Degradation Monitoring of Low-voltage Electromagnetic Coil Insulation Based on Microscopic Image Analysis

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***Abstract*—Electromagnetic coils are widely used in a variety of industries, and their insulation damage is one of the main factors which results in failure of solenoid-operated valves and motors. This paper provides a novel method for degradation monitoring of low-voltage coil insulation based on microscopic image analysis. Degradation-sensitive color features from RGB, HSV and HSL color spaces are identified to quantify the appearance differences between healthy and degraded magnet wires, which provides a new way for coil health monitoring. Comparing to the existing high-frequency electrical signal based degradation monitoring methods, the proposed method is low-cost and easy to apply for coil insulation test.**

Keywords—low-voltage electromagnetic coil, insulation degradation monitoring, microscopic image analysis

I. Introduction

Electromagnetic coils are fundamental energy conversion and transformation components of many systems, widely used in motors, transformers, and solenoids [1]. However, they have been shown to be failure prone. Many papers have reported that stator-winding insulation is one of the weakest components in a drive (around 25% to 40% of failures)[2-5]. A study conducted by Oak Ridge National Laboratory [6] showing that over 50% of solenoid valve failures (SOVs) in U.S. nuclear power plants were attributed to electromagnetic coil faults (e.g., coil open, coil short). As for the electric generators, 56% failures were originated by electrical insulation damage [19]. Considering that insulation failure usually occurs suddenly and causes catastrophic effects, methods to perform degradation monitoring for coil insulation are preferred to enable predictive maintenance of the electromagnetic coils prior to development of a fault that could cause catastrophic damage.

A few coil insulation degradation monitoring methods have been proposed. Werynski et al.[7] performed an accelerated aging test on twisted pairs of magnet wire and found that the insulation capacitance increased as breakdown voltage decreased. The phase shift between a signal injected at the coil resonant frequency and the resulting magnetic field is used as a health indicator for the insulation. Perisse et al. [8,9] presented a decision-making process regarding the aging of the machine based on the fusion of information provided by high-frequency measurements of current and magnetic fields. Savin [10,11] also placed twisted pairs under thermal stress and found that the partial discharge inception voltage decreased, which is an indication of insulation degradation, while the turn-to-turn capacitance increased. Thus they claimed that the capacitance can be used as an aging indicator of the self-bonding winding insulation. Zoeller [12-14] proposed a method for stator insulation defect detection in traction drives machine windings by evaluating the current response after a voltage step excitation, which is based on the fact that parasitic winding capacitances changes as the insulation degrades. Nussbaumer et al [15] proposed a method to monitor changes in the insulation health state by evaluating the machine high-frequency properties. Jameson et al. [16] proposed an SOV coil insulation health monitoring method based on the impedance spectrum, in which the accelerated degradation test of the SOV coil was performed and Spearman correlation coefficient was used to find frequency regions of interest within the impedance spectrum.

In essence, all the methods mentioned above used certain high frequency electrical parameters (such as impedance, capacitance, and so on) under certain featured frequency for coil insulation degradation monitoring. High-frequency signal injection into the devices under test/monitoring is a prerequisite for applying these methods in practice. Therefore, high-frequency signal generators should be developed and integrated into the devices under test/monitoring in order to perform health assessment, which causes additional test / monitoring cost. To address this issue, a novel degradation monitoring method for coil insulation, which is based on microscopic image analysis, is proposed in this paper. The appearance images of magnetic wires with different degraded status were

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acquired by an optical microscope and microscopic image analysis is applied to extract degradation-sensitive color features from several color spaces for coil health monitoring.

This paper is organized as follows. In Section II, failure analysis of coil insulation is given. Then, in Section III, the coil insulation degradation monitoring method based on microscopic image analysis is described. Section IV concludes the paper.

II. Failure Analysis of Coil Insulation

A cross-sectional view of the coil is shown in Fig. 1. The wire used is generally referred to as magnet wire, which is constructed of conductor (usually copper) coated by insulation material (usually made by some kind of polymer). Failure analysis of coil insulation is described as follows. As an electric current is passed through the wire, Joule heating causes an increase in the wire temperature and the expansion of the conductor, placing mechanical and thermal stresses on the insulation [17,18]. Thus, the elevated temperature combined with the mechanical stresses will lead to insulation degradation. Further, because the dielectric material between the wires degrades, its mechanical strength decreases and the turn-to-turn or layer-to-layer insulation layer will be extruded and deformed under the mechanical stresses, resulting in a turn-to-turn or layer-to-layer short. The short can cause the coil resistance to decrease, thus pulling a greater current into the valve. At the location of the short, a hot spot can form, where the local temperature is great enough to cause the wire to burn out, resulting in an open circuit, and finally, failure of the complete coil. This paper focuses on the coil insulation degradation process, which is referred to when the turn-to-turn or layer-to-layer short has not formed yet. A novel insulation degradation monitoring method will be proposed in the next Section, which presents opportunities for predictive maintenance for motors, SOVs, transformers, and the like.

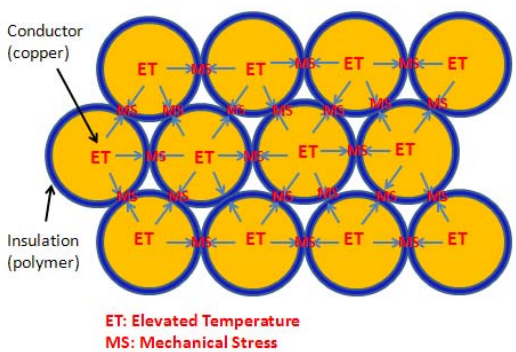

Fig. 1. Cross-sectional view of a multi-layer winding.

III. A Novel Coil Insulation Degradation Monitoring Method Based on Microscopic Image Analysis

Due to the fact that degraded coils usually show a darker appearance comparing to the healthy ones in practice, a microscopic image analysis based method is proposed for coil insulation degradation monitoring. The basic idea is to acquire the appearance images of the coils with different degraded status by an optical microscope and then microscopic image analysis is utilized to quantify the color difference of appearance between healthy and degraded coils by extracting related color features from several color spaces. Thus health indicators for coil degradation monitoring can be identified by analyzing the evolution trend of related color features as the insulation degrades.

Because thermal stress is the dominant aging factor for electromagnetic coils, a thermal deterioration test was performed to provide specimen with different degraded status for microscopic image analysis. In detail, a hand-wound coil and magnet wires, as shown in Fig. 2. were placed in a test chamber set to 235 °C. The specimen's information is shown in Table I. The deterioration cycle is set to be 18 hours. After each deterioration cycle ten small sections of magnet wires were cut from the magnet wires and microscopic images of their appearances were acquired by an optical microscope, as shown in Fig. 3. Further the DC resistance (DCR) of the hand-wound coil was measured by a multimeter to indicate if turn-to-turn short has occurred. The DCR measurement result was shown in Fig. 4. The DCR kept in around 3.15 ohm in the first 3 cycles while dropped to 2.95 ohm at the 4th cycle, which means that the turn-to-turn short has occurred. Therefore, the aging time of this experiment was set to be 72 hours. Then, magnet wire specimen with different degraded status, which were obtained by the 72 hours thermal deterioration test, were fixed to glass slides for optical observation, as shown in Fig. 5.

Fig. 2. A hand-wound coil and magnet wires under test.

TABLE I SPECIMEN INFORMATION

Nominal coil resistance	3.15 Ω (25 °C)
Magnet wire insulation class	Class B (130 °C)
Voltage rating	DC 24 V
Working temperature	−5 °C−120 °C

Fig. 3. Optical microscope measurement platform.

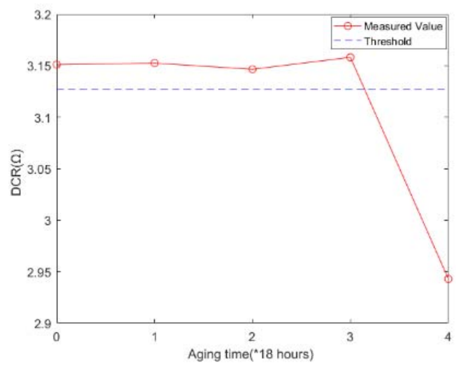

Fig. 4. Coil DCR measurement result during the thermal deterioration test.

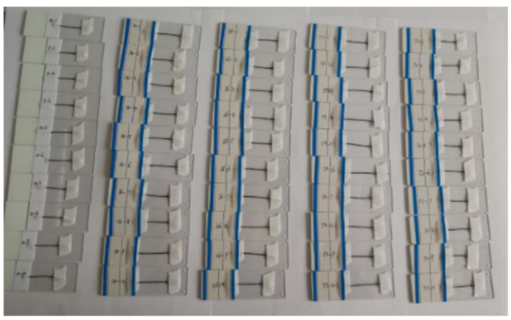

Fig. 5. Specimen of the magnet wires with different degraded status for optical observation.

The representative microscopic images of the magnet wire specimen with different deterioration status, which were acquired by the optical microscope, were shown in Fig. 6. Microscopic image analysis was applied in order to provide quantitative information on the appearance change during the deterioration test. As shown in Fig. 7, first, image pre-processing was performed to localize the main body of the objects to be analyzed on the original microscopic images. Second, the following three color features from 3 different color spaces, namely, RGB, HSV and HSL, were extracted respectively for each image: (1) Color feature in X-direction, which is defined as the sum of gray levels of every column in the image to be analyzed; (2) Color feature in Y-direction, which is defined as the sum of gray levels of every row in the image to be analyzed; (3) Global intensity, which is the pixel density with a certain gray level in the whole image. Finally, the similarity was defined to quantify the difference between healthy and degraded images for each color feature from these 3 color spaces. Similarity is calculated based on the Euclidean metric between the feature vectors of healthy and degraded images and after normalization it is defined as

$$S = 1 - \frac{\sqrt{(x_1 - y_1)^2 + (x_2 - y_2)^2 + \cdots + (x_n - y_n)^2}}{n \times \max(|x_i - y_i|)} \quad (1)$$

where S is the similarity and its range is [0,1]. The value 0 indicates that the difference between the two images is maximum, whereas the value 1 indicates that the difference is minimum; $x_1, x_2, \ldots, x_n$ represents the feature vector for the healthy image; $y_1, y_2, \ldots, y_n$ represents the feature vector for the degraded image, and n is the length of the feature vector.

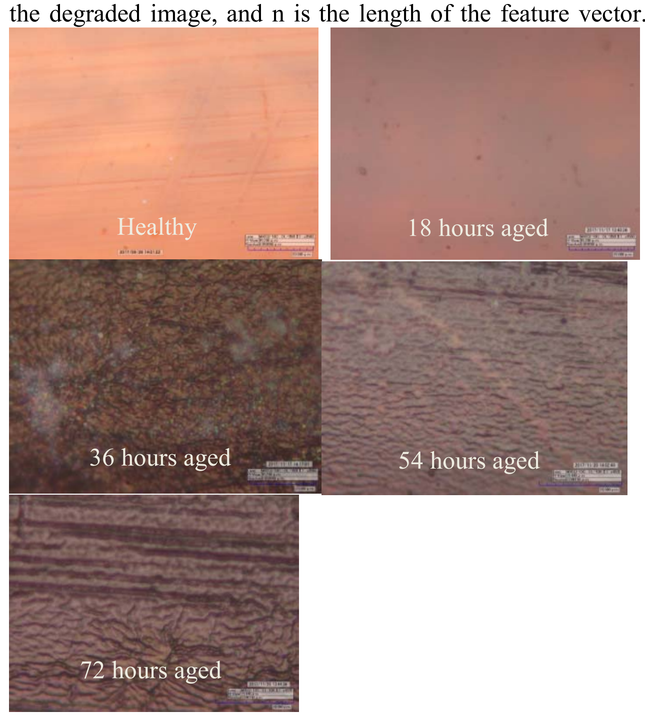

Fig. 6. Representative microscopic images of the magnet wire speicmen in each deterioration cycle.

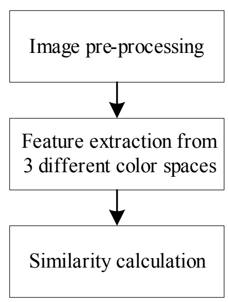

Fig. 7. Microscopic image analysis process.

The calculated results for the similarity between healthy and degraded images from different color spaces are shown in Table Ⅱ, III, and IV, which provides quantitative information of differences between healthy and degraded images. As for each color space, the correlation analysis between each color feature from the corresponding color channel and aging time is performed and the results are shown in Fig. 8, 9, and 10, respectively. Thus the evolution of the color features as the insulation degrades can be explored. In each color space, there are some specific color features, like the global intensity for Green channel from RGB color space, showed a monotonic decreased trend during the thermal deterioration test, which demonstrates that these color features are degradation-sensitive. All these degradation-sensitive color features can be used as potential health indicators for insulation degradation monitoring for coils, which are summarized in Table V.

TABLE II CALCULATED RESULTS OF SIMILARITY BETWEEN HEALTHY AND DEGRADED IMAGES FOR RGB COLOR SPACE

Channel	aging time	Similarity for color feature in X-direction	Similarity for color feature in Y-direction	Similarity for global intensity
Red	0h	1	1	1
	18h	0.028759	0.13984	0.949
	36h	0.041035	0.10464	0.94904
	54h	0.033475	0.052739	0.94736
	72h	0.037768	0.064143	0.94613
Green	0h	1	1	1
	18h	0.058745	0.21867	0.93588
	36h	0.070575	0.16201	0.89705
	54h	0.068741	0.12316	0.89495
	72h	0.047431	0.051594	0.89455
Blue	0h	1	1	1
	18h	0.47129	0.84143	0.96659
	36h	0.14089	0.29174	0.92051
	54h	0.16537	0.28029	0.91757
	72h	0.073092	0.10574	0.89471

TABLE III CALCULATED RESULTS OF SIMILARITY BETWEEN HEALTHY AND DEGRADED IMAGES FOR HSV COLOR SPACE

Channel	aging time	Similarity for color feature in X-direction	Similarity for color feature in Y-direction	Similarity for global intensity
Hue	0h	1	1	1
	18h	0.18698	0.83528	0.98954
	36h	0.74202	0.9249	0.97961
	54h	0.6329	0.61968	0.97294
	72h	0.52282	0.92559	0.9835
Saturation	0h	1	1	1
	18h	0.041263	0.046063	0.94246
	36h	0.047154	0.04326	0.9266
	54h	0.03773	0.045528	0.93952
	72h	0.049719	0.050771	0.88743
Value	0h	1	1	1
	18h	0.029331	0.14034	0.93577
	36h	0.041671	0.10523	0.93499
	54h	0.034188	0.053437	0.93456
	72h	0.038169	0.064533	0.93123

TABLE IV CALCULATED RESULTS OF SIMILARITY BETWEEN HEALTHY AND DEGRADED IMAGES FOR HSL COLOR SPACE

Channel	aging time	Similarity for color feature in X-direction	Similarity for color feature in Y-direction	Similarity for global intensity
Hue	0h	1	1	1
	18h	0.18698	0.83528	0.98954
	36h	0.74202	0.9249	0.97961
	54h	0.6329	0.61968	0.97294
	72h	0.52282	0.92559	0.9835
Saturation	0h	1	1	1
	18h	0.041263	0.046063	0.94246
	36h	0.047154	0.04326	0.9266
	54h	0.03773	0.045528	0.93952
	72h	0.04979	0.050771	0.88743
Lightness	0h	1	1	1
	18h	0.04928	0.23657	0.92718
	36h	0.060074	0.17905	0.92858
	54h	0.076008	0.11771	0.92732
	72h	0.062008	0.078032	0.92907

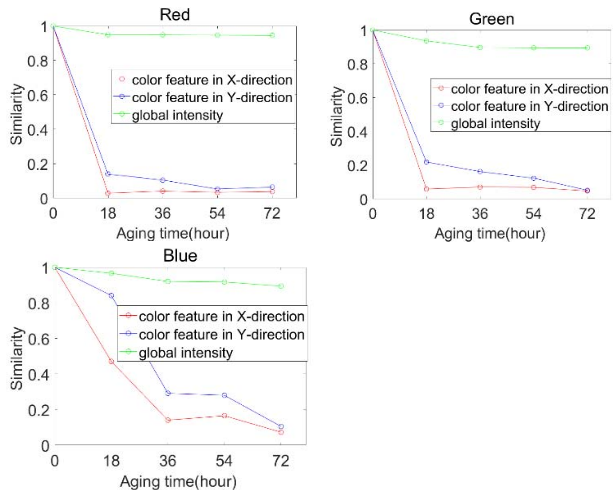

Fig. 8. Correlation between similarity and aging time for color features from RGB color space.

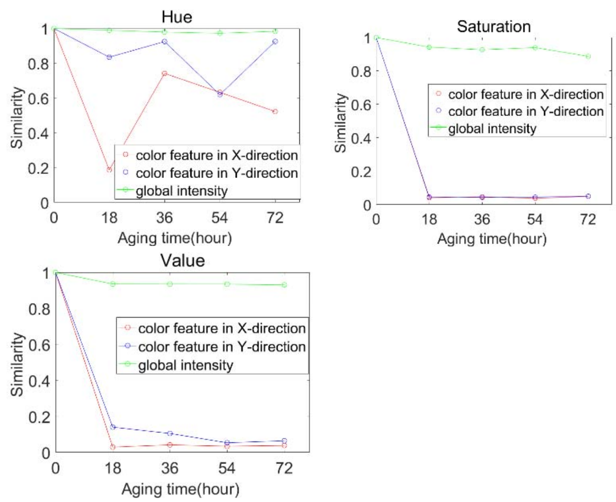

Fig. 9. Correlation between similarity and aging time for color features from HSV color space.

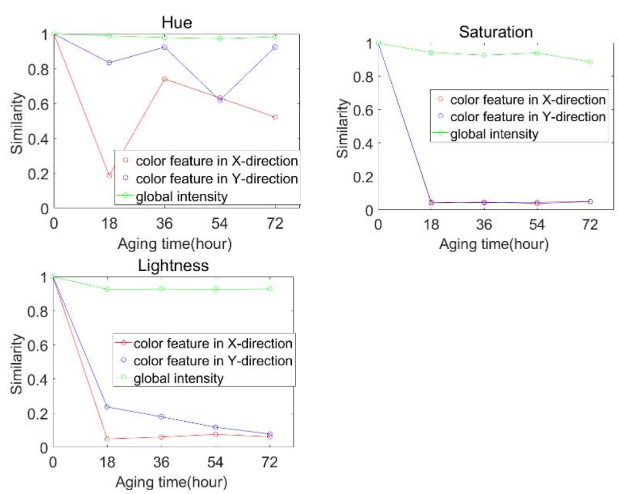

Fig. 10. Correlation between similarity and aging time for color features from HSL color space.

TABLE V DEGRADATION-SENSITIVE COLOR FEATURES FROM DIFFERNT COLOR SPACES.

Color space	Degradation-sensitive color features
RGB	Color features in Y-direction of Green and Blue channels
	Global intensity of Green channel
HSV	Global intensity of Value channel
HSL	Color feature in Y-direction of Lightness channel

IV. CONCLUSIONS

Prognostics of electromagnetic coils enable their forecasted maintenance prior to the development of a failure. A novel microscopic image analysis based method was proposed for degradation monitoring of coil insulation in this paper. A thermal deterioration test was performed and appearance images of magnet wires with different degraded status were acquired by an optical microscopic. Degradation-sensitive color features from RGB, HSV and HSL color spaces are identified, which provides opportunities for predictive maintenance for components or systems that incorporate electromagnetic coils, such as motors, relays, SOVs, or transformers. Comparing to the existing electrical signal based monitoring/test methods, no additional detection devices are required during the test. So the proposed method provides a low-cost and easy-to-apply way for coil insulation test or monitoring.

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