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Classification of degradation in oil-impregnated cellulose insulation using texture analysis of optical microscopy images

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ABSTRACT

Oil-impregnated Kraft paper samples normally used for power transformer electrical insulation have been artificially aged thermally to produce a sample set with varying levels of insulation deterioration. The samples were aged in an oven at a temperature above the normal operating temperature of a power transformer.

Digital images obtained from optical microscopy measurements on the paper samples have been analyzed using a texture analysis method which converts each image into a spatial gray level dependence matrix (SGLDM). The SGLDM contains information about the statistical variation of pixels gray-level intensities in an image and thereby information about the sample texture. Mathematical operators applied to the SGLDM have been used to extract 22 different statistical texture features for each sample image.

Optical microscopy images of the thermally aged samples show that thermal deterioration of the insulation paper produces changes in morphology and physical structure. These changes are detectable by the statistical texture features extracted from the SGLDM texture analysis. Statistical classification is performed on the feature set to demonstrate that differentiation between oil-impregnated paper samples with different levels of thermal degradation is reliable with low error rates. Therefore, development of a practical method to assess condition of oil-impregnated paper insulation using optical microscopy and texture analysis is promising.

1. Introduction

Oil-filled power transformers are highly reliable apparatus with life expectancies that can exceed 40 years when operated under normal loading conditions and system voltages [1]. Shortened life spans can be expected when power transformers are operated at or near their full load rating continuously and ageing models used within the utility industry predict end-of-life criteria may be reached in as little 20.5 years (180,000 h) [2]. Some utilities in Asia have reported less than 5% of their 110 kV class power transformers achieve an operational life of 30 years, and less than 1% reach 40 years [3].

Electrical insulation commonly used in large utility power transformers and reactors consists of oil-impregnated Kraft paper layered on or around energized conductors. Different forms of Kraft paper are used for different electrical insulating purposes. Kraft paper tape constitutes the major portion of the transformer insulation. This paper tape is wrapped on the winding conductors to insulate individual winding turns from one another. To insulate the lead connections from the transformer winding to the high-voltage bushings, a different type of Kraft paper, called crêpe tape, is used. Crêpe tape is more elastic than the Kraft paper tape and absorbs more oil per volume than regular Kraft paper. For insulation between the high-voltage and low-voltage windings, a denser cellulose product called pressboard is used.

Over time, the heat, produced by the transformer core and windings during normal operation, thermally ages cellulose materials, resulting in a loss of their mechanical tensile strength. As this deterioration becomes significant, the cellulose materials become more brittle. Most failures occur when deteriorated transformer insulation is subjected to a system disturbance, such as a through fault or

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load rejection [2]. Such electrical system events cause abrupt electromechanical forces on the windings which can disturb the brittle winding insulation between turns. The likelihood of the paper tearing is increased when the tensile strength has been compromised due to thermal ageing; this tearing can lead to an electrical fault [3–6]. Estimation of the retained tensile strength within a power transformer's paper insulation is a major challenge. Existing methods are either not suitable for localization of acute defects or they are considered too invasive and therefore not feasible [7].

In this work, optical microscopy in conjunction with image processing textural analysis are used as a method for classification of degradation in power transformer cellulose insulation. Oil-impregnated insulation paper samples were prepared individually in separate glass vials and thermally aged in an oven. Sample vials were removed from the oven at four different intervals. After aging, the paper portion of the samples was removed from the vials and imaged under a microscope. Using an image processing texture analysis method, the digital microscopy images were translated into a spatial gray level dependence matrix (SGLDM) [8] that contains information about the image texture. Twenty-two textural features were extracted from the SGLDM belonging to each ageing class. Using pattern recognition methods for supervised machine learning, a classifier was developed for the automatic identification of paper sample images belonging to one of the four different ageing classes. The performance of the classifier was then evaluated using images of aged paper samples not belonging to the original training data set used in the development of the classifier.

The motivation for this work is to develop an optical method for estimating the level of deterioration in power transformer paper insulation by extracting information from its microscopic surface morphology. Such a method could have benefits over the established degree of polymerization test. The sample size required for analysis is smaller and therefore the proposed approach may be less invasive. Also, the time required for analysis may be shortened because samples would not have to be sent to a chemical laboratory. However, similar to the degree of polymerization case, the method is limited to only the outer winding locations inside of a transformer, and although the removal of a physical sample of the transformer insulation may be reduced with this method versus degree of polymerization, it is still an invasive method of assessment.

2. Background

2.1. Ageing in oil-paper electrical insulation systems

Both oil and oil-impregnated paper components of the power transformer electrical insulation system age during operation as electrical, thermal, and chemical processes degrade the insulation system. The oil component of the system can be replaced during maintenance to re-establish its insulation performance but degradation of the paper component is permanent as it cannot be replaced.

Assessment of the insulating performance of the oil can be established from tests on oil samples taken from the oil as it circulates through the transformer. Typical testing consists of dielectric withstand test and/or chemical measurement of degradation byproducts that are associated with other defects in the insulation that indicate localized hot spots or internal partial discharges. Evaluation of the paper component is more difficult; though some indication of the condition of the paper can be inferred from chemical degradation byproducts (furans) found in oil samples [9].

However, evaluation of the paper condition from an oil sample is an indirect method and incapable of differentiating between multiple, slowly degrading regions of the insulation system versus a single region degrading more rapidly. In the latter case, the risk for failure is much higher. Localization of defects is not possible with this indirect method.

The degree of polymerization has been applied to power transformer paper insulation as a direct method for evaluation [10,11]. However, degree of polymerization measurements require physical samples removed from the transformer of at least 3 g [11]. Removal of samples can be considered invasive and potentially damaging to the integrity of the insulation system and the sampled locations usually require repairs or patches afterwards. For these reasons minimizing the size of the sample taken is desirable.

2.2. Optical/microscopy methods for classification of paper degradation

Optical measurements can be used to classify acute deterioration in transformer paper insulation by perceiving morphological changes associated with ageing of the paper and alteration of its properties and interaction with light. A recent report sought to assess transformer paper degradation by measuring changes in the refractive index of individual cellulose fibers [12]. However, the methodology relied on measurements of fibers suspended in the transformer oil that had broken away from the bulk solid insulation. Therefore, like existing methods for measurement of degradation byproducts in oil samples, this specific approach could not localize acute defects. Methods using optical spectroscopy in the near infrared (NIR) to visible light range have been used to identify degradation in transformer cellulose by measuring changes in reflectance as a function of frequency [13,14]. This approach has been successfully correlated with degree of polymerization measurements and is more suitable for acute classification. However, the method can be affected by irregular reflectance due to variations of curvature on insulation surfaces and the enhanced scattering of paper in the optical/NIR range.

The paper and pulp industry has lengthy experience using optical microscopy as a tool for quality assurance [15]. Paper samples are retrieved at different stages of the paper production. Microscopic images can be used to analyze individual paper fibers and their network structure. The mechanical properties of paper, such as tensile strength, are influenced by characteristics of individual fibers, their density, and their orientation inside the paper structure. Optical microscopy has been used to show that external stresses such as heat can disrupt and distort the paper network structure in cellulose papers [16].

For electrical papers used in power transformer insulation, scanning electron microscopy (SEM) has been used to characterize degradation of the paper fibers and structure as a consequence of thermal ageing. Degradation has been associated with thinning of the paper fibers, formation of cracks and holes in the fiber walls, and disruption to the interwoven network structure of the fibers [17–19].

2.3. Image texture analysis

In digital image processing, texture analysis refers to the extraction of metrics from a digital image which quantify physical attributes of the material surface such as smoothness or coarseness. In statistical texture analysis, these metrics are developed from statistical measures related to the frequency of occurrence for pixel gray level intensities and their arrangement spatially within an image [20]. For the extraction of textural features in this work, a spatial gray level dependence matrix (SGLDM) [8,21] was computed for each insulation paper sample image. The SGLDM contains information about the statistical variation in pixel gray levels in an image. For the microscopic images of aged paper samples, the statistical variation in gray levels is directly related to texture.