# On-line Intermittent Connector Anomaly Detection


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***Abstract*—This paper investigates a non-traditional use of differential current sensor and current sensor to detect intermittent disconnection problems in connectors. An intermittent disconnect, often resulting in an arc, creates an imbalance which is manifested in the current. The traveling wave generated due to the perturbation can be detected using current sensors. This paper shows the feasibility to detect disconnection based on this principle.**



***Keywords-Connectors; disconnection; arcing; PHM; fault detection***


## I. INTRODUCTION

As aircrafts and spacecrafts become "more electric", the need to develop innovative monitoring, diagnostic and fault tolerant techniques for the electrical systems is growing in importance [1-3]. One of most common and critical failures in electrical systems is the intermittent disconnection of connectors. Despite the extreme care in the design and quality control in manufacturing and installation of these connectors in avionics and military equipment [4], there are increasing number of problems associated with the physical connectivity that ranges from intermittent discontinuities, sparks, and breakages.

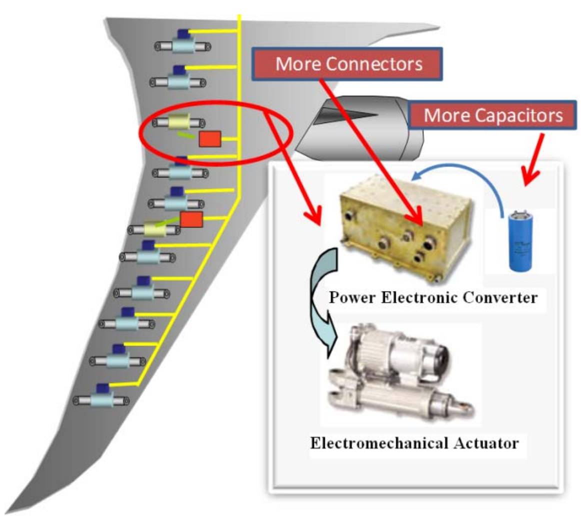


Figure 1: Connectors on a "more electric" airplane

Exploring a non-traditional use of differential current sensors, this paper studies the feasibility of detecting 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 interferences (EMI). A differential current sensor is proposed to capture the imbalance caused by the traveling wave or electromagnetic induction. This paper studies the possibility of detecting fault initiation, fault-to-failure progression, with online monitoring of the critical problems of intermittent disconnection in aircraft power systems using an actuator connector test bed. This novel sensing application, recently explored for fault detection in industrial applications [5], 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 can also be integrated with prognostic and health management system that are based on condition monitoring and system health assessment paradigms.

## II. ARC GENERATION AND DETECTION PRINCIPLES

### A. Failure Mechanisms

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

TABLE I. 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 [6]. The two main stress factors, as shown on Figure 2, are vibration and differences in thermal expansion of the contact materials [7]. Other physical parameters such as temperature, pressure, and humidity are also used to quantify these stresses.

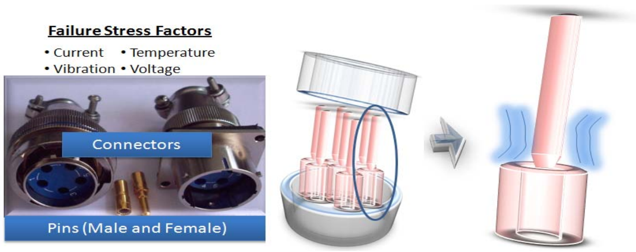


Figure 2: Failure stress factors in connectors

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 deterioration of its capabilities, as shown in Figure 3.

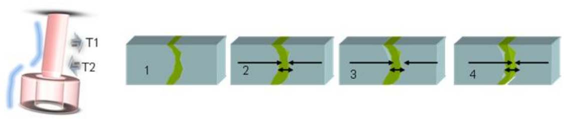


Figure 3: Process of connection failures induced from thermal cycling

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 connectors in the next generation systems (such as aircraft, ships, and automobiles) pose a significant challenge in performing detection and mitigation of the problems associated with loose connections. It would be highly desirable to find innovative sensing capabilities that can lead to more robust electrical power systems.

### B. Arc Generation Theory

The focus of the work presented in this paper is on the current interruption events - due to sudden disconnection of connectors in an inductive circuit, for example. Lorentz Law states that sudden changes in trap flux create a large voltage resulting in production of an arc. This spark, which is characterized as a travelling wave and RF emission (EMI), 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 (small $\Delta t$), in the current would lead to a change in the magnetic flux, resulting in generation of a large voltage.

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

where:
$V$ is the voltage
$\lambda$ is the magnetic flux
$t$ is the time
$L$ is the inductance

An arc is conventionally defined in the industry as "an unintentional electrical discharge". It is usually caused by faulty 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 through an arc across the terminals where the connection is broken. Since arcs are generated by 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 a power transmission line. Equations (2) and (3) describe current and voltage propagation through the system's transmission lines in terms of the circuit quantities [8]. The $\ell$ term represents the inductance per unit length (Henry/meter) and $\varsigma$ represents the capacitance per unit length (Farad/meter). These constants are the characteristic values of electrical transmission lines and can be determined 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 above partial differential equations and solving for the voltage and current propagating along the +z and –z directions, Equations (4) and (5) are derived [8]. 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 $Z_0 = \frac{\ell}{\varsigma}$ 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
$Z_o$ is the characteristic impedance of the transmission line

According to Maxwell's electromagnetic wave propagation model, (see Figure 4) electric and magnetic fields interact orthogonally to each other 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 perturbs normal electromagnetic wave propagation - a phenomenon that can be detected.

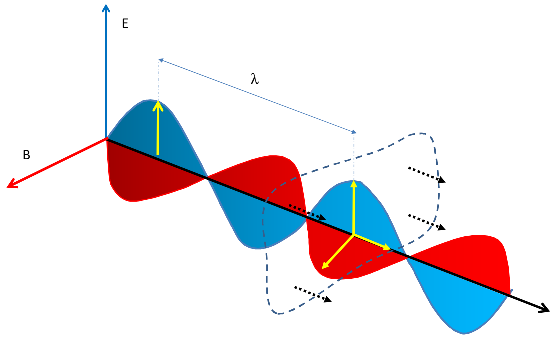


Figure 4: Electromagnetic wave propagation

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 a current sensor implemented in a differential configuration normally captures the leakage current which, during normal conditions, should be zero or very close to zero. Figure 5 shows an experimental setup configuration for detecting arc travel waves. As can be seen on the figure, if the switch, representing the connection, is closed, the current would flow in the DC bus and return, resulting in zero leakage current. If, however, the connection is suddenly disturbed, according to the aforementioned Lorentz Law an arc will be produced. The traveling arc wave will propagate through the DC bus and the measured leakage current will no longer be zero, indicating presence of an arc anomaly in the system. This configuration can be scaled up and implemented throughout the electrical system of an aircraft or another complex platform.

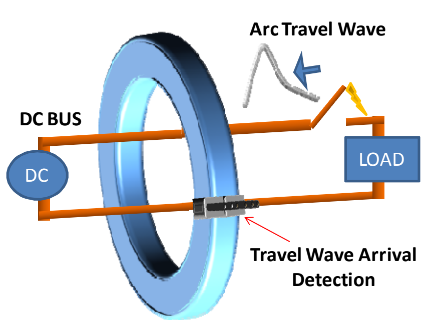


Figure 5: Arc anomaly detection experimental configuration

## III. Test Bench

### *A. General Description*

The connector test bench is designed to simulate intermittent disconnection that often results from improper connector locking during maintenance procedures or pin/receptacle failure due to contact loss. The test bench is designed to continue operating the load, in this case an electro-mechanical actuator, until a set point is achieved, even in presence of a seeded intermittent disconnection.

The control system block diagram for the test bench is shown on Figure 6. The main idea in implementing the test bench is to create a system that allows the overall system to keep operating while creating connector disconnections. To ensure that, a disconnection mechanism was implemented that disconnected and connected the connector quickly.

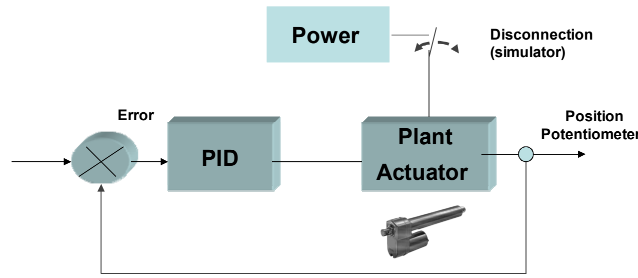


Figure 6: Connector test bench control system block diagram

The connector test bench includes the following elements:

- DC actuator as a load
- MIL-STD electrical connector
- Controllable speed disconnection mechanism

The test bench configuration shown in Figure 7 incorporates the abovementioned elements and the functional blocks shown in Figure 6.

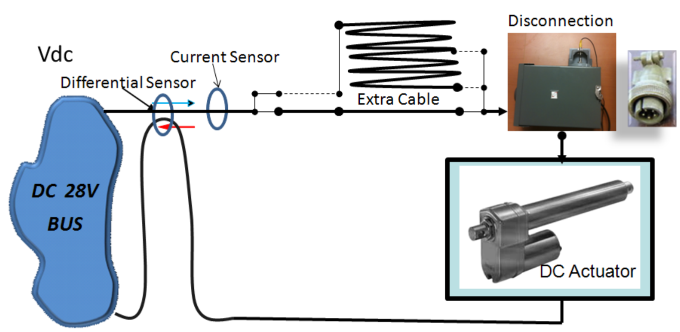


Figure 7: Illustration of the power drive test system

### *B. Test Connector*

There is a wide range of connectors that could serve as a representative test article for this paper. Due to its wide availability and low cost, a used 5-pin MIL-DTL-5015 series connector, consisting of a receptacle and plug has been selected. The connector is shown on Figure 8.

Figure 8: Several examples of MIL spec connectors (left) and the selected MIL-DTL-5015 connector (right)

### C. Test Bench Actuator

The actuator selected for this work is a low cost, 24 V DC permanent magnet motor unit powered by a 28 V DC power source. The actuator includes a 10 kΩ potentiometer for position feedback. The five pin version of the MIL-DTL-5015 connector is used in the circuit, with two pins used for power and three pins for the position potentiometer signals (Figure 9).

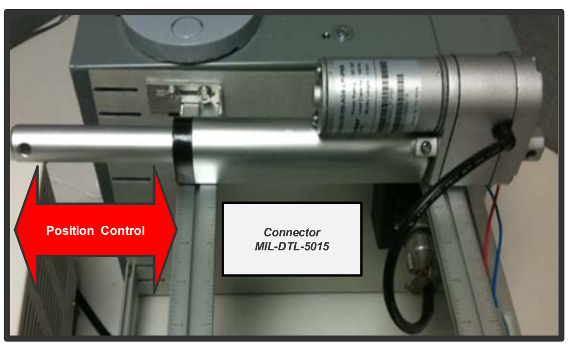


Figure 9: Selected actuator and connector

### D. Test Bench Disconnection Mechanism

A failing connector is simulated with a forced connection and disconnection mechanism that can operate at variable speed of up to 10 Hz. Figure 10 shows the progression of the connection and disconnection. It should be noted that in this configuration the actuator continues operating because the connection is restored quickly.

Figure 10: Connector disconnection progression

### E. Connector Test Bench Implementation

The test bench implemented is shown on Figure 11. Along with the components described in the previous subsections, the test bench also includes an instrumentation board to measure the relevant current and voltage signals. The measurement board allows high sampling rate data acquisition of up to three current and three voltage signals. The current sensors on the measurement board can be configured to support differential current sensing.

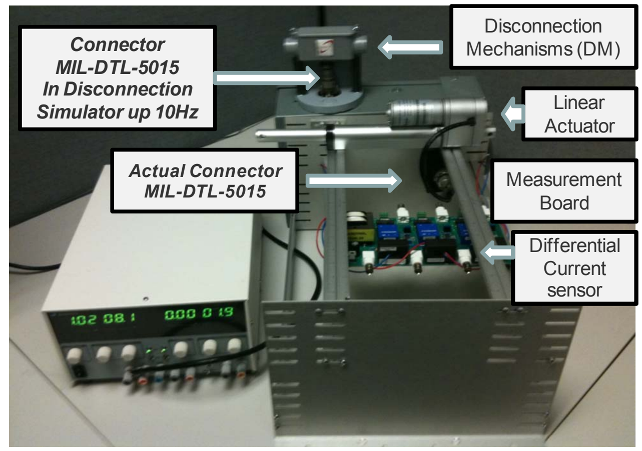


Figure 11: Actual connector test bench

### F. Sensor and Conditioning Hardware

The differential current sensor was implemented using an in-house signal conditioning board with Hall Effect sensors and a wideband low-cost current sensor (as shown on Figure 12). The two types of sensors are also used to validate the results in detecting the disturbance caused due to disconnection. The instrumentation board on the left supports Hall Effect current and voltage sensors. The current sensor shown on the right is a wideband sensor that allows detection of high frequency components of current signals.

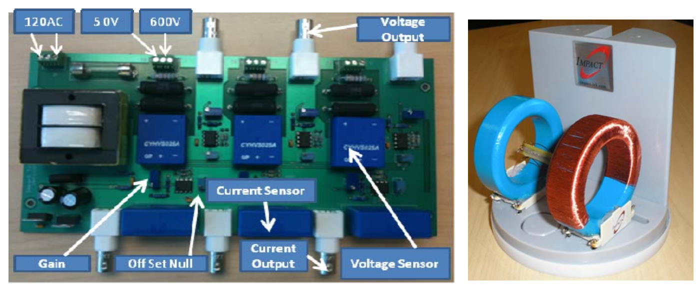


Figure 12: Signal conditioning board

## IV. Experimental Results

### A. Experimental Setup

Using the test bench system described in the previous section, an experiment was setup. The basic idea was to use the test bench to operate the actuator system with automatic disconnection capability. As described in the previous section, the test bench allows the connector to be disconnected at varying speeds. It should be the noted that the system continues to operated without stopping due to fast disconnection and subsequent connection. An oscilloscope was used to capture data which included the wideband differential current (Ch. 4), differential current using Hall Effect sensor (Ch. 1), actuator current (Ch. 2), and actuator voltage (Ch. 3). The speed of connection and disconnection was kept constant as well the load actuator was operated at constant speed.

### *B. Results*

Experimental results are illustrated on Figure 13. The figure shows, at a low sampling rate, how the intermittent disconnection is reflected in the measured current (blue signal). The purple signal is the DC value of the actuator voltage. The connection-disconnection cycle consisted of a disconnection phase lasting approximately 125 ms and the connection phase lasting 45 ms. The differential current signal is captured using the wide band current sensor (yellow) and a hall effect sensor (green). Both of the differential currents remained stable for the most of the operation. When signal instability occurs due to a disconnection, the spike triggered by the current imbalance is captured (as marked by the red ellipse on Figure 13). The green ellipses show places where a spike is expected, but not visible due to low sampling rate, as the oscilloscope was set for data acquisition at every 100 µs.

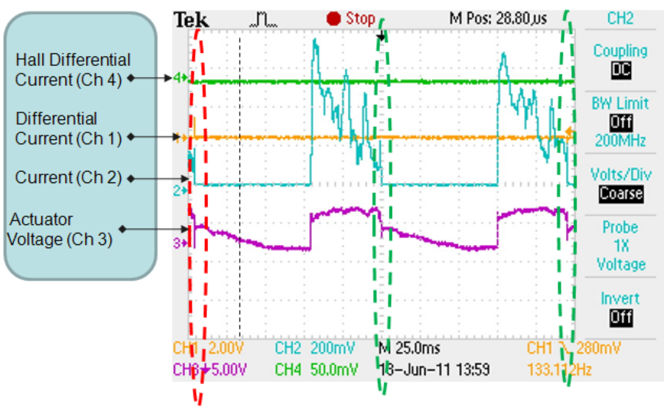


Figure 13: Experimental test bench in operation with intermittent disconnection

A 10 µs/div detail of a spike is shown in Figure 14. This figure shows how the intermittent disconnection can be detected at high sampling frequency (data acquisition every 0.04 µs) for both of the differential current sensors. The total time of intermittent disconnection ($t_D$) lasts about 80 µs. It should be noted that total disconnection occurs after several attempts (due to vibrating connector pins) until the current (blue signal) decreases to zero in the last 30 µs in the process. The electromagnetic ringing is reflected vividly in the two differential current sensors, validating its use their use as disconnection detection sensors.

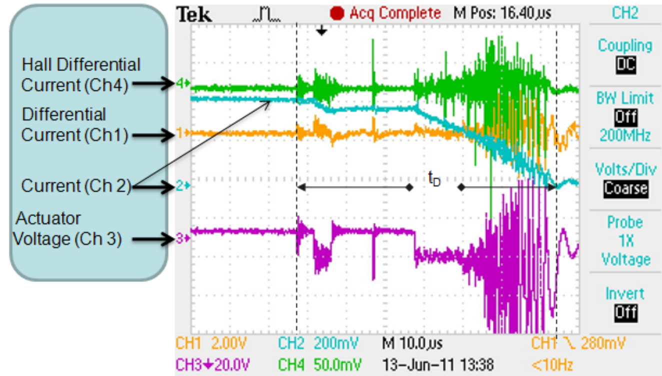


Figure 14:Leakage current measurement with perturbed disconnection

## V. CONCLUSION

In this paper feasibility of detecting an arc generated due to intermittent connector failure is demonstrated. Detection is based on a differential current sensing technique. Based on the results presented here, a sensor can be developed that can detect the travel wave that is propagated through the power transmission lines when an arc is generated. Future work will include development of a sensor capable of detecting an anomalous disconnection in real time and online. Other areas of research include the possibility of disconnection fault localization.

## ACKNOWLEDGMENT

This work was funded by the NASA SBIR program under contract number NNX11CD01P, with oversight and technical support provided by NASA Ames Research Center.

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