A Digital Signal-based Prognostic Approach to Factory Automation

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ABSTRACT

A data network from a control system is usually consist of complex wiring systems to communicate with manufacturing lines. The electrical connections by the wiring systems can be deteriorated by wire faults such as chafing in the wiring system. During the life cycle of the wiring system, field stress conditions such as mechanical stress condition often cause and intensify the wire faults. The progress of wire fault can cause other wire failures such as cutoff or arcing. Furthermore, failures in the connected wires may eventually cause malfunctions in facilities of manufacturing lines. In order to prevent serious failures, health of the wiring system can be monitored in real time to repair or replace the damaged wires before the time to failure. However, the conventional approaches to wire health monitoring often require additional connections to the wiring system due to additional monitoring devices. Thus, the operation of the facilities may be interfered when the monitoring devices monitor wires. As a result, the conventional approaches, which require additional devices, have difficulty detecting the extent of wire damages in real time, and may end up neglecting the progress of chafing.

In this study, a method for wire health monitoring is developed to prevent wire failures by monitoring wire damages in real time. Digital signal is affected adversely by impedance discontinuity on the transmission line. By monitoring the integrity of digital signal continuously, time to failure can be predicted in real time depending on the extent of wire damage. In addition, an accelerated wire abrasion test was designed to damage wires gradually. During the abrasion test, the integrity of the transmitted digital signal was continuously deteriorated. The monitored signal makes it possible to extrapolate the degradation pattern of the signal parameters depending on the extent of wire damage. Thus, the results in this study validate that the proposed method is capable of monitoring the wire damage to diagnose a wiring system with real-time information.

1. INTRODUCTION

As a factory with manufacturing lines is automated, the control system communicates with its facilities in the manufacturing lines to manage the factory. The communication uses a complex wiring system where branch wires are connected to the facilities. However, during the operation of the wiring system, environmental and operational stress conditions such as mechanical and thermal stresses can deteriorate the mechanical properties of wires. For example, wire chafing, which is the most frequent faults (Wheeler, Timuchin, Twombly, Goebel, and Wysocki, 2007), occurs when the insulation of a wire is scraped. In the factory, vibration from its facilities can cause chaffing, neglected wire chafing can cause wire failures such as arcing or cut-off, and the wire failures may eventually lead to malfunctions in the factory due to failures in data communication from the control system. Thus, monitoring wire health may be used as a means to monitor wire faults, which can be shared in real time to prevent accidents from the system failures.

In the field, downtime of a factory for the health management may cause loss of profit. Some approaches have been developed for a wiring system in the factory to monitor wire health while the factory is in operation. For instance, reflectometry is one of the common approaches to monitor wire health by analysis of reflected high frequency signals at wire faults. Smith, Furse, and Gunther (2005) developed spread spectrum time domain reflectometry (SSTDR) to monitor the health of the wiring system in operation. SSTDR injected a sinusoidal wave modulated by pseudo noise (PN) code. The PN code helps to monitor wire health without interference from other signals on the wire. The reflected signal was detected by cross correlation in accordance with the PN code.

Dong, Yang, Zhou, and Hepburn (2017) developed a method to detect sheath faults in the wiring system such as cross-bonded high voltage cables in operation. Current sensors are connected to metal sheath of each joint and termination in the wiring system. Based on current measurement by the sensors, a fault model is established. Dong et al. demonstrated the method with the established model can detect wire faults in simulation and field data. However, the conventional approaches may have difficulty monitoring wire health in real time because they require additional connections for external monitoring devices. The external devices may interfere with the operation of the control system. Although the conventional approaches can monitor the health of the wiring system in operation, the external devices may require downtime for the additional connection. Thus, in order to predict wire failures in real time, wire health should be monitored without requiring an external monitoring system.

This study introduces a health monitoring method that can help to predict wire failures in real time. In order to communicate between the control system and the facilities, a digital signal is transmitted continuously through the wiring system. During transmission, the digital signal can be deteriorated at impedance discontinuities where wire faults such as chafing deteriorate characteristic impedance of wires. Therefore, the integrity of the transmitted digital signal can indicate health of the wires without external devices. For demonstration, an accelerated wire abrasion test was designed to chafe wires gradually. During the test, the integrity of the transmitted digital signal was monitored to identify a diagnosis capability of digital signal to estimate the extent of wire damage, while depths of abrasion were measured to evaluate the extent of wire damage with respect to changes in digital signal.

2. METHODS

2.1.1. Digital Signal Degradation at Wire Fault

When a high speed digital signal is propagated through conductor such as the inner conductor of a wire, the digital signal is concentrated on the exterior site of the conductor by the skin effect. Eddy current during transmission causes the digital signal concentration by electrical density variation between exterior and interior site. The electrical density variation can be quantified by the skin depth(δ), which means the depth of a conductor layer where 63% of currents are concentrated. The skin depth is represented in the following equation with the frequency of signal (f)

$$\delta = \sqrt{\frac{\rho}{f\pi\mu}} \quad (1)$$

where ρ and μ denote the conductor resistivity and the material's permeability, respectively. Thus, the skin depth becomes shallow when the frequency of signal is increased. Therefore, the denser digital signal is concentrated in the exterior site of the conductor at a high frequency.

When digital signal is transmitted for data transmission in electronics, the characteristic impedance of the transmission line should be controlled for signal quality. The wiring system also should consist of impedance controlled wires such as coaxial cables in Figure 1.

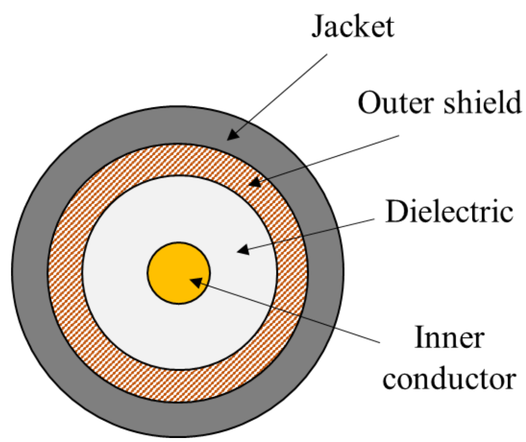


Figure 1 Schematic of a Coaxial Cable

The outer shield in the wire keeps transmitted signals by screening noise and leakage. The dielectric helps to control characteristic impedance (Z_0) represented by the following equation

$$Z_0 = \frac{60}{\sqrt{\varepsilon_r}} \ln\frac{D}{d} \quad (2)$$

where ε is a dielectric constant, D is the outer shield diameter of the wire, and d is the inner conductor diameter of the wire. However, external damage on insulation such as chafing can deteriorate the characteristic impedance of the transmission line because the damage can change mechanical properties of the wire. The digital signal is deteriorated when the signal passes impedance discontinuities. Especially, the digital signal is affected by external damage since the denser signal is transmitted on the exterior of the conductor rather than the center due to the skin effect. The skin effect of the digital signal enables the proposed method to monitor wire faults by analysis of the integrity of the digital signals transmitted through wires.

2.2. Monitoring Digital Signal Integrity

When digital signal propagates through the impedance discontinuities of the externally damaged wire, the integrity of the digital signal is deteriorated due to the skin effect. The integrity of digital signal can be monitored as quantitative characteristics to detect the signal degradation. In this study, an eye diagram was used to describe the characteristics of continuously transmitted digital signal. In order to transmit information for data communication, digital signal is a waveform with continuous transition between two states, logical 1 and 0. The waveform of the digital signal can be sampled at a regular time unit interval as regular bits of the digital signal. An eye diagram is created when the sampled signal are overlapped in accordance with transition edges. An analysis of consistency of the eye diagram shape can indicate the integrity of the digital signal because the eye diagram shrinks when the integrity of transmitted digital signal is deteriorated.

Eye parameters in Figure 2 are quantitative indices of the eye diagram. Eye parameters are determined by the distribution of overlapped signals. For instance, 1 level and 0 level denotes the mean voltage of signals for logical 1 and logical respectively. Rise time and fall time means the transition time of 0 level to 1 level and 1 level to 0 level, respectively. When the crossing points are determined by each mean value of two horizontal histograms across the narrow strip, jitter is determined based on the deviation of each histogram. Eye width is determined based on the two horizontal histograms on crossing points, while eye height is determined based on the two vertical histograms on 1 level and 0 level. In this study, all the eye parameters are monitored during the test to describe the deterioration of the digital signal.

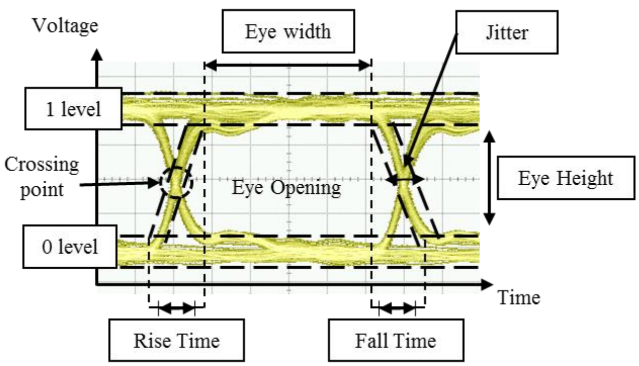


Figure 2 Schematic of Eye diagram with Eye parameters

2.3. Anomaly Detection in Digital Signal Characteristics

2.3.1. Sequential Probability Ratio Test

In order to detect faults in the monitored signal without a standard fault detection threshold, the sequential probabilistic ratio (SPRT) test introduced by Gross & Lu (2002) and Lopez (2007) was performed to determine the anomaly detection thresholds. SPRT can provide the statistical thresholds by the binary hypothesis test. When a null hypothesis and an alternative hypothesis of the binary test, respectively, indicate a health state and an anomaly state with manually fixed ratio of false and missed alarm, SPRT can help to determine whether or not the new measurement data fall in the null hypothesis. In order to apply the digital signal, a probability distribution of the null hypothesis can be assured as a Gaussian distribution with mean(0) and variance(σ^2) based on the data measured from the healthy wire. The alternative hypothesis for the mean test assures that the probability distribution of anomaly state is a Gaussian distribution with a mean of M and a variance of σ^2, where M is a defect level. A probability distribution of the alternative hypothesis for variance test is a Gaussian distribution with mean of 0 and variance of σ^2/V or $V\sigma^2$ where V is a sensitivity constant determined manually.

During the test, the mean values and variance values of the monitored eye parameters were changed. However, the mean values were different among wires, and a variance test was used to determine whether the eye parameters are falls in the distribution of the health state or the distribution of the anomaly state with variance of $V\sigma^2$. The SPRT index calculated by the following equation indicates the state of the monitored eye parameters:

$$\mathrm{SPRT} = -\frac{n}{2} \ln V + \frac{V-1}{2V\sigma^2} \sum_{k=1}^{n} x_k^2 \tag{3}$$

where x_k represents the sequentially measured data for the test. An upper limit and a lower limit were determined by the fixed ratio of false and missed alarm to indicate the state. When the SPRT index was under the lower limit, SPRT judged that the measured wire is in the health state. On the contrary, when the SPRT index was over the upper limit, SPRT indicated that the wire is in the anomaly state. In this study, signals from undamaged wires were used in training the health state. Using the training data as a criterion, SPRT indicated continuously whether the measured data were statistically different from the probability distribution of the training data. Thus, SPRT identified significant changes from the eye parameters.

2.3.2. Elbow Point

According to Equation (2), the characteristic impedance of a wire is not deteriorated when only the jacket is chafed. Therefore, the eye parameters may show a degradation trend after the jacket is chafed entirely. However, anomaly detection by SPRT has difficulty in finding the start of the degradation trend because the training data for SPRT cannot detect the best point due to noise. Therefore, the monitored eye parameters have an actual time when they start to be deteriorated before the anomaly detection by SPRT. In this study, the time to start degradation was determined using an elbow point which is the best trade-off point on a curve as shown in Figure 3. When $\vec{a}$ was determined as a vector from the first measurement to the anomaly point, a, by SPRT, the elbow point can be supposed as a point which has the farthest vertical distance from the vector $\vec{a}$ between the first point and the anomaly point. The elbow point, b, can be calculated by the following equation

$$\underset{b}{\operatorname{argmax}} \left| \vec{a} - (\vec{b} \cdot \hat{a})\hat{a} \right| \tag{4}$$

Where $\vec{b}$ denotes a vector from the first point to the point, b, and $\hat{a}$ denotes a unit vector of $\vec{a}$.

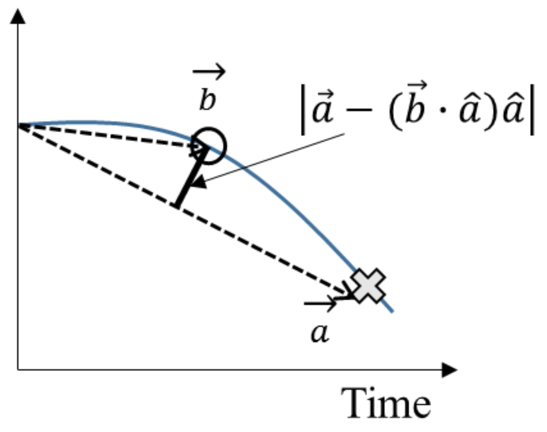


Figure 3 Calculation of elbow point

3. EXPERIMENTS

In order to demonstrate that the method using digital signal can measure the extent of wire damage, the digital signal was monitored during an accelerated life test (ALT) with a wire abrasion tester. While a wire was chafed gradually, the eye parameters were monitored regularly.

The RG174 wire, a coaxial cable with characteristic impedance at 50Ohm, was determined as the device under control (DUT) for the ALT. The wire was insulated by Polyvinyl Chloride (PVC), which is one of the common materials for jacket insulation. Mechanical properties of RG 174 are shown in Figure 4. For the test, A RG 174 wire was connected to the test circuit using SMA connectors.

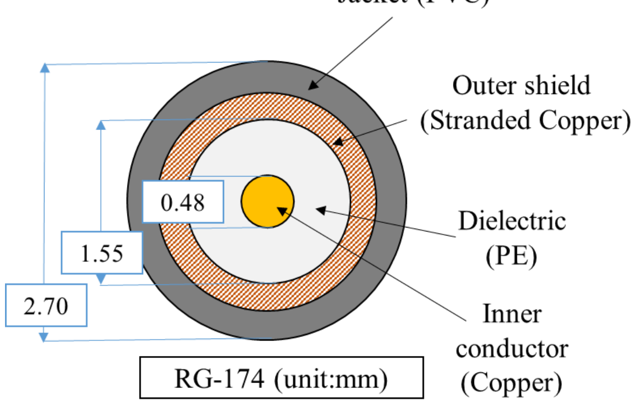
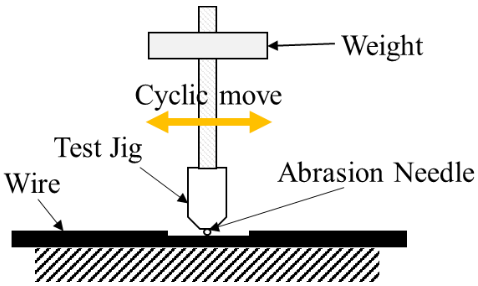


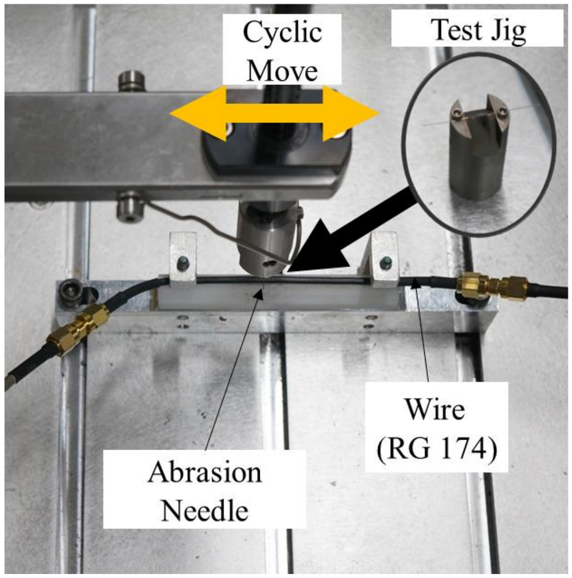
Figure 4 Mechanical Properties of RG 174

Following the scrape abrasion procedures in the report (ISO, 2011), our wire abrasion test was designed to damage a wire gradually. A linear abraser, Taber 5750 in Figure 5, was used to chafe the wire regularly. After the wire for DUT was fixed on the abraser, an abrasion needle was made to travel horizontally on the insulation of the wire with a normal force as shown in Figure 6. Travel length and speed of the test zig were determined to be 15.49mm and 2 cycles/min, respectively. A 150g weight and 0.25mm diameter needles were used.

Figure 5 Taber 5750 Linear Abraser



(a)



(b)

Figure 6 Wire abrasion (a) schematic (b) picture

During the gradual chafing, an Altera Stratix V GX transceiver generated PRBS7 (Pseudo-Random Binary Sequence 7) patterned digital signal at the speed of 1.25Gbps. The conditions of the digital signal revealed significant degradation of the signal integrity. A digital communication analyzer (DCA) Kesight 86100D monitored the transmitted digital signal. The digital signal was accumulated for 30 seconds to create an eye diagram. An external clock set at 156.25MHz by the signal generator helped to conduct sampling the transmitted digital signal. The monitoring process was conducted every 1 minute. The characteristic impedance of the test circuit was controlled at 50Ohms as shown in Figure 7. An instrumental control software controlled all the devices in the test circuit for the automated monitoring process. The test was manually stopped when the conductor of the wire was exposed before the conductor was damaged.

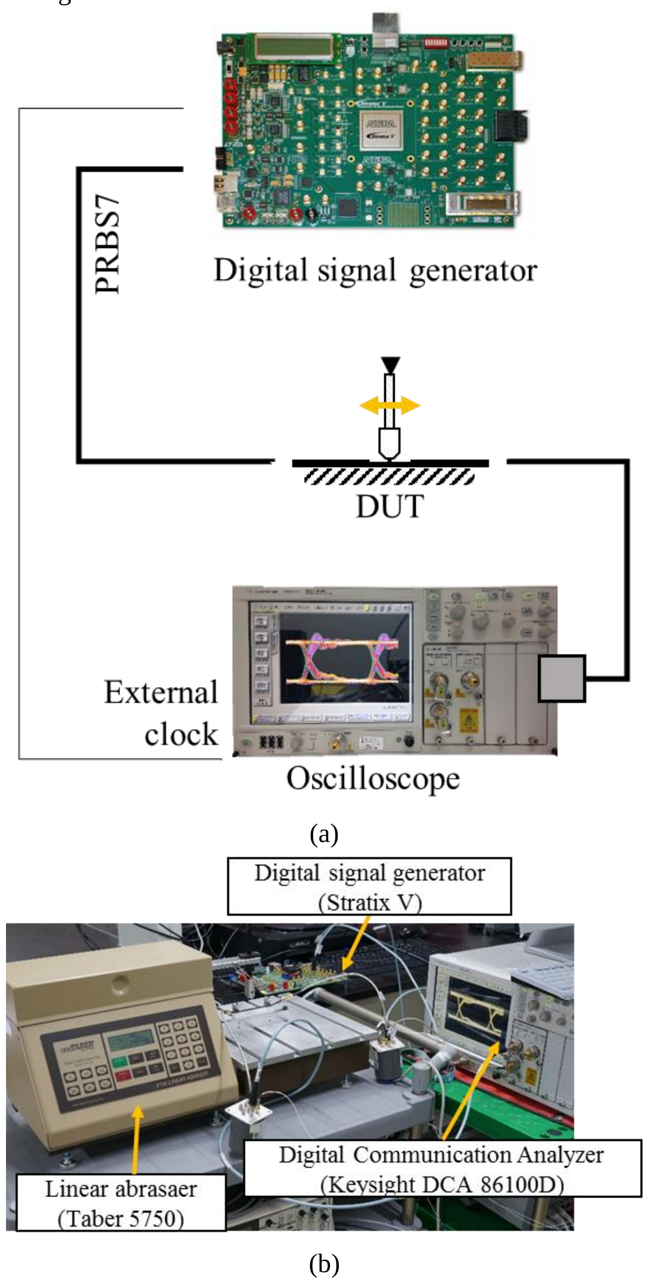


Figure 7 Wire abrasion (a) schematic (b) picture

The monitored eye parameters were analyzed by SPRT to detect wire faults. For the training state of SPRT, eye parameters were measured for 70 hours before the test. Based on the training data, the variance of the alternative hypothesis for SPRT was determined to be $2\sigma^2$ depending on the degradation trend of the signal. In order to confirm that the eye parameters deteriorate depending on the wire chafing, the 1st test was halted every 30 minutes and the depth of abrasion of a wire was measured during the 1st test. Based on the results from the 1st test, the second test was also halted every 30 minutes and the depth of abrasion was measured. The depths of abrasion measured from the two tests were compared with the degradation of the eye parameters.

4. RESULTS

In order to demonstrate diagnosis capability of eye parameters, we correlated the eye parameter and depths of abrasion. In this study the eye height was analyzed in monitored eye parameters. Using the monitored eye height in the 1st test, the eye height was plotted with depth of abrasion as in Figure 8. The eye height showed a degradation trend at the early phase after a flat trend while the wire was chafed gradually. A qualitative analysis indicated that the measured eye height was significantly deteriorated after the elbow point.

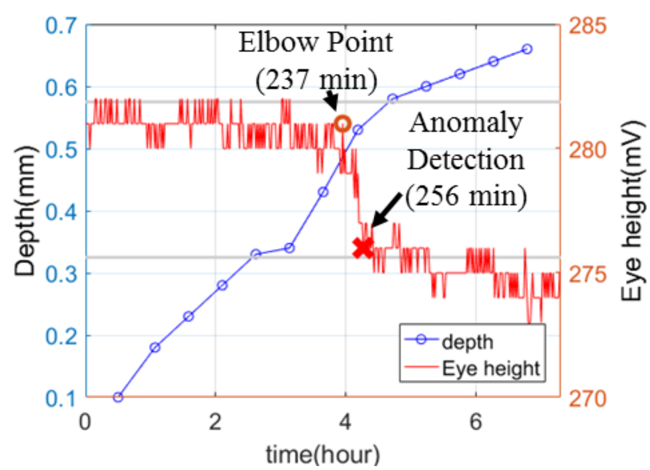


Figure 8 Plot for Eye height and Depth of abrasion

In order to identify the extent of chafing when the eye height was deteriorated, the measured depths of abrasion were analyzed in accordance with the measured times. The schematic of a chafed wire shown in Figure 9 was created based on the mechanical properties of RG 174 wire and the measured depths of abrasion. Additionally, microscopic views were analyzed to identify the actual chafing as shown in Figure 10. The depths of abrasion and microscope views show that the elbow point was measured while the outer shield was being chafed. The time to fault was detected by SPRT when the dielectric started to be chafed. The flat trend of the eye height is measured when the jacket of the wire was chafed because the jacket chafing cannot affect characteristic impedance in accordance with Equation (2).

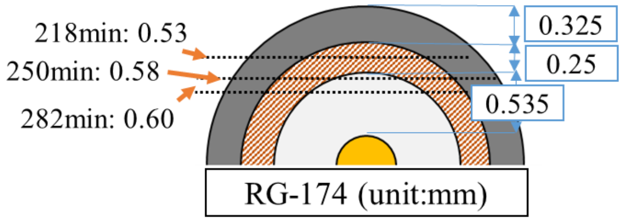


Figure 9 Half Region of RG 174 with Depth of abrasion

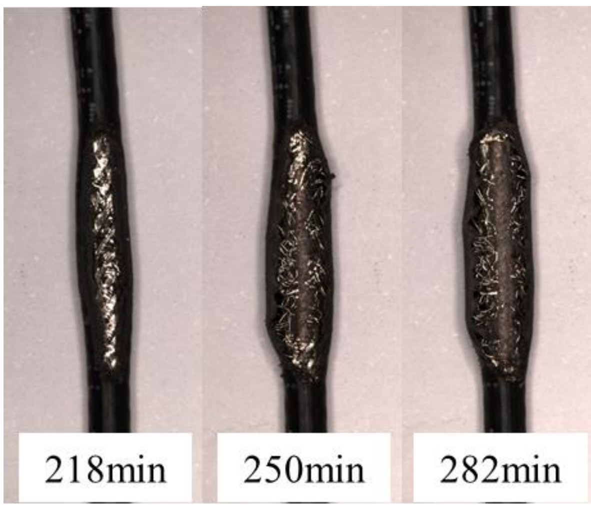


Figure 10 Microscope View of Chafed Wire

In order to validate the repeatability of the results of the 1st test, the 2nd test also measured depth of abrasion every 30 minutes. The eye height and depths of abrasion from the 2nd test are shown in Figure 11. Figures 12 and 13 also show the depths of abrasion and microscopic views. The results are similar to the 1st test: the elbow point was measured while the outer shield was being chafed. The time to fault was also detected when dielectric was chafed. The correlation between eye height and depths of abrasion in the two tests indicated that wire faults in the insulation such as the outer shield and the dielectric was enough to deteriorate the eye parameters. Thus, wire faults inducing the impedance discontinuities on a transmission line can be diagnosed based on monitoring variance of the eye parameters.

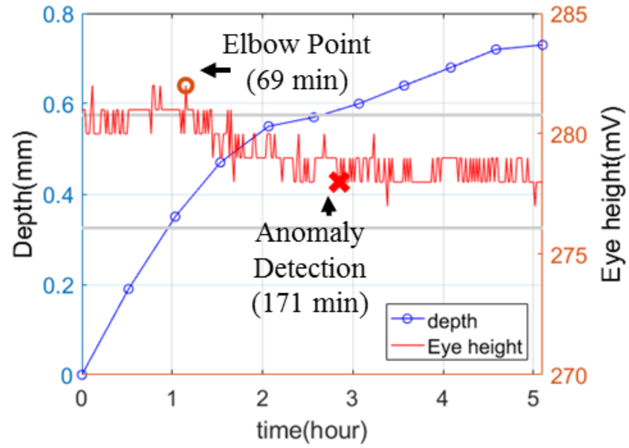


Figure 11 Plot for Eye height and Depth of abrasion from 2nd Test

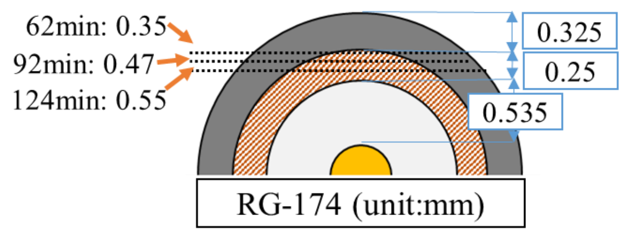


Figure 12 Schematic of RG 174 with Depth of abrasion from 2nd Test

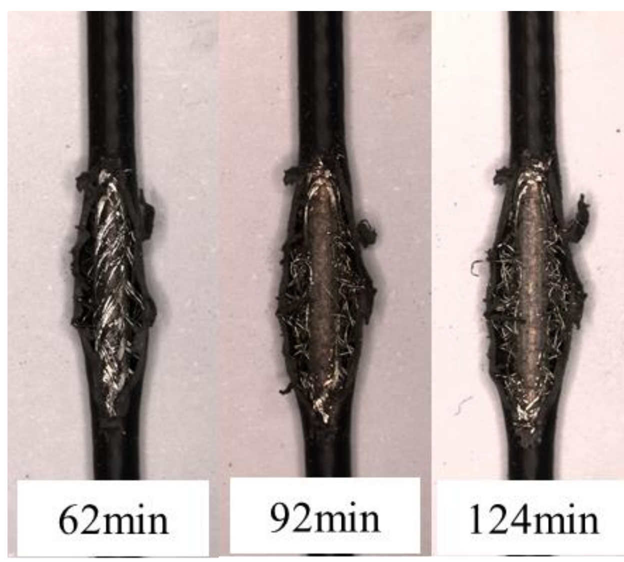


Figure 13 Microscope View of Chafed wire in 2nd Test

5. CONCLUSIONS

In this study, we developed a real-time wire health monitoring method that can help to predict wire failures by monitoring the integrity of digital signal in real-time. Digital signal was used for real-time health monitoring to prevent wire failures in a wiring system. In order to demonstrate that digital signal is affected adversely by impedance discontinuities caused by wire faults, the integrity of transmitted digital signal was monitored during an accelerated wire abrasion test. The test results indicated that the integrity of digital signal starts to be adversely affected when the chafed outer shield deteriorates the characteristic impedance of the wire. Thus, based on the wire health monitoring, the proposed method can help to prognosticate the extent of wire faults before wire failures take place.

The proposed method is capable of monitoring wire health in real time owing to continuously generated digital signal. Although this study designed the test circuit with an additional signal analyzer, a field-programmable gate array (FPGA) can be implemented in order to generate digital signal and analyze the characteristics of the digital signal in the field. Thus, health of a wiring system in operation can be monitored in real time if a software module for signal analyzer is installed in the FPGA. Conventional approaches to wiring system maintenance using external monitoring systems usually require downtime of the monitored system operation for additional connections to the wiring system. Digital signal can be analyzed by signal analyzing modules connected to the wiring system. Therefore, the time for system maintenance can be reduced by monitoring health of the wiring system while the monitored systems are in operation. The proposed method is cost effective because it can help to maintain health of the wiring system in a factory control system with minimum system downtime, reducing the maintenance time and increasing the factory availability.

In the field, wiring systems are often complex with branch wires connected with each other to control manufacturing lines. Although the wiring system is diagnosed by cost-effective methods, wire maintenance for repairing or replacing the fault wire may require additional labor and cost to find the fault wire in the complex wiring system. The proposed method can monitor wire faults on transmission lines in real time by signal generating and analyzing modules connected to the terminations of the transmission line. Therefore, the complex wiring system can be managed using the proposed method by transmission lines. The partitioned health monitoring process can reduce costs and maintenance time for the wiring system maintenance.

Our future study includes methods of applying the proposed method to diagnose complex wiring system, developing test circuits without an additional analyzer by a digital signal transceiver, diagnosing wiring systems in field using the proposed method, and predicting the remaining useful life time of wires with prognostic algorithms based on the proposed method.

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REFERENCES

Wheeler, K., Timucin, D., Twombly, I. X., Goebel, K. F., and Wysocki, P. F., (2007) *Aging aircraft wiring fault detection survey*. NASA Ames Research Center, Moffett Field CA 94035, http://citeseerx.ist.psu.edu/viewdoc/download;jsessionid=2C68027E1714466845047B737F43E6E6?doi=10.1.1.154.5095&rep=rep1&type=pdf.

Smith, P., Furse, C., and Gunther, J., (2005) Analysis of spread spectrum time domain reflectometry for wire fault location. *IEEE Sensors Journal*, vol. 5(6), pp. 1445–1450, doi: 10.1109/JSEN.2005.858964

Dong, X., Yang, Y., Zhou, C., and Hepburn, D. M. (2017). On-line Monitoring and Diagnosis of HV Cable Faults by Sheath System Currents. *IEEE Transactions on Power Delivery*, doi: 10.1109/TPWRD.2017.2665818

Liu, S., Wang, Y., and Tian, F. (2015). Prognosis of underground cable via online data-driven method with field data. *IEEE Transactions on Industrial Electronics*, vol. 62(12), pp. 7786-7794. doi: 10.1109/TIE.2015.2458300

Gross, K., and Lu, W., (2002) Early Detection of Signal and Process Anomalies in Enterprise Computing Systems, *Proc. IEEE Int. Conf. Mach. Learning Appl. (ICMLA 02) (204-210)*, Jun. 24-27, Las Vegas, Nevada, USA.

Lopez, L., (2007) Advanced electronic prognostics through system telemetry and pattern recognition methods. *Microelectronics Rel*., vol 47(12), pp. 1865-1873, doi: 10.1016/j.microrel.2007.02.018

International Standards Organization (ISO) (2011), Road vehicles -- 60 V and 600 V single-core cables -- Part 1: Dimensions, test methods and requirements for copper conductor cables. In ISO, *ISO 6722-1:2011(en)*, Geneva, Switzerland: International Standards Organization

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Jinwoo Lee was born in Daegu, South Korea, 1993. With Bachelor of Science in system design and control engineering from joined the Ulsan National Institute of Science and Technology (UNIST), South Korea, he is working on a master's degree in system design and control engineering from UNIST. He is interested in reliability of electronic components, accelerated life test, failure prognostics, and machine learning algorithms.

Daeil Kwon (M'07) received the bachelor's degree in mechanical engineering from POSTECH, South Korea, and the Ph.D. degree in mechanical engineering from the University of Maryland, College Park, USA. He joined the Ulsan National Institute of Science and Technology (UNIST), he was a senior reliability engineer at Intel Corporation, Chandler, AZ, USA, where he developed use condition-based reliability models and methodologies for assessing package and system reliability performance. He is currently an Assistant Professor of Human and System Engineering, UNIST, Ulsan, South Korea. His research interests are focused on prognostics and health management of electronics, reliability modeling, and use condition characterization.