A Novel Intermittent Fault Detection Algorithm and Health Monitoring for Electronic Interconnections

Wakil Ahmad Syed, Suresh Perinpanayagam, Mohammad Samie, and Ian Jennions

***Abstract*— There are various occurrences and root causes that result in no-fault-found (NFF) events but an intermittent fault (IF) is the most frustrating. This paper describes the challenging and most important area of an IF detection and health monitoring that focuses toward NFF situation in electronics interconnections. The experimental work focuses on mechanically-induced intermittent conditions in connectors. This paper illustrates a test regime, which can be used to repeatedly reproduce intermittence in electronic connectors, while subjected to vibration. A novel algorithm is used to detect an IF in interconnection. It sends a sine wave and decodes the received signal for intermittent information from the channel. This algorithm has been simulated to capture an IF signature using PSpice (electronic circuit simulation software). A simulated circuit is implemented for practical verification. However, measurements are presented using an oscilloscope. The results of this experiment provide an insight into the limitations of existing test equipment and requirements for future IF detection techniques. Aside from scheduled maintenance, this paper considers the possibility for in-service intermittent detection to be built into future systems, i.e., can IFs be captured without external test gear?**

***Index Terms*— Fault diagnosis, fault detection, NFF, and intermittent fault detection.**

I. Introduction

MOST DEVICES and systems contain embedded electronics modules for monitoring, control, and to enhance the functionality of cars, trains, ships, and aeroplanes. The shrinking size and complexity of electronic circuits, with added redundancies, have led to difficulties in the maintenance of these systems. This becomes a challenge when faults are intermittent in nature.

Intermittent faults (IFs) are a growing problem in electronics interconnection systems, especially for aircraft, satellites, and other vehicle industries and are safety critical to unmanned/autonomous connected vehicles. Interconnections have significantly increased in modern systems and these are prone to high stress of temperature, humidity, power fluctuation, electromagnetic interference, critical timing, aging, and vibration.

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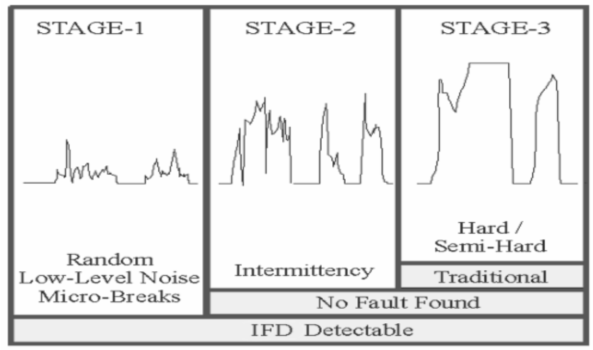

Fig. 1. IF detectability [3].

No-fault-found (NFF) has financial impact on all industries, but the transport and aerospace sectors suffer more than others [1]. The American Trans Air member airlines spend \$100 million annually on NFF in terms of thousands of flight delays and cancelations [2] and the cost of aircraft troubleshooting and recovery.

The fundamental problem of NFF has been highlighted that focuses to its main cause of IF for electronics interconnection systems, such as sockets, wire harnesses, wires, and printed circuit boards (PCBs). It shows that IFs are detectable with high accuracy and with minimum false alarms that occur in existing intermittent continuity tests and health-monitoring systems.

When the fault is consistent, it is not difficult to isolate and repair. However, this is not true for faults that occur intermittently. In general, component degradation caused by these faults worsens with time, until they eventually cause a hard fault [3].

Fig. 1 shows that at the very early stage of degradation, there are very weak unwanted signals but they do not affect the system's performance. These grow and cause intermittent problems, before the system stops working. For safety-critical applications, these must be addressed to avoid malfunction.

To enhance system reliability and safety, complex interfaces/interconnections must be monitored all the time during operation. As the nature of IFs is random and unpredictable, there should be a health-monitoring system that is able to monitor all points with minimum added redundancy. The resolution of the health-monitoring system should be selected according to system requirements. Fixed frequency signals are better than constant amplitude due to channel's noise characteristics that could trigger false alarms. A desired frequency should be selected according to the system's operational band and the required resolution.

Modeling for early fault detection of intermittent connections on a control area network (CAN) has been presented in [4]. The authors have monitored data errors for a CAN to detect IFs. This technique works on data communication links with the assumption that data errors in CAN are only due to intermittent discontinuities. This paper ignores the facts that data errors could occur due to intersymbol interference, nonsynchronization, and high-noise level. Added redundancies can also cause intermittent malfunction and result in data errors. Another limitation of this algorithm is that it is application-specific and can only be used for CAN and not for other interconnection systems.

A novel IF detection algorithm is presented to overcome the above limitations. A physical layer is used to avoid possible false alarms. This novel algorithm detects IFs in wires/wire harnesses, interfaces, and other electrical/electronic interconnections. This could be used to monitor data cables, PCBs, and connection sockets or other electronic interconnections. This approach is unique and different from previous diagnostic methods of interconnection fault detection. It sends sinusoidal signals and the health-monitoring system detects an IF when it happens. This technique reduces false alarms with adjustable resolution according to requirements.

Section II describes NFF models for wiring and a novel adopted NFF model. Section III describes a novel algorithm and its validation in PSpice with some useful discussion to improve and enhance fault detection by Fourier analysis. The subsequent Section IV describes the implementation of the designed technique with experimental work and measurements. The conclusions and future work are discussed in Section V.

II. NFF Models

Despite significant improvements in various engineering disciplines of measurements, programming, and computing, there is still a lack of adequate knowledge in modeling NFF. In particular, meeting requirements are highly needed to detect the NFF of wires and connections. However, while there are general modeling approaches, they are hardly acceptable to be used for wired communication channels, considering various issues arising from noise, vibrations, temperature, and degradation. The two approaches that have been already employed for modeling the NFF of communication channels are aircraft wiring model (AWM) and time-domain reflectometry (TDR). AWM is the U.S. aviation research that attempts to model an aircraft's electric power wire using distributed passive components (resistance, inductance, shunt capacitance, and shunt conductance) found in transmission lines. In Fig. 2, dx is the length of the wiring segment with Rdx series resistance and Ldx series inductance. A shunt capacitance Cdx is associated with dielectric, and shunt conductance of Gdx is associated with dielectric in Fig. 2. Components' values are defined per unit length and are considered as a single lumped element whose value is dependent upon total length of wires.

The inductance (Ldx) is a function of the physical properties of the wire and, for installed wiring, can be assumed to be constant. The capacitance of a wire (Cdx) is a function of

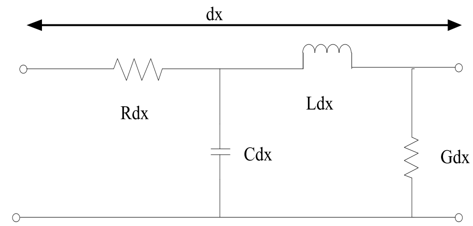

Fig. 2. AWM [5].

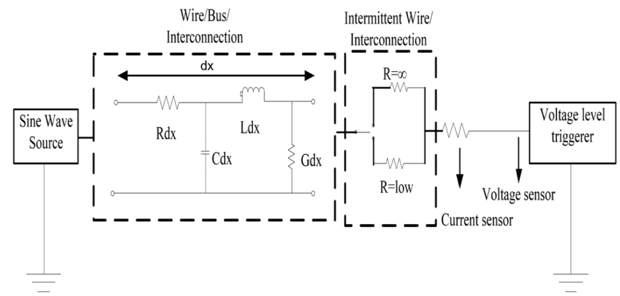

Fig. 3. NFF/IIDM.

geometry, the insulation materials, and the presence of any contamination.

Yaramasu *et al.* [6] have used the same AWM wiring model of an aging airplane in their research by adding load resistance to it for TDR.

In this paper, we have presented an intermittent interconnection and detection model (IIDM) that consists of source, wire, and IF detection, as shown in Fig. 3.

In our IIDM, an IF is modeled by two parallel resisters with a switch. In normal operation, it follows a low-resistance path, while an intermittent open path has high resistance. In this model, we have only included an intermittent interconnection due to vibration only.

III. Novel Intermittent Fault Detection Technique

In communication, a carrier signal carries information safely from A to B. Mixing of information with carrier signals is known as modulation. In mathematics, this operation shifts the signal to carrier frequency. There are many modulation schemes but fundamentally, there are three modulation schemes, referred to as amplitude modulation, frequency modulation, and phase modulation. In AM, the amplitude of the carrier signal changes according to the input signal or modulating signal.

With regard to fault detection, we have used a radar detection approach in which a blank carrier signal propagates through a channel and variation is extracted from received signal, i.e., IF information from channel. This could be described using a block diagram, as shown in Fig. 4. It consists of an input carrier voltage signal, an IF amplitude modulating circuit, a demodulation circuit, a sensor, and IF latching subblocks.

The oscillator generates a sine wave of constant amplitude as a source for unit under test. If there is an intermittent

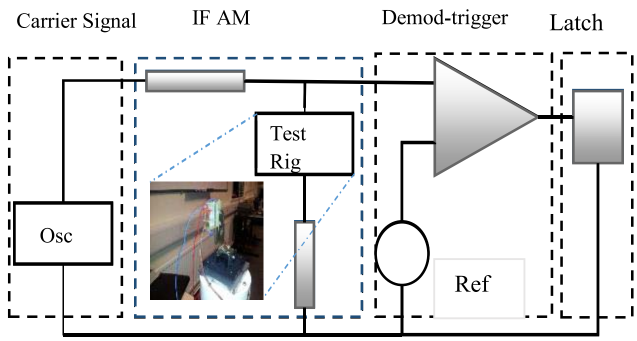

Fig. 4. IF detection block diagram.

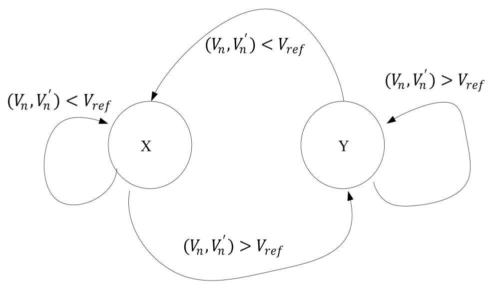

Fig. 5. State representation of IF detection system.

discontinuity, this will be modulated on carrier frequency, i.e., it will change the amplitude of the carrier signal. The demodulation circuit removes the carrier frequency and IF discontinuity captured and latch using a voltage sensor and a latch, as shown in Fig. 4.

V_s is the carrier voltage, and V_n and V_n' are the voltages at sensor with normal and intermittent open, respectively. If $V_s = A \sin(2\pi f t)$, then

$$(V_n, V_n') = Z_2 A \sin(2\pi f t)/(Z_1 + Z_2) \quad (1)$$

and $V_n' \approx V_s$ where Z_1 and Z_2 are the impedances of the circuit and A is amplitude. If $(V_n, V_n') < V_{\text{ref}}$, then

$$V_{\text{out}} = X \quad (2)$$

and if $(V_n, V_n') > V_{\text{ref}}$, then

$$V_{\text{out}} = Y. \quad (3)$$

In these equations, V_{ref} is a reference voltage and V_{out} is the output of the circuit. Whenever there is an IF, output will change a state from X to Y and back to X.

This system has been modeled as a two-state machine, as shown in Fig. 5.

This algorithm can be explained using a flow diagram, as shown in Fig. 6. The carrier sends electrical signals to the unit under test continuously and monitors the demodulated signal's amplitude. If there is an IF, it latches the fault. The fault will only be captured when it goes from state $X(V_{\text{ref}})$ to $-Y(V_{\text{ref}})$ and from $Y(V_{\text{ref}})$ to state $X(V_{\text{ref}})$. Sections III-A and III-B explain how this algorithm improves the detectability with precision.

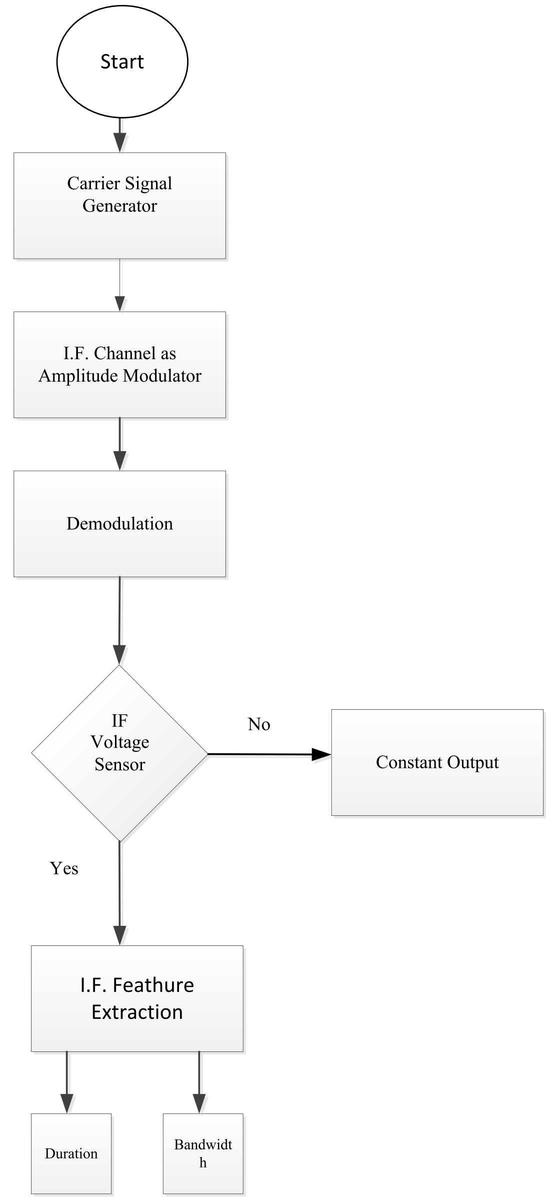

Fig. 6. IF detection algorithm.

A. Resolution of Intermittent Test

This section discusses how sharp IFs could be captured by a carrier frequency of f in Hz with a close circuit amplitude of $\pm a$ and an open circuit amplitude of $\pm A$, and the voltage sensor reference level at $\pm V_{\text{ref}}$ volts. The ratio between the threshold and the peak sine voltage is $(V_{\text{ref}}/(a, A))$.

The angular frequency (ɯ) of the input sine wave is $=2\pi$ times linear frequency (f), i.e., ɯ $= 2\pi f$, where ɯ is in radians and f is in Hz

$$ɯ = 2^*\pi^* f \text{ radians.}$$

Time of signal below of threshold is $\sin \omega t = h/A$, where A is the peak amplitude and h is the threshold amplitude of the sine wave

$$t = \sin^{-1} \text{h/A seconds.}$$

The resolution to detect the intermittent change will be 2^*t, because the sine wave will remain below for positive and negative thresholds of sine wave.

In the test setup, the sine peak is adjustable to increase/decrease the resolution if required by simply increasing the sine wave peak amplitude and decreasing the voltage divider ration, such that it remains below the threshold for close circuit, i.e., under normal condition.

If we increase the peak voltage from A to $2A$, we will get $\approx(t/2)$, i.e., almost half the time by doubling the sine wave amplitude.

This threshold level could also be used to change the IF capturing precision, as we discussed previously.

The other way to increase the detection resolution is to increase the input frequency from f to $2f$. This will almost narrow it to half and double the resolution.

B. Need to Use AC Rather Than DC Signals

Direct current (dc) could be used to capture very small transients but this is not desired due to white, thermal, and particularly flicker noise. For dc measurements, flicker or $1/f$ noise can be troublesome as it significantly occurs at low frequencies, tending to infinity with integration/averaging at dc. Flicker noise, also known as pink noise, is inversely proportional to frequency, i.e., $S(f) \propto (1/f^{\alpha})$, where f is frequency and $0 < \alpha < 2$, usually close to 1.

IFs in interconnects are due to disconnection of circuits for very short durations but not due to other noise. IFs in vehicles are mainly due to vibration or other means of loose connections and that could not be small as picoseconds, because engine does not vibrate at such high frequencies. This means that a connection cannot generate a gigahertz signal, but further investigation is needed to develop better understanding to quantify the frequency of the most common IFs.

IFs can only be detected if there is a disconnection of the circuit for a short duration. An alternating current (ac) signal is the best choice to avoid other nonloose connection triggers. The frequency could be selected according to requirements.

AC signals could also be used *in situ* to detect an IF but the health-monitoring system must be operated at different bands of frequency of the system.

The power dissipation of ac signals is less than that of dc signals and the probability of false alarms is also lower. One of the main benefits is its use for health monitoring of high-value products.

C. Simulation of Circuit

This algorithm is simulated using PSpice software with two profiles. One with a closed circuit and the other with an open circuit using a switch, as shown in Fig. 7. In the first profile, the connection is simulated by a closed switch.

The simulation results are shown in Figs. 8 and 9. In Figs. 8 and 9, the green marker (dotted line) shows the input signal and the red marker (solid line) shows the output of the circuit. There are ripples in the output but these do not affect the threshold level trigger points.

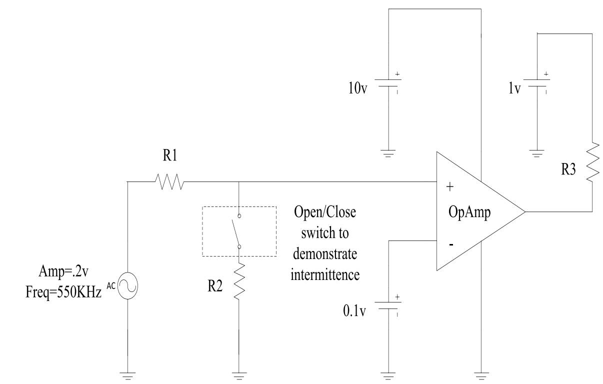

Fig. 7. IF detection circuit.

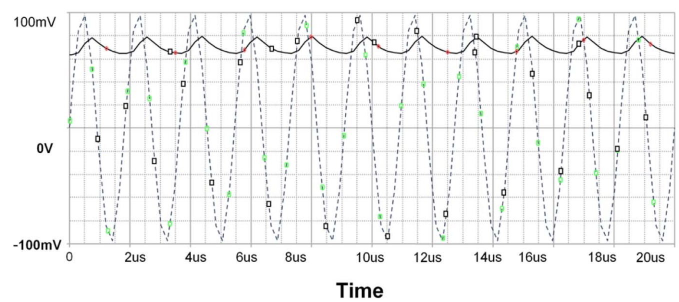

Fig. 8. Input/output waveform of IF detection circuit—Profile 1.

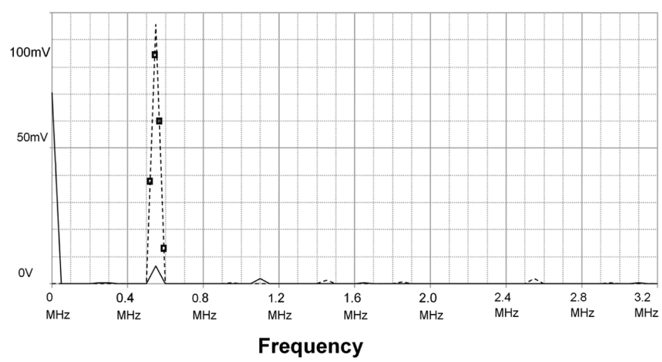

Fig. 9. Frequency domain plot of input (dotted line)/output (solid line) of Profile 1.

The frequency domain plot is shown in Fig. 9, where the input signal's fast Fourier transform (FFT) at a center frequency of 0.55 MHz and a magnitude of 100 mV or −20 dbV while the output frequency plot (solid line) of ≈5 mV or −46 dbV is present. These small signals are far below the threshold point that could be used to latch at a latching circuit.

When the switch is open in the circuit, the voltage at the node increases above the threshold point. This increase will exceed the reference voltage and it triggers the output. The comparator output is pulled up to 1 V through resistor R3, as shown in Fig. 7.

The simulation results of Profile 2 are shown in Fig. 10. The input signal in green marker and the output signal in red marker show that when the input voltage exceeds the reference voltage of 0.1 V, it produces the square wave.

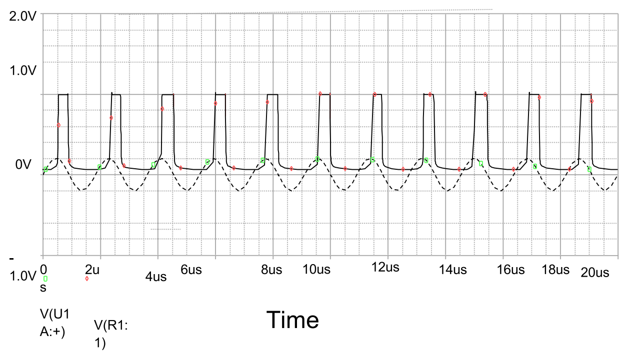

Fig. 10. Simulation of IF detection—Profile 2.

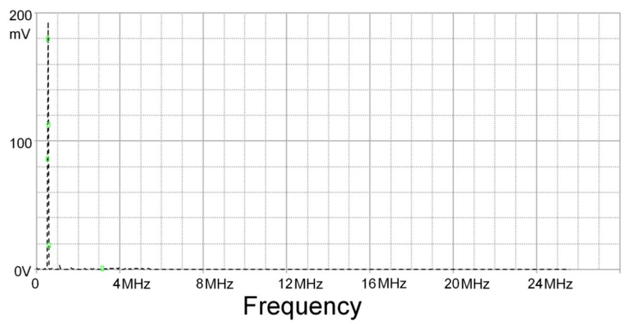

Fig. 11. FFT plot of input signal of Profile 2.

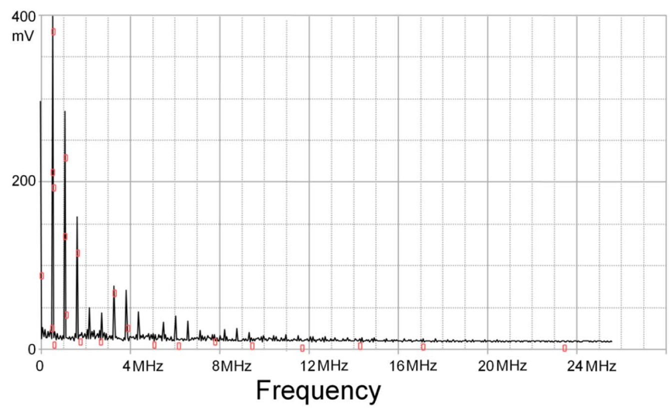

Fig. 12. FFT plot of output signals of Profile 2.

The FFT of the input and the output of Profile 2 is shown in Figs. 11 and 12. Fig. 11 shows a narrow band input carrier frequency at 550 kHz and Fig. 12 shows three major frequencies at 550, 1100, and almost 1600 kHz with other noise components.

IV. Experimental Verification of Novel Algorithm

The algorithm described in Section III has been verified with an experiment. It is tested/verified on mechanically-induced IFs. The details of the test rig and measurements are described in Sections IV-A and IV-B, respectively.

A. Experimental Setup and Circuit

An RJ45 Ethernet socket with an Ethernet cable/plug under external vibration is used to generate intermittence in the connection, as shown in Fig. 13.

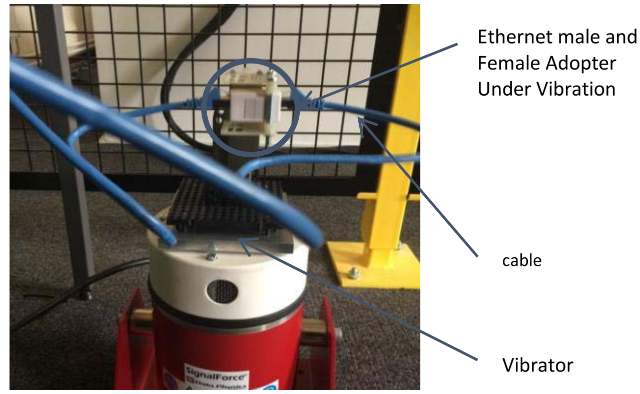

Fig. 13. Ethernet male and female socket with cable connection as an intermittent test rig.

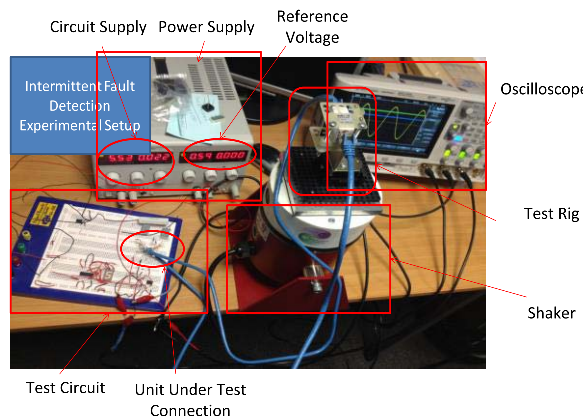

Fig. 14. Experimental setup for IF detection.

The grid has been installed on the shaker by screws and a metal plate, as shown in Fig. 13. This Ethernet connection assembly is used to produce the IF under vibration.

The other ends of the Ethernet cable are connected to a circuit. A complete circuit setup is shown in Fig. 14. It consists of a test rig, oscilloscope, dual power supply, and a prototype board.

This oscilloscope has four channels, 4-Gb/s sample rate, 200-MHz bandwidth, and a built-in function generator that can output a variety of signals but we used 550 kHz, 3 V peak-to-peak sinusoidal signal as a voltage source to the voltage divider circuit. A dual mode power supply is used to provide supply and threshold reference voltage to the analog and digital circuit. A TS393 CD micropower dual CMOS voltage comparator operational amplifier is used as a voltage comparator to trigger the input signal. The divider circuit consists of two 1-kΩ resistances. The 1N4148 diode and 200-pF capacitor are used to smooth the output of the test connection/channel for threshold monitoring. The output of a comparator is fed to a CMOS decade counter integrated circuit CD4026B that is used to count intermittence and to display on a seven-segment display.

B. Measurements

An IF generator circuit, i.e., RJ45 test rig is connected to an IF monitor circuit, as described in Section III, in such

Fig. 15. Test signal of open circuit.

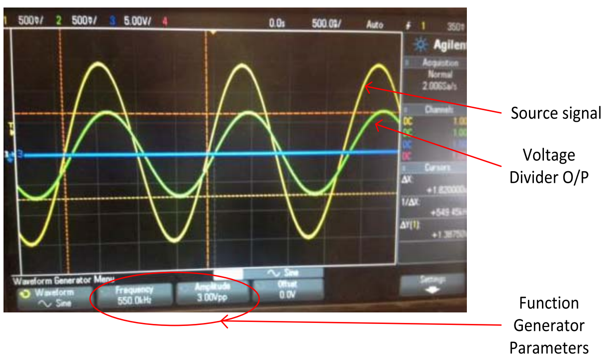

Fig. 16. Test signal for close circuit.

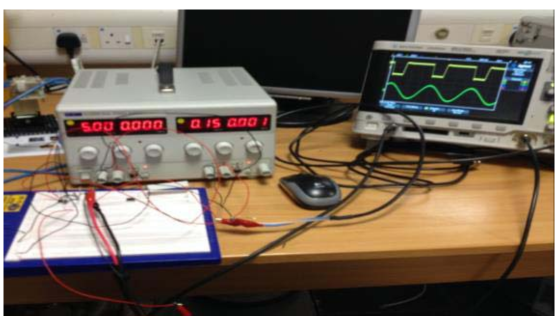

Fig. 17. IF detection measurements—Profile 1.

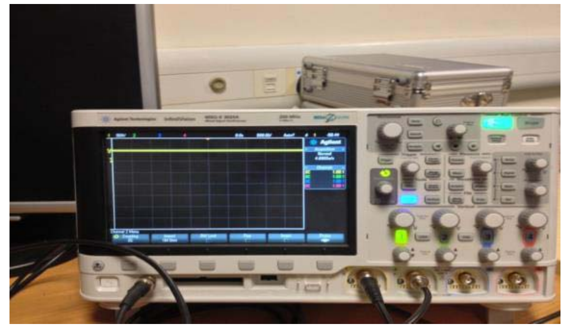

Fig. 18. IF detection measurements—Profile 2.

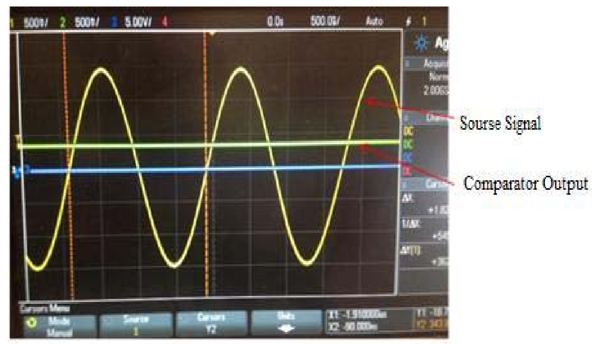

Fig. 19. Output Profile 2.

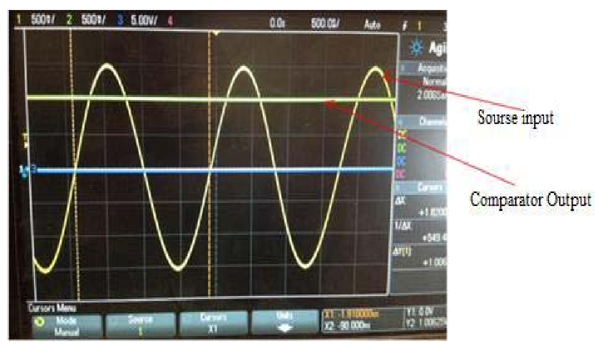

Fig. 20. Output Profile 1.

a way that it connects an electronic circuit under normal operation and disconnects when there is an intermittency. The oscilloscope displays the voltage source output in yellow lines and the output of voltage sensing in green lines, as shown in Figs. 15 and 16. These show the voltage level when the circuit is open and closed. When the Ethernet cable is unplugged, the amplitude of the sine wave is almost 2.58 V peak-to-peak (V_{pp}), as shown in Fig. 15.

When the Ethernet cable/test rig is connected to complete a circuit, the voltage divider drops the voltage to almost 1.38 V_{pp}, as shown in Fig. 16. Theoretically, this should be 1.29 V_{pp}, because it is divided by two circuits.

This variation is due to the components' tolerances. The measurements are shown in Figs. 17 and 18 with open and closed circuits, respectively, similarly as it has been described in Section III-C. Here, Profile 1 shows the output of the open circuit, while Profile 2 shows the output of the closed circuit to illustrate an IF. The comparator's output of Profile 1 shows a square wave, when there is an IF, while Profile 2 shows a constant amplitude because there is not any IF.

The overall responses of the circuit after filtering and demodulation are shown in Figs. 19 and 20.

This circuit changes its transition from low to high and back to low when there is an IF. We have used flip-flop to capture this transition, while count circuit counts the number of IFs and seven-segment LED shows these numbers.

V. Conclusion and Future Suggestions

The literature review and correspondence with the industrial sector show that 80% of NFF problems are due to IFs in interconnection systems of electronic devices. This paper has presented the fundamental problem of IF detection to overcome NFF scenarios.

An electronic circuit for IF detection and health monitoring has been simulated and its time/frequency plots highlight that this method is useful to detect and classify an IF. It is also seen from the spectrum that an IF is like a colored noise for intermittency that is subject to vibration. To understand the duration and frequency of IFs for further investigation, this circuit uses FFT and time duration of intermittence by measuring the number of pulses and spectrum analysis. One of the advantages of this algorithm is that it could be used *in situ* for health monitoring and IF detection. This could also be used to monitor the degradation of wires and connectors with minute modification using its spectrum, as degraded cable will effect the signal's bandwidth.

Verification of this novel algorithm in time domain has been implemented with an experimental setup to create repeated IFs under vibrational stress, but this could be used for any high/low-power interconnection system. It is verified using an oscilloscope and bespoke intermittent detection equipment. It also shows that an oscilloscope is not adequate to capture IFs due to lack of latching very fast transitions.

It was described how to adjust the resolution, and to overcome false alarms. Intermittent discontinuities could be efficiently detected by ac signals of particular frequency. It is concluded that the frequency of carrier signals is very important to eliminate other noises to improve diagnostic confidence level. Another big advantage of this method is that this could be used *in situ* with different frequencies other than the operational band of frequencies.

This IF diagnosis technique may not always be adequate as it indicates intermittence only when the connection resistance goes to infinity (open circuit) for very short durations. However, if the resistance goes high (but finite value) for a very short duration, this and the degradation of the connector will be undetectable. The Fourier analysis presented could be used to overcome this problem. Filtering techniques could also be used in the future to detect IFs and degradation.

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