Prognostics of connection defects in electronics modules

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ABSTRACT

Electrical connection anomalies are widely known as problems in industrial applications. In machinery these can occur in a printed circuit board, for instance in a control unit, in the interfacing connectors, or even in the inter-connections within a sensor or an actuator. Different methods have been proposed in the last decades to detect these anomalies. Most of these methods are working on non-powered systems for instance by measuring reflections of a high speed pulses (reflectometry principle). However, the most challenging connection anomalies have intermittent nature, often in applications where vibration stresses are dominant (e.g. automotive sector). In these cases, detecting these anomalies in a live (powered) system is needed. Although some methods exist which allow such a detection, they are expensive, limiting the targeted applications (e.g. aeronautics). We developed low-cost methods to detect connections anomalies in live systems. These methods use measured signals, for instance across a sensor, not only to detect a fault in its connections but also to localize the position of such a fault. The used 'diagnostic' systems will trigger a warning at a very early stage of the connection anomaly. The proposed methods have been applied and validated on different industrial cases and proved to be able to localize within 30 cm accuracy and to detect connection degradation before corrupting the operation of the system.

1. INTRODUCTION

Aging electrical systems are prevalent in today's society. They are abundantly present in buildings, aircraft and transportation systems, consumer products, industrial machinery, etc. Wiring and connections failures could be seen as dominant failures in such electrical systems and are the most significant potential causes of catastrophic failures and maintenance cost in these systems. Furthermore, airline crashes attributed to aging wires and connections have brought this issue into the public eye (Furse, 2006). A wiring system does not only distribute electrical power but also provides control and information links between multiple systems and sub-systems. The components to make-up the wiring system include power and control conductors, signal and instrumentation conductors, fiber optic cables, connectors, circuit breakers, relays, power distribution and control panels, etc. Failure of any of these components can disable the functioning ability of a system (Kiptinness, 2004). Different techniques exist which allow to detect, or monitor the aging of wires and connectors and sometimes localizing the defects location. Reflectometry is commonly used for detecting faults in a wiring harness and localizing their positions (Lynch, 2002). Different reflectometry methods exist, such as time domain reflectometry (TDR), frequency domain reflectometry (FDR), etc. (Sharma, 2005), (Smith, 2005). The reflectometry methods are often used when the wiring system is not powered. This makes the detection of intermittent connections problems not possible. These intermittent failures only occur in live (active) systems and often when the system is exposed to an external stress (e.g. temperature swings, vibration), for instance in a car. They can have a very short duration (down to µs) (Kuhn, 2006). Such intermittent connection faults can be fatal in some applications because they are not detectable offline and when happening, online, they may lead to a loss of system functionality in critical conditions (e.g. for safety critical systems). Therefore, it would be logical to develop techniques which can detect, monitor and if possible localize these faults in live systems. Although some techniques belonging to the reflectometry family can deal with intermittent faults, for instance spectral time domain reflectometry (STDR) (Sharma, 2005), these techniques require expensive components (e.g. high frequency generator, mixer, etc.) which makes these techniques not suitable for industrial and automotive applications with their low-cost requirements. Other alternative technologies for connections defects detection and localization consist of impedance measurements (LCR as a reference to inductance [L], capacitance [C] and resistance [R] measurements) of the wire and/or the connector. LCR meters exist already for a long time to perform equivalent impedance measurements of an electrical circuit (Agilent, LCR meter operating and service manual, 1983). Some papers used this principle to develop a low-cost equipment to measure equivalent capacitors or inductances of a circuit which will be associated to open or short connection faults (Chung, 2009). The method used in that paper does not work in live systems. Using impedance measurement technique for detecting impedances in live circuits has its own challenges and limitations (e.g. used frequencies, needed filters, change of impedance due to additional measurement equipment, etc.). An analysis of such impedance measurement in live mains have been done using expansive lab equipment's (Coenen, 2013).

In this paper we investigate the detection and localization of intermittent connection faults in live industrial applications. We propose two different low-cost methods (using commercial off-the-shelf components) for this purpose that allow:

1. Detection and localization of intermittent connection faults using an extended impedance measurement technique
2. Detection of intermittent faults based on applying a band-pass filter on measured signals from a circuit

These methods will be explained in details in this paper which is organized as follows. In section 2, the two concepts will be further elaborated. In section 3, the validation of the online impedance measurement concept on some set-ups for industrial applications will be highlighted. While in section 4, the band-pass filtering approach will be validated on industrial applications. Conclusions will be drawn in section 5.

2. CONCEPTS FOR CONNECTION DEFECTS DETECTION, PROGNOSTICS AND LOCALIZATION

In this section the concepts of the two proposed methods will be explained.

2.1. Method for connection defects detection and localization – based on online impedance measurements

Impedance measurement can be used to detect different connection faults by estimating the additional impedance, due to connection faults, to the equivalent impedance of a circuit. The type of the fault can be differentiated by looking to the imaginary part of the impedance (capacitive in case of open connection fault or inductive in case of short connection fault). Different methods exist depending on the used diagnostic circuits (Agilent, Impedance measurement handbook: 4th edition, 2013): bridge method where a bridge of impedances (including the impedance of the device under test) is used to estimate a balance point, resonant method where a circuit is adjusted to resonance by adjusting a tuning capacitor, I-V method to calculate the unknown impedance by measuring the current and voltage across the impedance. We adopted the I-V method in this work which we adapt to be suitable for working in a live (powered) system. The basic schematic is shown in figure 1. To make it suitable for online usage, the diagnostics circuit parameters need to be selected such that it has no influence on the original sensor measurements. These parameters are related to the transmitted sine wave that is superimposed to the original circuit signals. The frequency of the transmitted sine wave should be selected beyond the bandwidth of the electrical circuit such that it is not influencing it's working. For instance for a 5kHz bandwidth circuit, choosing a diagnostics frequency of 10 times higher magnitude would be largely safe to avoid interferences with circuit signals. The amplitude of the transmitted sine wave should be small enough to avoid disturbing the circuit but large enough to be detected. These parameters were tuned properly to the target applications.

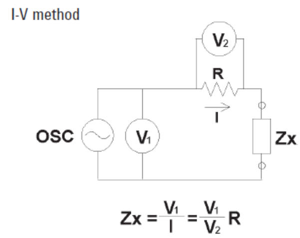

Figure 1. Basic circuit for impedance measurement

A typical representation of this circuit in a final industrial application is shown in figure 2a and 2b, respectively to capture open or short connection faults.

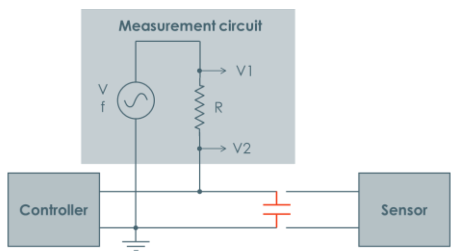

Figure 2a. Impedance measurement circuit used to diagnose open connection fault in an industrial circuit. R should be large.

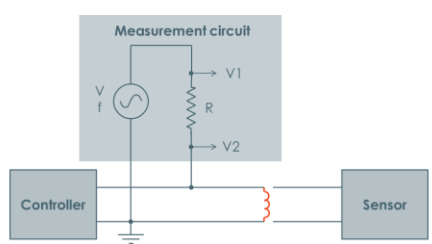

Figure 2b. Impedance measurement circuit used to diagnose short connection fault in an industrial circuit. R should be small.

For the configuration used in figure 2a, the diagnostics resistance *R* should have a high value (in kΩ) to allow seeing the phase difference between voltage and current signal. This value should however be smaller (in hundreds of Ω) in case a short connection fault needs to be detected as depicted in figure 2b.

The diagnostic circuit would provide diagnostic voltage and current which should be analyzed both in amplitude and phase to extract the equivalent impedances (capacitive for open and inductive for short). An application specific example of a signal captured when using a resistive load is depicted in figure 3. An algorithm has been developed which conditions the measured signals by fitting automatically a sine wave to the measured signals and use these fits to reliably estimate the amplitude and the phase of voltage and current.

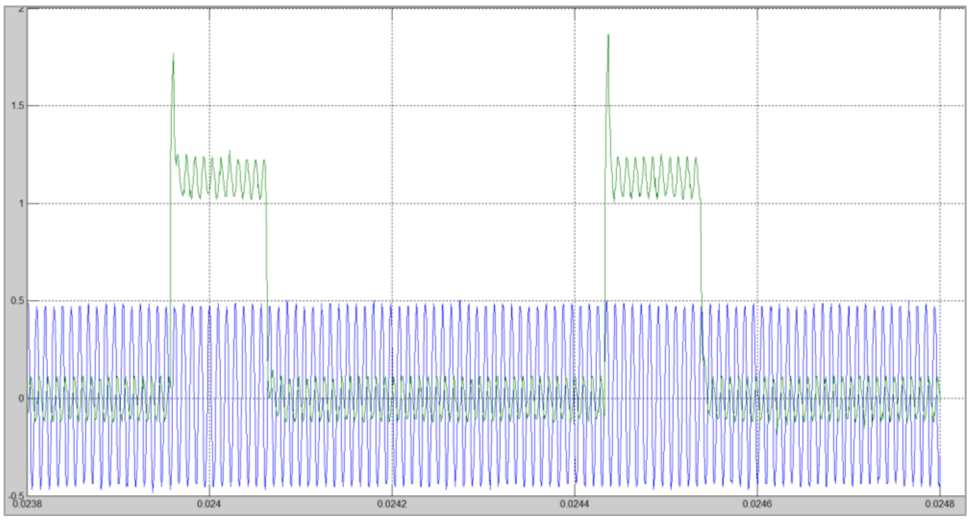

Figure 3. Captured voltages V_2 (green) and V_1 (blue) (as described in figure 2a and 2b) when using a resistive sensor

As shown in figure 3, the green graph illustrates the resulting measured signal seen across the sensor after adding the diagnostics signal. Depending on the circuit equivalent load (for instance from controller and sensor side), the measured signals can be very weak where the automatic fitting becomes necessary to obtain accurate estimates of the impedance, as depicted in figure 4.

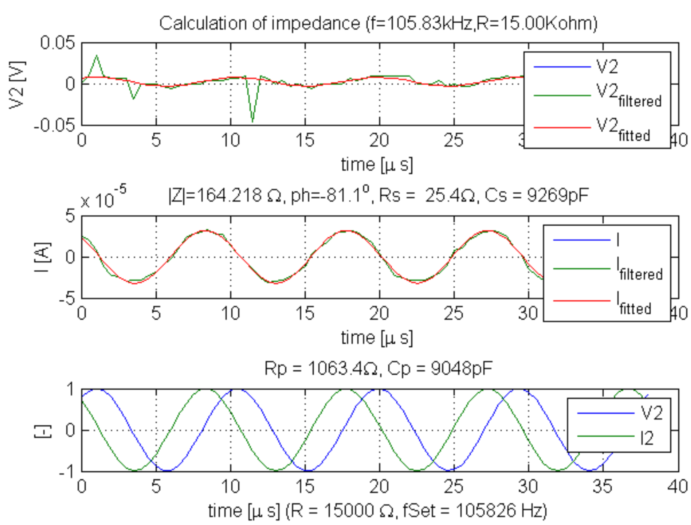

Figure 4. curve fitting and equivalent impedance estimation (|Z|: equivalent estimated absolute impedance, ph: estimated phase between current and voltage, Rs, Cs: Equivalent series resistance and capacitance), Rp, Cp: equivalent parallel resistance and capacitance)

After fitting a sine function to the measured signals, the estimation of the amplitude and the phase difference between the two signals is reliably determined. Using these two parameters, the resistive and capacitive parts of the equivalent impedance can be calculated. In this examples an equivalent resistance of 1063 Ω and an equivalent capacitor of 9048pF, which corresponds to the load impedance, is found. Assuming now that a connection problem occurs between the controller and the sensor, the online estimated resistance and capacitance will be different and would be proportional to the length of the wire where the fault occurs allowing thus localization of the fault. If instead of open, a short fault will occur, an inductance will be estimated instead of a capacitance value (using the diagnostic circuit depicted in figure 2b using small diagnostic resistance)). The validation of this concept to detect intermittent connection faults will be presented in section 3.

2.2. Method for connection defects detection – based on band frequency filtering

In various applications, localizing the connection faults positions is not necessary. In these cases, detecting the connection faults will be sufficient. Based on connectors tests we performed for different connectors, and as reported in different literature studies (Lau, 2013), the measured signals of an electric circuit with a degrading contact resistance would present relatively high frequency noises. Examples of captured faults during tests on different connections is shown in figure 5.

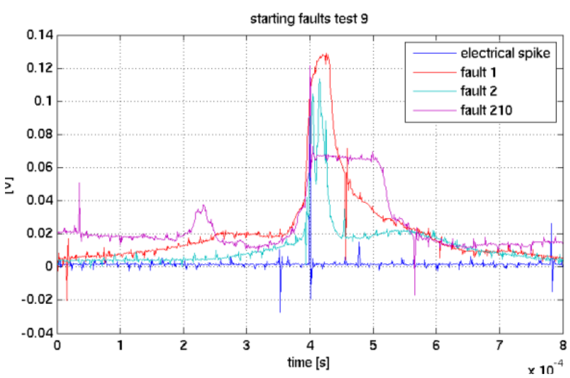

Figure 5. captured voltage for different connection faults during a test

These variations of fault amplitude and duration can be explained by the number of irregularities in the surfaces of the connectors which, due to thermal changes and/or vibration of the connectors, introduce intermittent loss of contact which increases versus time. By analyzing carefully, the characteristics of these contacts noises on different industrial applications, it has been concluded that an algorithm based on band pass filtering, using generic parameters, could be used to detect these noises whose amplitude is correlated to contact degradation level. This is very advantageous for industrial applications since no external diagnostics hardware would be needed. A description of such an algorithm is given in figure 6.

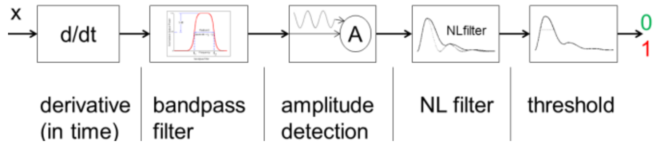

Figure 6. Block diagram of the connection fault detection algorithm

The 1st derivative of the signal *x* acquired for instance in a control unit which is coming from a sensor, as shown in figure 2a, & 2b, is feed to a bandpass filter whose cut frequencies were chosen based on different datasets. The output of such a filter is likely to be the connection noise whose amplitude is further processed by using a non-linear (NL) filter with a forgetting factor to smoothen the obtained amplitude. The output of this NL filter is then compared against a threshold to trigger a warning. This output can also be used directly for prognostics purposes as will be explained in next section.

2.3. Prognostics – based on features trending

Prognostics is often used in industrial applications to predict when a 'serious' failure will happen which may damage the complete system or part of it. By taking safety margins on the predicted periods, a proper maintenance action could be planned to avoid such a failure. Traditional trending could be applied when the monitored feature is monotonously correlated to the studied fault. When this later has an intermittent nature, this trending needs to be adapted to be able to capture these intermittent faults. In this section we discuss some of these analyses for connection faults. As it is observed, for example from figure 5, basing a trending feature on the fault amplitude would not show monotonous changes versus time as, for instance, amplitude of fault 210 is lower than the first or the second one. However, monitoring the fault duration as a feature could bring more valuable information. The evolution of the connection faults durations observed for 20 hours accelerated lifetime testing on industrial connectors is illustrated in figure 7.

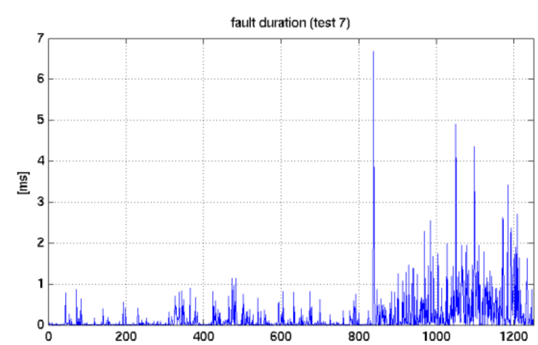

Figure 7. Connection faults duration on 20 hours accelerated lifetime testing of industrial connectors.

3. VALIDATION OF CONNECTION DEFECTS DETECTION AND LOCALIZATION USING IMPEDANCE TECHNIQUE

In this section the methods presented in section 2 are validated on different industrial applications.

3.1. Intermittent open fault localization under a resistive load

In order to validate the impedance measurement technique described in section 2.1. a set-up as depicted in figure 8 has been made using different wires lengths. The equivalent capacitance of the control unit and the wire's capacitance per meter have been determined offline. A controlled switch has been placed before the sensor in order to simulate an open connection fault.

Considering 2 wire's lengths of respectively 3m and 5m between the control unit and the sensor (by placing two sensors/switches in parallel at different distances), the estimation of the distance to fault is done using our technique online and the results are shown in figure 9.

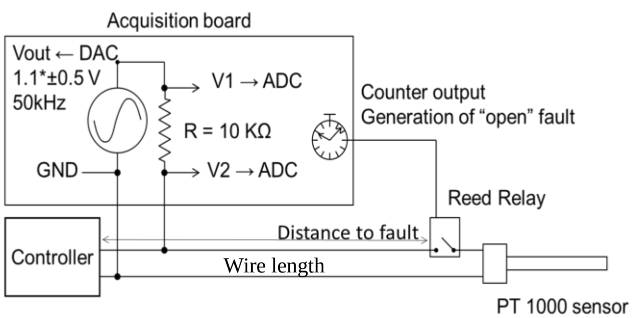

Figure 8. validation set-up for impedance measurement with a resistive load

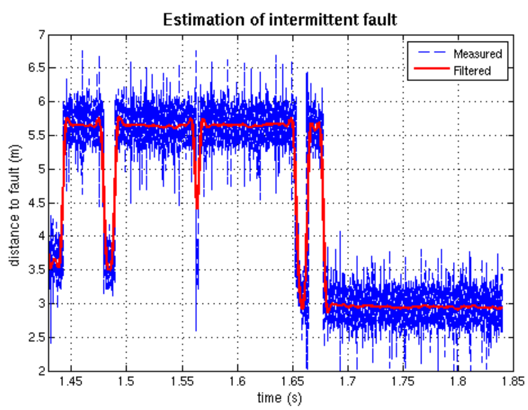

Figure 9. estimation of distance to fault for an intermittent open connection fault

As depicted in figure 9, the intermittent duration of the faults that can be detected is limited by the used acquisition system (ms in the graph). The accuracy of this estimation is quantified by plotting the estimation error in a histogram (figure 10).

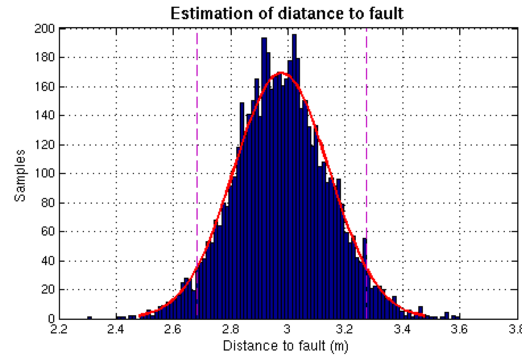

Figure 10. distance to fault accuracy estimation

The accuracy of the fault localization reaches 2σ ± 30cm, which in many industrial application is sufficiently accurate to determine the location of the defected connector.

3.2. Intermittent open fault localization under a load with a complex impedance

The impedance technique was also validated on another load type (solenoid valve). Such a load with its driving circuit does not only have a resistive impedance but a complex one. The solenoid valves are often used in industrial applications to regulate a fluid flow and are sometimes put in a safety critical path of a system. Therefore, detecting a connection problem in such a part is quite important. A set-up has been made for connection fault monitoring in a valve system This shown in figure 11.

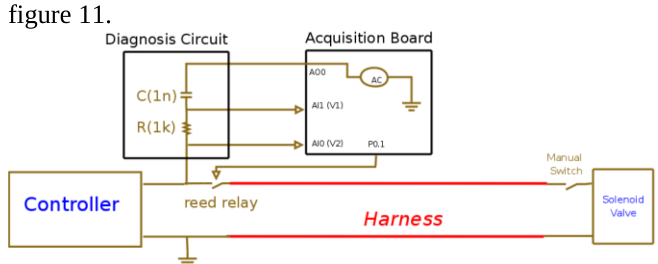

Figure 11. validation set-up for impedance measurement with a complex load

As indicated before, the solenoid valve and its driving circuit have a complex impedance therefore the diagnostics circuit contains a capacitor which was selected for this case to avoid current flowing back in the diagnostics circuit. Furthermore, for a better control of the valve, it is driven using a PWM (Pulse Width Modulation) signal. In case of an open connection fault, the equivalent line capacitance changes with the voltage needed to drive the solenoid with PWM with a given duty cycle (for relevant duty cycles, this voltage ranges from 10.5V to 12V). This is due to the equivalent capacitance of the MOSFET switch used to control the PWM signal and which depends on the voltages. In order to compensate for this variation a lumped parameter model of the equivalent electrical circuit is fitted to the measured data. This is depicted in figure 12.

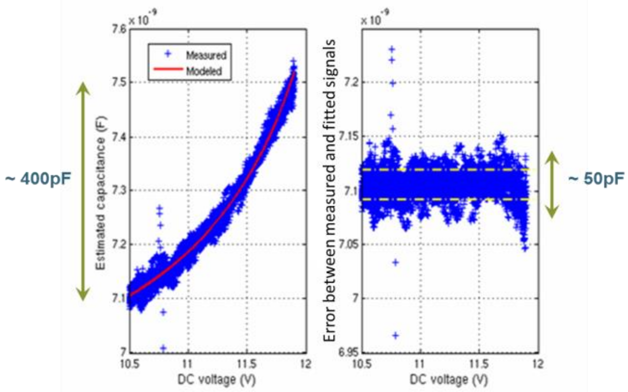

Figure 12. Compensation for equivalent impedance variation due to PWM voltage (left graph: non-compensated capacitance estimate, right graph: compensated capacitance)

The resulting capacitance after compensation (right side of figure 12) corresponds closely (max. error of 50 pF) to the equivalent wire capacitance indicating an open connection at the solenoid side. The compensation consists of removing the capacitance dependency of the load versus voltage.

4. VALIDATION OF CONNECTION DEFECTS DETECTION USING BAND-PASS FILTERING

The advantage of the band-pass filtering method for detecting connection defects, as explained in section 2.2, is that it can be applied without adding a diagnostics circuit. Therefore, the method can be validated using recorded signals which potentially contain emerging connection faults. In this section we will validate this technique on two cases: (1) where a set-up is made to mimic starting connection faults, at different degradation levels, in a pressure sensor signal; (2) signals recorded in an industrial environment from temperature sensors where one of them contains connection faults signatures.

4.1. Intermittent open fault detection in a pressure sensor signal

A set-up is made for measuring the pressure signal and easily add the connection noise in the signal. This is depicted in figure 13.

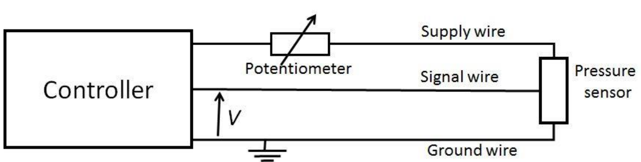

Figure 13. Set-up for connection faults generation in the supply wire of a pressure sensor.

As illustrated in figure 13, the pressure sensor is a ratiometric sensor with three wires. The connection faults are added in every wire separately by adding initially a potentiometer that can be tuned manually and later a grid of resistances that can be controlled automatically to generate different connection faults profiles.

Once the signal, including connection faults, is recorded, the algorithm described in section 2.2. is applied to detect these faults. An example is illustrated in figure 14.

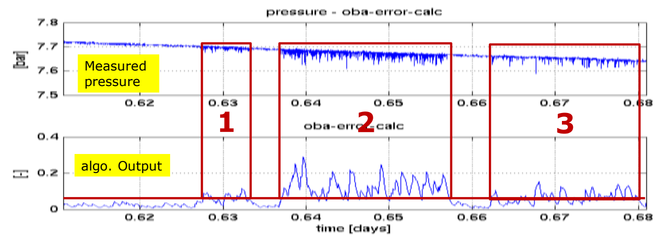

Figure 14. Top graph, measured pressure signal. Bottom graph, output of connection defects detection algorithm

Three zones with different connection fault levels were added to the pressure signal. The amplitude of these faults change from low to high respectively in zone 1, 3 and 2. The output of the detection algorithm signal amplitudes are perfectly correlated with the faults levels. In the graph a fixed threshold is used to trigger a warning of connection problem. More advanced prognostics methods can be used for that purpose depending on the requirements of the case study.

4.2. Intermittent open fault detection in a temperature sensor signal

The signals described in this section were recorded in an industrial machine making use of different temperature sensors close to each other. One of these signals contains connection faults which were clearly seen after some time (spikes). Our approach is to apply the same algorithm validated in section 4.1 (without changing any parameter) to these datasets and try to predict the connection fault at an early stage (before they can be visually seen in the signal). The recorded signals are show in figure 15.

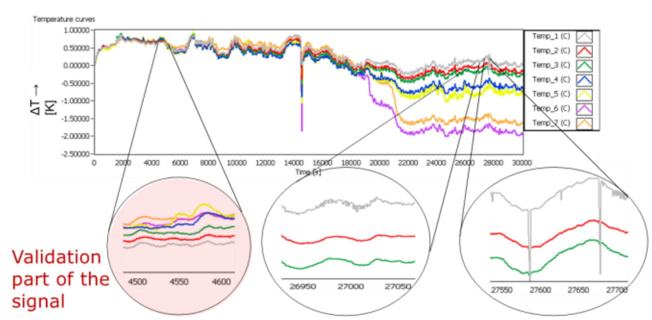

Figure 15. Measured temperature signals from an industrial application where one of the measured signals contain connection faults

One of the recorded signals in figure 15 contains connection faults that are visually seen after some time (right circle zone) in the form of spikes in temperature signal. The goal is to apply our connection faults detection algorithm in the validation zone (1st circle zone) where it is not possible to see these faults visually. The results are shown in figure 16.

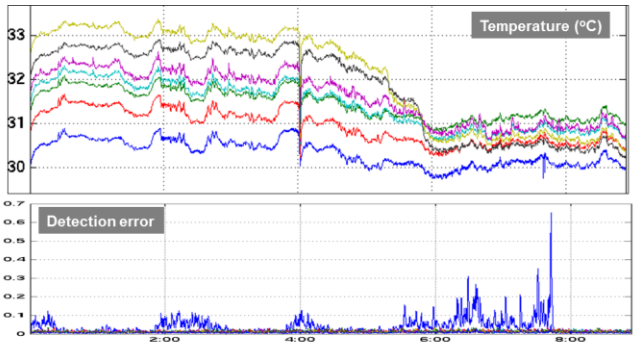

Figure 16. Detected connection fault in one of the temperature signals

The algorithm successfully detects the connection faults in a very early stage. Initially the behavior is quite intermittent but after some time the faults can be permanently captured.

5. CONCLUSION

Feasibility of prognostics of connection defects (faults) in electronics modules has been shown in this paper both for detection and localization. For detection and localization, impedance based measurement technique have been developed with possibility to be applied in live powered systems. Two different cases with equivalent resistive and complex impedances have been considered for validating this technique. Accuracy in the order of 30 cm have been demonstrated for localizing the connection fault. For applications where no alteration of the circuit is possible, by adding a diagnostics hardware, we developed an algorithm based on band-frequency filtering to highlight connection faults and detect them in a very early stage. The validation of this algorithm on pressure and temperature signals proved the capability of this algorithm to detect the faults in a very early stage and proved also that this algorithm is generic. These methods show a high potential of connection faults detection and localization for industrial applications.

The economic value of the developed methods for industrial applications is straight forward. The diagnostics hardware use cheap off the shelf components and the developed software is easy enough to be executed in a low-cost processor. Compared to state of arts methods, the published methods can be seen as breakthrough for electrical wires and connectors integrity

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BIOGRAPHIES

Abdellatif Bey-Temsamani received his master in engineering from University of Mons in 1996. He received a PhD in engineering at Free University Brussels (VUB) for the dissertation entitled ‘Parametric modeling and estimation of ultrasonic bounded beam propagation in viscoelastic media’. He is (co) author of different journal and proceedings papers in the field of non-destructive testing, condition monitoring, maintenance optimization, and data mining. His current research interests are in condition monitoring hardware / software, smart systems, decision making in industrial processes, reliability and safety of industrial systems.

Stijn Helsen was born in 1966 in Belgium. He graduated as a Mechanical Engineer in 1989 and Engineer in Mechatronics in 1990. After working in an independent industrial company for 15 years, he started as a project engineer at FMTC, which became Flanders Make in 2015.

Maarten Witters received his master in engineering from University of Leuven in 2005. He received a PhD degree in mechanical engineering at the same university for the dissertation entitled ‘Black-box identification and control of semi-active suspension systems for passenger cars’. His current research interests are in mechatronic system design for industrial applications

Marc Engels is currently the COO of Flanders Make. Before he performed and managed research at FMTC, IMEC, Stanford University and K.U.Leuven. He was also involved in the creation of two start-up companies, Septentrio and Loranet. He has a master (1988) and a PhD (1993) in electronic engineering, both from K.U.Leuven