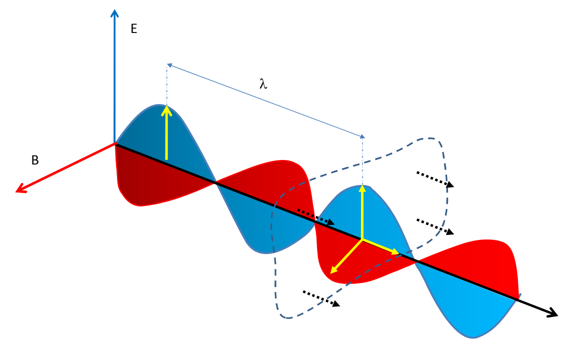

Figure 4 - Electromagnetic wave propagation

Accounting for energy conservation, the energy associated with the disconnection is radiated around the cable. To illustrate this concept the energy irradi ated in a dipole is shown in Figure 5.

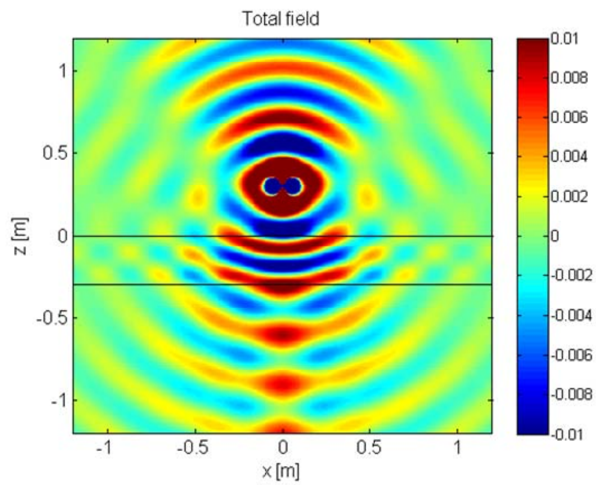

Figure 5 - Dipole electromagnetic irradiation

The traveling wave produced by the arc impulse creates an imbalance in the system creating an opportunity for a high sensitivity wide-band differential sensor to capture the anomalous behavior. It should be noted that the current sensor implemented in a differential configuration normally captures the leakage current which for the normal conditions should be zero (or very close to it). Figure 6 shows the configuration for detecting the arc traveling wave in an experimental setup. As it can be seen from the configuration, if the switch, representing the connection, is closed the current would flow in the DC bus and return resulting in zero leakage current. However, if the connection is suddenly disturbed, an arc will be produced based on the Lorentz Law, described earlier. The traveling arc wave will propagate through the DC bus and the measured leakage current will no longer be zero, indicating the detection of an arc anomaly in the electrical system. This configuration can be scaled up and implemented throughout the electrical system of aircraft and other vehicles.

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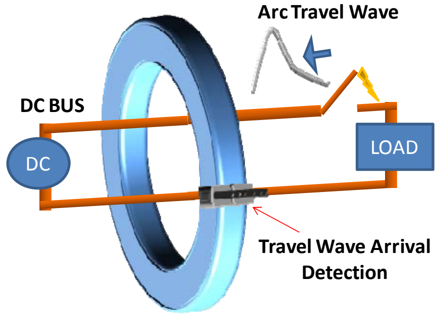

Figure 6 - Arc anomaly detection experimental configuration

3. TEST BENCH

General Description

The connector test bed is intended to simulate the intermittent disconnection that often results from improper connector locking during maintenance procedures or pin/receptacle failures due to contact loss. The test bench is designed to continue operating, in this case an actuator operation, until a set position is achieved, even with a seeded intermittent disconnection. The control system block diagram regulating the test bench is shown in Figure 7.

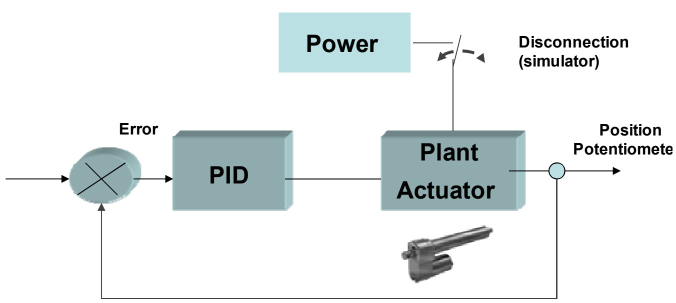

Figure 7 - Connector Test Bench Control System Block Diagram

The connector test bench includes the following elements:

- DC plant actuator as load
- MIL-STD electrical connector
- Controllable speed disconnection mechanisms up to 20Hz
- Varying lengths of cable for exploring 'localization' of disconnection up to 500 ft
- The possibility of using variable loads

A diagram of test bench shown in Figure 8 shows the elements listed above in a hardware-in-the-loop (HITL) configuration that was implemented for testing and evaluation of the arc detection techniques.

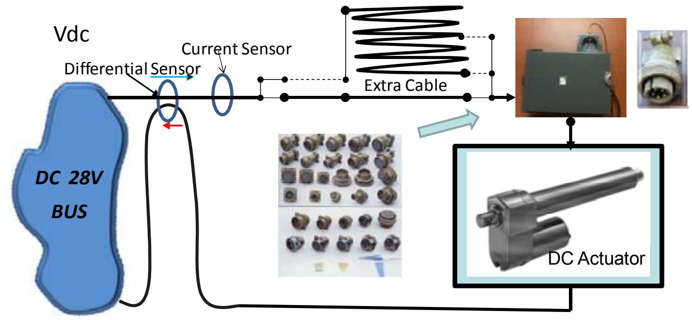

Figure 8: Illustration power drive test system

Connector Selection

There was a wide range of connectors that provided a representative sample for the connector test bench. Due to easy availability and low cost, a used 5-pin MIL-DTL-5015 series connector that consists of a receptacle (P/N CA3102E-14S-5S) and plug (P/N CA3106E-14S-5P-A95) was selected. The connector is shown in Figure 9.

Figure 9 - Several Power MIL Spec Connectors (left) and the Selected MIL-DTL-5015 Connector (right)

Connector Test Bench Actuator Selection

The actuator selected for this work was a low cost, 24 V DC permanent magnet motor operated by a 28 V DC power source. The actuator included a 10 kΩ potentiometer for position feedback. The MIL-DTL-5015 series five pin connector was adapted to the actuator with two pins for power and three pins for the position potentiometer (Figure 10).

Figure 10 - Selected Actuator and Connector

Test Bench Disconnection Mechanisms

The failing connector was simulated with a forced connection and disconnection mechanism at variable speeds of up to 20 Hz. Figure 11 shows the progression of the connection and disconnection of the entire connector with the receptacle. It should be noted that with this configuration the actuator continued operating because the connection was restored very quickly.

Figure 11 - Connector disconnection progression

Connector Test Bench Implementation

The actual test bench implemented is shown in Figure 12. Along with the components described in the previous sub-sections, the test bench included an instrumentation board to measure the relevant current and voltage signals. The measurement allowed high-speed data acquisition capability for up to three current and three voltage signals. The current sensors on the measurement board were configured to support differential current sensing as well.

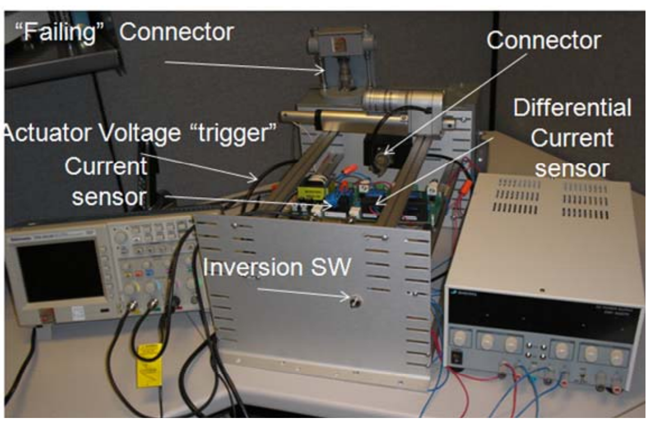

Figure 12 - Actual Connector Test Bench

Sensor and Conditioning Hardware

The differential current sensor was implemented using an in-house signal conditioning board based on a Hall Effect current sensor and a wideband low cost sensor, as shown in Figure 13.

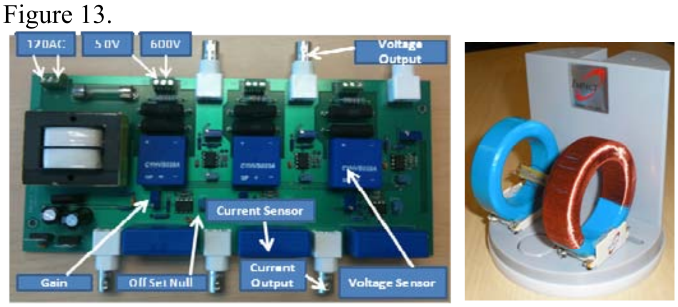

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Figure 13 - Signal Conditioning Board and Impact's Differential Current Sensor

4. EXPERIMENTAL RESULTS

Tests were conducted using the test bench where the disconnection mechanism was engaged to simulate connector failures. The disconnection mechanism was designed to ensure that the loss of connection would be restored very fast such that the overall operation of the actuator continued despite of the regular disconnections. For this work the experimental results focused on two main areas:

- Detection technique validation
- Effects of varying cable lengths (simulated varying fault locations)

Technique Validation

The experimental results are shown in Figure 14. It shows the current and voltage signals captured at low sampling rates during intermittent disconnection of the connector indicated by the blue signal (channel 2). The purple signal (channel 3) is the DC value of the actuator voltage. The cycle of low disconnection speed was approximately 125 ms, whereas the disconnection time was 45ms. The differential current signal was captured by the wide band in-house current sensor, shown in yellow (channel 1). The green signal (channel 4) was captured by the Hall Effect sensor. Both of the differential current signals remain stable for most of the operation. When signal instability occurred due to a disconnection, the spike triggered by the current imbalance is captured (as denoted by the red ellipse in Figure 14). The dotted greed ellipse shows the place where a spike was expected but not present because of a low sampling rate, as the scope was set for data acquisition every 125 µs.

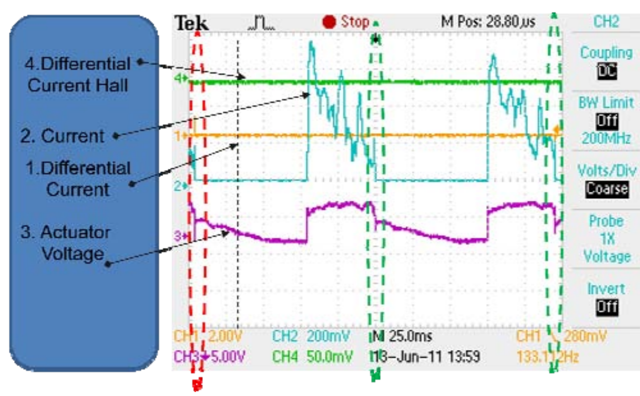

Figure 14 - Experimental test bench in operation with intermittent disconnection

A 10 µs/div detail of the spike is shown in Figure 15. These results show how intermittent disconnections can be detected at high frequency with both of the differential current sensors. The total time of disconnection (t_D) lasted about 80 µs. Towards the end of the current signal, shown in blue (channel 2), the several attempts of disconnection can be noticed until the current settles back down to zero in the last 30 µs of the process. The electromagnetic ringing was reflected noticeably in the two differential current sensors, validating their use as disconnection detection sensors.

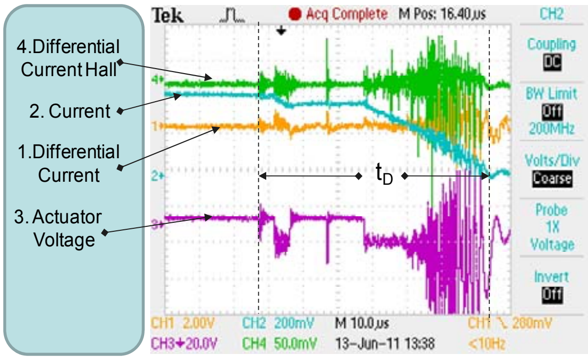

Figure 15 - Leakage current measurement with perturbed disconnection

Varying Cable Length – Simulated Fault Location

In order to simulate disconnection fault at various locations within a closed system, two different lengths of cables were introduced in the test bench. Disconnection of the connector at 15 Hz with a short connector cable (2 ft) was compared with a long-length cable setup (500 ft). The results showed a clear difference between the acquired differential current signals for the two cases. Figure 16 shows that in the case of the short cable, the interruption of the current is shorter by about 3 µs because there were low levels of energy to radiate, as described by Lorentz Law. In case of the longer cable, as shown in Figure 17, the magnetic energy associated with the cable was larger leading to longer interruption times (up to 30 µs) and higher frequency oscillation associated with the phenomenon.

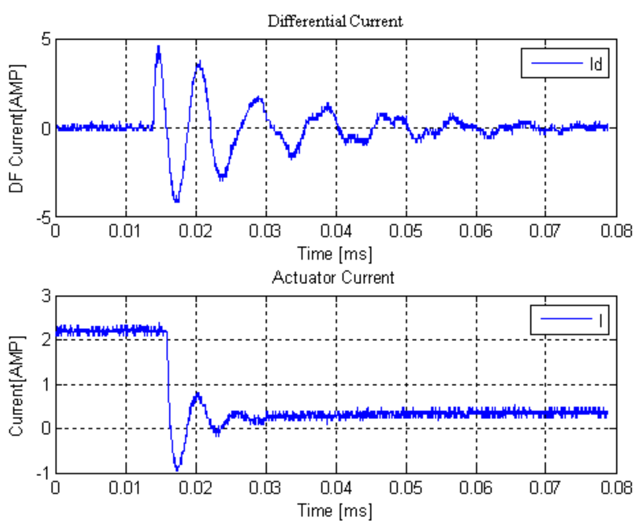

Figure 16 – Typical different current signature for connector with a short cable (2 ft)

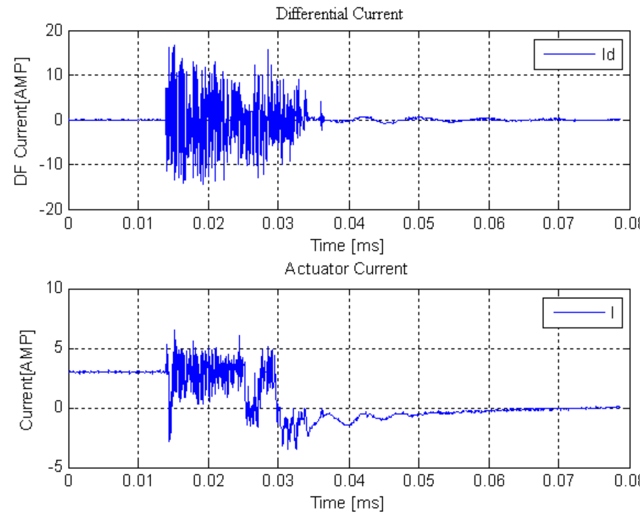

Figure 17 - Typical differential current signature for connector with a long cable (500 ft)

5. Conclusion

In this paper we established the feasibility of detecting an arc generated due to intermittent connector failure. The detection method is based on the differential current sensing technique. Further work is needed to classify and characterize the disconnection fault in different systems. Based on the results presented here and planned future research, a sensor can be developed that can detect the travel wave propagated through the transmission lines when an arc is generated. The differential current sensor also shows a very distinct signature when long versus short cables lead to the connector, suggesting the possibility of incorporating fault localization into a future detection system.

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BIOGRAPHIES

Antonio E. Ginart *(S'89–M'01–SM'07) Received the B.Sc. and M Sc degrees in Electrical Engineering from Simon Bolivar University , Caracas, Venezuela in 1986 and 1990, respectively, and the Ph.D. in Electrical Engineering from the Georgia Institute of Technology in 2001. He has over 20 years of experience in motors, electronic drives, and industrial controls. He was an Instructor, Assistant Professor, and later Associate Professor at Simon Bolivar University from 1989 to 2002. He was a consultant for Aureal Semiconductors, Inc. in power amplification from 1999 to 2000, where he pioneered the effort to develop Class AD amplifiers. At Impact Technologies, he is responsible of developing intelligent automated monitoring systems for electrical and electronics equipment for industrial and military applications. His research has led to over 50 publications.*

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Jonathan Goldin *is Senior Project Engineer at Impact Technologies, LLC. In his 5 years at Impact Technologies, he has worked on a wide array of projects. He is experienced in developing agent-based software that can predict and schedule maintenance to minimize downtime. Embedded systems are also an interest. He has worked on a several embedded platforms, including Impact's sensor mote used in Impact's eSPAN and Missile Monitor programs. Jonathan also has hands-on skills used to design, build and test hardware. He is an alumnus of Georgia Institute of Technology, earning a B.S. degree in Electrical Engineering in 2005.*

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