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Detection and Location of Intermittent Faults by Monitoring Carrier Signal Channel Behavior of Electrical Interconnection System

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***Abstract*—Intermittent faults in electrical interconnect system are short duration transients which would be completely missed by traditional monitoring and protection schemes but are the incipient events of a precursor of permanent faults to come. Due to random and non-reproducible nature, the intermittent faults are the most frustrating, elusive, and expensive faults to detect and locate in wiring systems. The novel approach of the author injects a modulated signal or carrier at one location of electrical wire system and diagnoses the health status of the wire by measuring the error rate of the carrier signal at another location of the system. This paper describes the carrier signal technology and its methods devised for detection and location of faults. The paper also reports the functionally tests of the proto board system of the proposed methods. The results demonstrate remarkable consistency in the error rates with staged fault conditions and clear discriminatory capability of locating faulted segment. Monitoring of the disruption of carrier signal over electrical wire between a transmitter and a receiver provides the most effective tool for continuously watching the wire system for detecting and locating the random, unpredictable intermittent faults, the harbingers of disastrous electrical failure.**

I. INTRODUCTION

An intermittent fault is a physical event that develops from long process of electric wire degradation, cuts, rubs, or loose contacts, and manifests itself intermittently in an unpredictable manner. Unless detected timely, it would gradually develop into permanent fault and lead to many problems of mission abortion, electrical fire or, even worse, fuel tank explosion ignited by arc and sparks that progressed from such faults. Intermittent faults are not permanent faults and, thus, the wiring system would behave normally as if nothing happened after the short duration of transient; however, the intermittent transients are the incipient events of a precursor of permanent faults to come. Due to the random and non-reproducible nature of the incidents, the intermittent faults are the most frustrating, elusive, and expensive faults to detect and locate in wiring systems.

Previous attempts at identifying electrical faults have relied upon the visual or instrument-aided inspection of electrical systems. However, various disadvantages exist with these approaches: operation suspension for inspection as well as ineffectiveness due to the inspection points being in the location frequently hard to reach or observe. These approaches also prove unable to detect the fault in many cases since the duration of the fault was often short and the system would behave normally after the incident and the approaches would find the wire system normal or "no fault found (nff)" status. Therefore, it is relatively easy for the observer or instrument to miss the occurrence of the fault.

Much research has been done on the subject of "live" wiring fault detection. A group of approaches under category of reflectometry relies on transmitting electromagnetic waves across the wire. In reflectometry, incident standing waves or impulses are transmitted and then reflected from the impedance-changing point of the wire system, and then the time between the incident pulse and the reflected pulse is calculated to determine the distance to the location where the pulse is reflected. Different criteria are then used to determine if the reflection is a potential fault. One problem with this technique is that any change in the wire material (e.g., a branch-out in circuit) reflects the incident waves resulting in erroneous fault determination. Another problem with this technique is that it requires the transmission of high voltage pulses.

Recently, another type of reflectometry approach has been applied by transmitting direct-sequence spread-spectrum modulated signals, instead of high voltage signals, and employing signal processing techniques in an attempt to find and locate electrical faults [1]. These approaches, however, still relies on reflectometry, and as a result, although this approach may have, under some circumstances, overcome the need to use high voltage incident voltage pulses, it still has the problem of reflection occurring at all points of branching in the circuit. Still another problem of the reflectometry approach is that the location of the device must be close to one

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end of the electrical system, either the line end or the source end. Otherwise, the injected signal would be reflected from both ends and result in a combined, distorted, and reflected signal. This requirement of locating the device at either end is very difficult to meet since many electrical networks are connected in a complicated format, often in mesh architecture.

The novel approach of detecting and locating intermittent wire faults developed by the author is very different from traditional diagnostic methods of monitoring high-frequency component of signals generated by arc/spark in faulty wire via analog signal acquisition, filtering, and signal processing detection, or the reflection of waves from impedance mismatches. The new approaches of the author inject a modulated signal or carrier at one location of the electrical wire system and diagnose the health status of the wire by measuring the error rate of the carrier signal at another location of the system. The essence of the approach is using the communication channel characteristics, in terms of data error rate, of the carrier signal system as an indicator of the transmission medium, electrical wire. The transient caused by the intermittent fault in the wire would disrupt the carrier signal sent over the wire from a transmitter, and thus the carrier signal arriving at the receiver would contain errors. When the transmission errors are found, accumulated, and later compared with a threshold, an alarm or annunciation is activated to alert the system of an intermittent fault.

This paper reports the initial experimental results of using carrier signal technology devised for intermittent electrical fault detection and location in electrical wire system. In the next section, we describe the carrier signal technology and its devised method for detection and location of faults in terms of communication errors, communication handshake, and transmitter and receiver configurations. Then, section III describes, first, the hardware structure of the prototype system developed and, later, the experiments performed using the prototype system and the preliminary results obtained from the experiments. Section IV concludes the paper.

II. CARRIER SIGNAL APPROACH FOR INTERMITTENT FAULT DETECTION

A. *Carrier Signal Technology*

A carrier wave or carrier signal is waveform of a specific frequency in a communication channel that is modulated with an input signal to be transmitted for information exchange. A well-known carrier communication method, power line carrier communication, is a method of transmitting data through existing electrical lines alongside electrical current. This traditional application of using narrowband power line carrier can be found in remote monitoring and in some applications in the development of a smart motor that combines both the power and control lines into a single wire [2]. The power line communication now stands even as an enabling technology for broadband networking, termed BPL (Broadband over Power Lines), by the ability to transmit data over the existing power lines for homes and offices [3]. Related to fault detection, Taylor and Faulkner proposed direct-sequence spread-spectrum modulation on power line carrier, and outlined optimal signal processing techniques and frequency domain correlation techniques for the on-line test in high voltage line [4]. Lately, slightly different use of spread spectrum was reported from the research result of on detecting avionic wire problems [5].

The novel approach of carrier signal in fault detection comes from the idea that, since random and unpredictable intermittent would be detected, if detectible, only when the event is active, the ideal solution method would place something continuously on the wire system that can be causally influenced by any event on the wire. The proposed approach applies as the "something" carrier signal, populates the wire system under observation all the time with carrier signal, and utilizes the disruptions made in the carrier signal caused by any event on the wire, even by random, unpredictable intermittent fault as the main discriminatory feature of intermittent faults. In terms of signal communication, the received carrier signal against expected signal reveals the status of the wire as carrier signal channel characteristics. Since it is believed that an intermittent fault along the line would disrupt the carrier signal, enough would be even a simple carrier signal modulation scheme like frequency shift keying (FSK) which varies the frequency of the carrier signal according to the value of each bit in the digital data stream transmission [6].

In practice, with the FSK scheme, transmitted over electrical interconnect system, carrier signal would not be disrupted if the medium is clean, healthy, and quiescent, and therefore there would not be data error in the received data. However, when the medium is under interruption, disruption, or intermittent excursions, the carrier signal would be disrupted, which in turn results in disruption or error in the data stream. The error in data stream indicates certain abnormal event a wire section between a transmitter and a receiver. In other words, the erroneous information or missed information against the correct information between a transmitter and a receiver would indicate that the carrier signal communication channel, the segment of the electrical wire in electrical system, is faulty. Also, an open circuit can be easily recognizable by the no received data stream for a period.

Fig. 1 shows streams of digital data and their corresponding carrier signals of FSK modulation. The digital date streams are shown in the upper trace and modulated carrier signals in the lower trace. The carrier signal, once amplified, passes through the filtering circuit into the electric circuit, resulting in the co-existence in the circuit of high amplitude low-frequency power signal and low amplitude high-frequency carrier signal.

At the receiver side, the modulated signal is FSK demodulated accordingly, and the data stream is reconstructed. If the received data stream matches with the data stream from a transmitter, it can be said that the communication medium, the wire, is quiescent and healthy. In such quiescent circuit, as depicted in Fig. 2, it is expected to have the identical digital data streams of both transmitter (upper trace) and receiver (lower trace). The time shift between two data streams, determined by the bit rate of the carrier signal modem, is clearly seen in the figure.

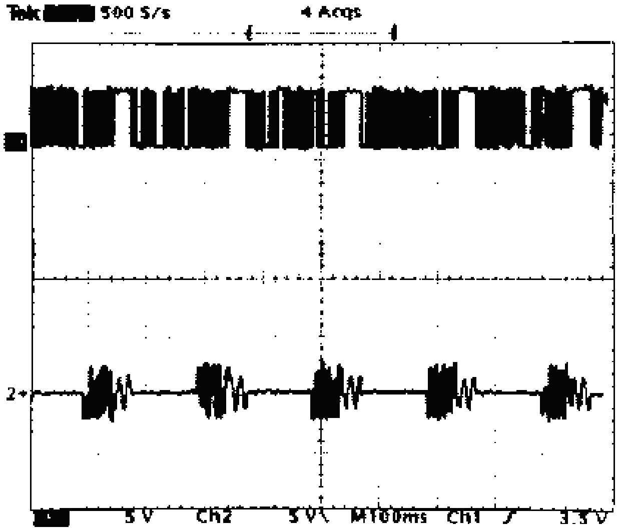


Figure 1. Transmitted digital data stream (upper trace) and corresponding carrier signals (lower trace).

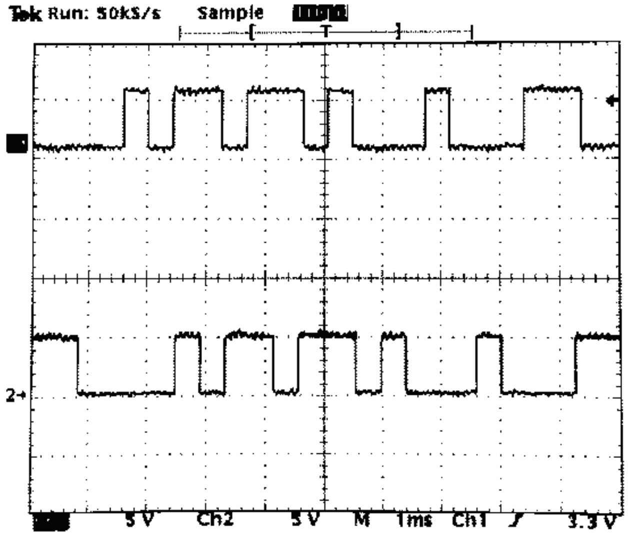


Figure 2. Transmitted (upper trace) and received digital data streams (lower trace) in the quiescent states in wire.

When the carrier signal communication channel of wire system is disrupted by intermittent or incipient fault, the signal over the wire would also be interrupted. In Fig. 3, the upper trace is data streams of a transmitter, and the lower trace shows the modulated carrier signals received at a receiver disrupted by a staged intermitted fault condition. The carrier signals are much different from those in Fig. 1 of normal condition.

Then, the received data stream would be also different from the transmitted data stream. Fig. 4 shows the disrupted and thus erred received data in the receiver side (lower trace) against the data stream sent from a transmitter (upper trace). The received data in lower trace is starkly different from the transmitted bit stream of the upper trace.

As illustrated, using the carrier signal scheme, by analyzing the erred received data stream against expected data, abnormalities in electrical system can be detected and located in real time.

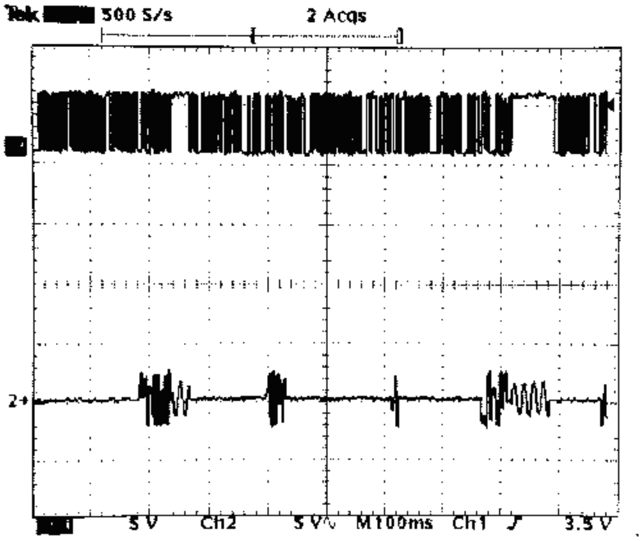


Figure 3. Disrupted carrier signal example (lower trace) caused by intermittent fault.

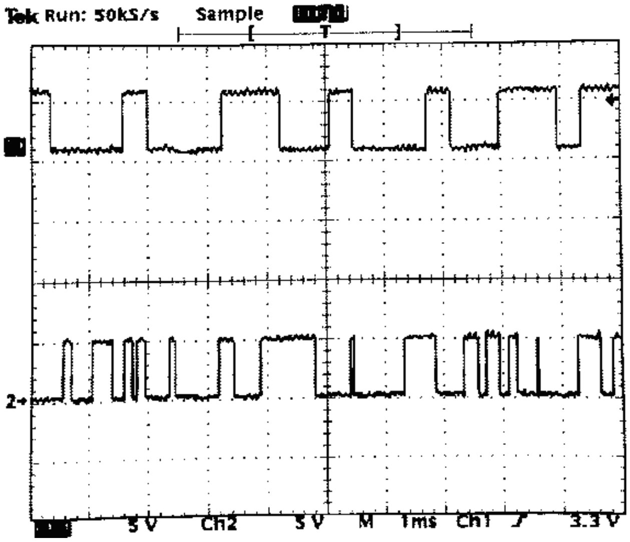


Figure 4. Disrupted and erred received data (lower trace) vs. the transmitted data (upper trace).

B. *Data Stream Errors*

To detect an error or fault, the receiver compares the data received from the transmitter against pre-assigned data that it has stored regarding each transmitter. For a definite detection of fault while reducing false-alarm possibility, the mismatch would better be accumulated, instead of just one transmission of data stream, over multiple data streams sent and received on the wire. For the digital data stream mismatch over multiple data streams, three types of data errors are considered: data mismatch rate, lost data rate, and total error rate. Data mismatch rate is defined as the percentage of the number of data streams arrived with mismatch per total number of received data streams. Since some data streams can be completely lost in transit and can not be seen by the receiver, the lost data rate is accommodated, defined as the percentage of data streams that are lost in transit per total number of sent data streams. In order to accommodate and consider the intrinsic bit error rate of carrier signal modem, the total error rate is defined as the percentage of data errors plus lost streams out of the total number of sent data streams. When the accumulated errors are compared with a threshold, an alarm would be activated to alert of intermittent fault condition.

Other than these error raters, once can devise other types of errors for application. Alternatively, instead of looking into errors, one can rely on correct number of data streams. However, the error rate we adopt for the paper is NER (noise error rate) or FER (fault error rate). In initial trials with the two configurations, we first noticed that errors were reported even in normal condition. Further investigation revealed that there were carrier signal modem inherent errors and they generally caused a large number of incorrect bytes within a data stream. We also noticed that there was another type of errors with a small number of incorrect bytes, with only 1 or 2 bits in mismatch. Finally, we reached at a conclusion that this type of error, an erred byte with 1 or 2 bit mismatch, was generated by noise in the circuit from staged intermittent fault condition. The noise error can be termed as fault error because the “noise error” is believed to be originated from the spikes and short bursts from staged fault conditions. Then the noise error rate is the percentage of data streams with noise errors out of the total number of data stream received.

C. Methods for Transmitter and Receiver Configuration

Practical use of the carrier signal approach can be made in two ways. The first one is single transmitter and single receiver configuration (STSR) which works best for a dedicated safety-critical electrical circuit such as rudder control electrical system, aircraft wheel well electrical system, or fuel pump system, for continuous real-time intermittence monitoring with carrier signal populated over the circuit. In the STSR, the detection and location of the fault are the same: when a fault is detected, the location is the dedicated circuit itself.

Another way of applying the carrier signal approach is to use multiple transmitters and a single receiver configuration (MTSR) which can be applied to a circuit which branches into many different sub-circuits each having electric load. In this configuration, each transmitter is installed at the end of a sub-circuit where load is installed, and the receiver is positioned at the end of the main circuit so that the receiver can receive data streams from all transmitters. Well configured protocol and transmitter identification, and collision avoidance and arbitration enable this configuration possible. As an example, Fig. 5 illustrates such a MTSR carrier signal system with a receiver on the main circuit and three transmitters in the 3 branches. All the segments of the main circuit and the sub-circuits are labeled for the discussion of fault location method.

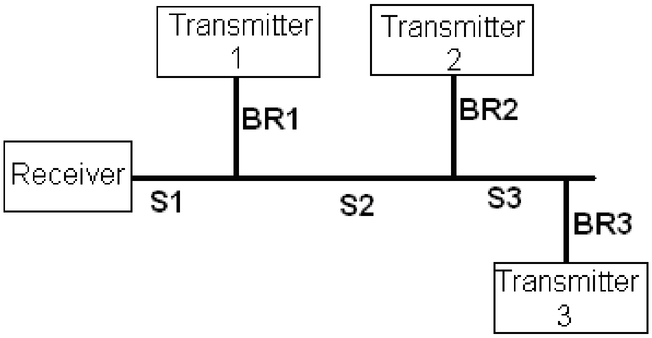


Figure 5. Example circuit with MTSR configuration of carrier signal application.

For transmission across circuits and sub-circuits, various approaches of handshakes may be used to ensure that signals sent by multiple transmitters do not interfere with one another. We consider two types of handshake which can be used for any configuration with at least one transmitter and a receiver: "Multi-master transmitters" handshake and "single-master receiver" handshake.

In the approach of multi-master transmitters in which multiple transmitters send signals one at a time without the control of the receiver, each transmitter monitors the wire via a "carrier detect" that detects if there is any carrier signal present on the wire, and waits to send its signal until there is no signal on the wire. Therefore, at any one moment, only one transmitter is allowed to send signals. To ensure signal integrity, at each transmitter, random pause duration would be mandated after each signal transmission so that other transmitters have chance to transmit. By this accommodation, each transmitter would have an equal chance to send a signal and, therefore, each sub-circuit segment would be monitored at the same priority with an equal chance of detecting errors.

In "single master-receiver" handshake, at a given time, only a specific transmitter that is commanded by the receiver is allowed to send a signal. For example, the receiver would send a data stream to a transmitter and, after the transmitter recognizes and receives the data, the transmitter would copy the data and transmit the data back to the receiver. The comparison of the received data at the receiver against the sent data determines if there is an error in the signal, which in turn indicates that a fault exists in the circuit segment between the receiver and the commanded transmitter. The receiver would select a transmitter sequentially in a set order or randomly.

D. Fault Location Method

The location of faults in MTSR, either in the main circuit or at a sub-circuit, of the intermittent incidents can be easily acquired by the analysis of the erred data streams of the transmitters. If needed, with real-time tagging feature, the incident time could be also obtained for the occurrence timing determination and other analyses. Referring to Fig. 5, one example of using the carrier signal approach is described to detect and locate fault in a circuit. In the figure, a receiver is positioned at the end of the main circuit and three transmitters are connected each to one of the three sub-circuits. The circuit is segmented by the branching points of sub-circuits from the main to segments S1, S2, and S3 and branches BRl, BR2 and BR3.

By the detection methods described above, it can be determined if a particular error exists in one of the sub-circuits associated with a particular transmitter. For example, the mismatch of expected data from the Transmitter 1 versus received data, while there is no mismatch from the Transmitters 2 and 3, may indicate that a fault exists in branch BR1. To take a few more examples, if no errors are determined for Transmitters 1, 2 and 3, no fault exists in the network. If no errors are detected from Transmitters 1 and 3, but an error is detected from Transmitter 2 then a fault may exist at segment S2 and/or both branches BR2 and BR3. Table I summarizes for the receiver to use to determine the possible location or locations of electrical faults within the example network of Fig. 5. In the table, binary numbers 0 and 1 are used to indicate "no mismatch" and "mismatch", respectively, between the received and expected data streams. The decision-making table can be any type of data structure and may vary depending upon the placement of the transmitters and the receiver and the exact configuration of the circuit or other circumstances.

TABLE I. EXAMPLE DECISION-MAKING TABLE FOR FAULT LOCATION

Transmitter 1	Transmitter 2	Transmitter 3	Fault Location Section
0	0	0	No Fault
0	0	1	BR3 or S3
0	1	0	BR2
0	1	1	S2 or (BR2 and BR3)
1	0	0	BR1
1	0	1	BR1 and (BR3 or S3)
1	1	0	BR1 and BR2
1	1	1	S1 or (BR1 and BR2 and BR3)

III. FUNCTIONALITY TESTS OF CARRIER SIGNAL APPROACH

The main purpose of the functionality test is to evaluate the carrier signal method's capability of determining intermittent fault conditions in electrical circuit. The principle of the test is to send a message of prescribed data protocol over electrical wire from at least a transmitter and to compare the message received at a receiver for mismatch or complete loss of message. The prototype carrier signal controller and the experiments conducted are described here.

A. *Prototype Development*

Realization of the carrier signal approach consists of one or more transmitters and a receiver. A carrier signal controller can server as a transmitter or a receiver, or a transceiver. The controller can be easily implement by either commercial off-the shelf (COTS) microprocessor and carrier signal modem or application specific integrated circuit (ASIC) of combining microprocessor and modem, along with coupling circuits.

The prototype controller board developed for the functionality test is built on a low-range microprocessor, a 2400 bps FSK modem, and a coupler circuit (See Fig. 6). The microprocessor contains the micro-codes of protocol, data stream, and operation of the carrier signal method. The modem modulates digital data stream into carrier signal for transmission and, in reception, demodulates carrier signal to digital data stream. The controller, when used as a transmitter, sends data stream in digital format via modem in which it is modulated by the modem and injects the modulated signal through the coupling circuit to electrical wire. When used as a receiver, the controller receives the carrier signal which is filtered through the coupling circuit, and demodulates it to digital data stream. The receiver, upon the arrival of the digital data stream, checks if there is mismatch in the received data against the transmitted data. The coupling circuit, made of a transformer and capacitors, serves multiple functions: isolation of the modem and controller from the wire; injection of the carrier signal on the wire; extraction of the carrier signal from the wire; filtering out the high-amplitude low-frequency signal of the wire; and the filtering out the harmonics of the carrier signal.

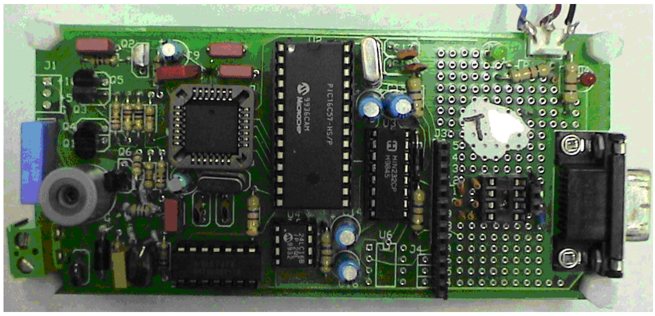


Figure 6. Carrier signal controller prototype.

B. *Test Circuit and Fault Staging Methods*

The functionally test was performed in a simple circuit of one main and two branches under staged intermittent fault conditions. A segment of wire from exterior complex harness specimen taken from the wheel well of 747 aircraft was used to form the circuit. As depicted in Fig. 7, a receiver (RX1) was positioned near the end of the circuit and two transmitters (TX1 and TX2) were in the two branches. Three bulbs (labeled as "L") were connected to the circuit for load simulation at the circuit segments. Also, three arc/spark generators (K1, K2 and K3) were inserted each at a segment. For STSR tests, K3 was removed from the circuit so that the sub-circuit of TX2 and the sub-circuit load were entirely removed from the circuit; only K1 or K2 was connected or staged for intermittent fault. For MTSR tests, all three arc/spark generators were in place and operated in order for different test scenarios. Since the location of fault was simple enough for the experiment, we focused instead, but for the same effect, on the discrimination of the faulted segment.

In all the test conditions, only multi-master transmitters handshake was employed.

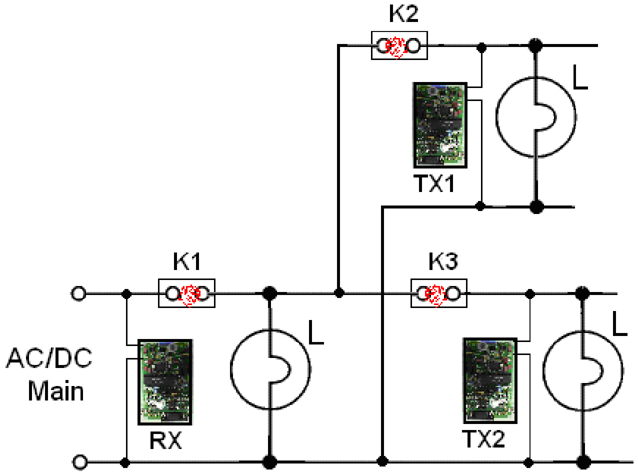


Figure 7. Circuit diagram for functionality test.

The arc/spark generator staged intermittent fault conditions in one of two methods: rubbing the contact blades of a knife switch or touching a copper strip sporadically on a revolving drum with a hanging wire. Fig. 8 depicts two mechanisms of staging methods of intermittent faults and the arc/sparks generated by the methods.

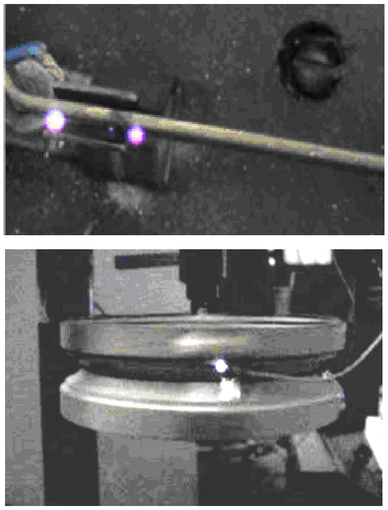


Figure 8. Intermittent fault staging by knife switch blade rubbing (top) and sporadic touching of grooved copper strip on revolving drum with hanging wire (bottom).

C. *Experimental Results*

In the test run, the following example protocol was adopted for data stream transmission with a total of 16 bytes: 1 preamble byte for alerting the receiver of an incoming data stream, 2 sync bytes for notifying the receiver of oncoming valid data stream, 1 byte for receiver identification (ID), 1 byte for transmitter ID, 1 byte for data stream number, and 10 bytes of data of any combination or, in the test, all same byte as the sender ID. In the test, while the arc/spark generators in operation, the data stream of the above protocol was transmitted from a transmitter into the circuit and the receiver, upon reception of the data, compared with corresponding expected data stream from the transmitter for number of bytes and bits that were incorrect. In the computer attached to the receiver, either the mismatch flag or the number of errors from each transmitter was displaced on screen. These tests were run multiple times and an average error rate was calculated.

Under staged fault condition, there was a big increase in the error rate which indicates a large increase in the number of noise errors that were believed to be caused by the spikes of very short duration. Fig. 9 displays one of the spike bursts captured by high speed oscilloscope with the sinusoidal carrier signal in the background. The figure supports the conjecture that the "error noise" of having only 1 or 2 bit errors in the erred byte, which numbered also 1 or 2, is mostly likely from the short-burst of intermittent fault and its monitoring would be a good metric for detection of such fault.

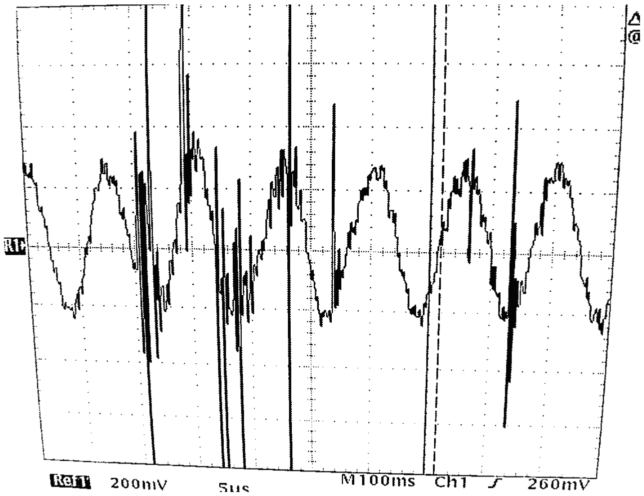


Figure 9. High frequency spike generated by staged intermittent fault.

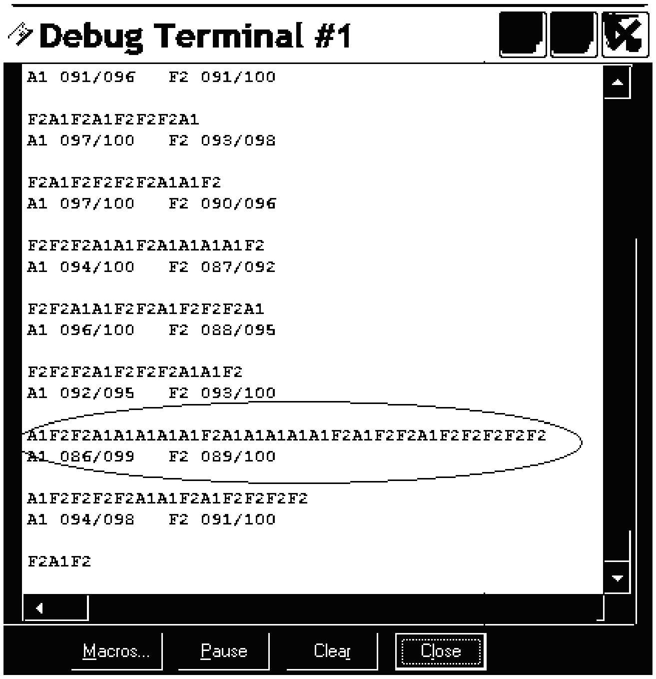
In general there was a direct relationship between the error rate and the occurrence of the intermittent fault. Table II shows the cumulative results of noise error rate for normal and staged intermittent fault conditions under STSR configuration.

TABLE II. TEST RESULT COMPARISON OF NOISE ERROR RATE FOR BASELINE AND FAULT CONDITION

Experiment Condition	**NER**
No intermittent fault (baseline)	0.34
Intermittent faults condition	9.18

For the MTSR testing, the arc/spark generator K1 was replaced by a solid contact and only K2 and K3 were used, one at a time, for the condition of intermittent fault or normal condition in the sub-circuits. In this case, a different way of finding carrier signal disruption was applied by measuring, instead of noise error rate of data stream, the rate of matched data stream with expected one. In this particular case, the ID and the byte data for transmitter 1 were set as A1 in hexadecimal format or 10100001 in binary format. For transmitter 2, they were set to F2 or 11110010. By this measure, possible loss of data stream due to the collision of two data streams from both transmitters (even with "carrier-detect" measure of the modem) would be accommodated. For the result, only mismatch data stream was displayed by the ID on the screen. After 100 data streams received from either transmitter a correct data rate was calculated for each transmitter.

Fig. 10 shows one sample screen shot of test results. As in the screen display, during the normal baseline cases, A1 and F2 are randomly placed, which indicates random error caused by the data stream collision or inherent error from the modem. On the other hand, when faults were staged, each several times at a time, either A1 or F2 are consequently displayed continuously, but not both. In the longest text display circled in the figure, after mixed A1's and F2's, first A1's are repeated (from the operation of A2) followed by mixed F2's and A1's (caused by the transition from K2 to K3 staging) and then, finally by the continuous F2's from K3 staging alone.



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A1 091/096   F2 091/100

F2A1F2A1F2F2F2A1
A1 097/100   F2 093/098

F2A1F2F2F2F2A1A1F2
A1 097/100   F2 090/096

F2F2F2A1A1F2A1A1A1A1F2
A1 094/100   F2 087/092

F2F2A1A1F2F2A1F2F2F2A1
A1 096/100   F2 088/095

F2F2F2A1F2F2F2A1A1F2
A1 092/095   F2 093/100

A1F2F2A1A1A1A1A1F2A1A1A1A1A1F2A1F2F2A1F2F2F2F2F2
A1 086/099   F2 089/100

A1F2F2F2F2A1A1F2A1F2F2F2F2
A1 094/098   F2 091/100

F2A1F2
```

Figure 10. Screen shot of test results of MTSR configuration.

In conclusion, the functionally tests of the proto board system demonstrated the promise of the carrier signal approach in detecting intermittent fault in electrical wires. The results showed remarkable consistency in the error rates with staged fault conditions. Also they exhibited discriminatory capability of faulted segment location. In all, the approach, with data error rate or correct data rate as the main discriminator between no-fault and fault conditions, passed the feasibility test of its use in detecting intermittent faults in electrical systems.

IV. CONCLUSIONS

We investigated the carrier signal technology as a tool for determining intermittent faults in electrical systems. We discussed about the schemes of the technology in terms of controller configurations for transmission and reception of the signal, protocols and handshakes for carrier signal for integrity of the communication system, and the communication channel characteristics in terms of errors of the wire status. In practice, we transmitted a known data repeatedly over the system and observed the number of data that contained errors when received by a receiving station. Also, we were able to successfully simulate intermittent faults by rubbing two blades of a knife switch and by sporadically touching hanging wire to a grooved copper strip surrounding a revolving drum.

In the functionality test, we observed that staged intermittent faults caused a big increase in the noise error rate. In another approach of detecting faults with MTSR configuration, we could observe the discriminatory capability of the approach in locating the faulted segment in wire network.

Monitoring of the disruption of carrier signal over electrical wire between a transmitter and a receiver provides the most effective tool for continuously, real-time, watching the wire system for detecting and locating the random, unpredictable intermittent faults, the harbingers of disastrous electrical failure. The strength of the proposed approach is in its application freedom: any number of controllers can be installed at any location for any segment of the wire in the electrical system. This approach holds a promise of being easily realizable to light-weight, small footprint apparatus that can be seamlessly integrated into the existing or new safety-critical vehicles of aerospace, sea, or undersea. The apparatus, installed in such vehicles, is expected to contribute to the reduction of mishaps, mission abortions, "nff" puzzles, and maintenance costs.

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