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Research Article

Investigation of electrical tree stress using colour techniques

Mohammad Abderrazzaq[1,*]

[1] Department of Electrical Power Engineering, Yarmouk University, Irbid, Jordan.

*Corresponding author: abder@yu.edu.jo

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ABSTRACT

Treeing is one of the severe problems which cause the deterioration and breakdown of electrical insulation materials. Different approaches have been used to characterise this phenomenon, from experiments to analysis. The results of both methods were criticised for their dependence on the assumptions and applied conditions. In this work, the role of colours in understanding the characteristics of electrical treeing in composite insulation was employed. The relationship between the induced strain, associated with the electrical tree, and the change of colour parameters, represented by hue, saturation, and value indicators, was presented. The images were created by relative retardation orthogonal components of the polarised white light used to illuminate the specimens in the microscope. An image-editing software was used to analyse the tree colours, whereas the MATLAB program was written to determine the colour mapping of examined image. The variation of each colour parameter was linked with the tree distribution. It was then introduced as an indicator of stress at each examined point. Therefore, the contribution of the present paper is summarised as an introduction of a new tool to characterise stress in insulation materials by converting a treed image into a numerical array of data without the need to follow a complex mathematical procedure. Finally, this paper can better assess the treeing phenomenon by correlating the direction of tree growth to the rate of change for each colour parameter in that direction.

1. INTRODUCTION

In the last three decades, there has been a significant rise in the applications of composite materials in electrical equipment. These materials are still widely used in generation and transmission systems, especially in power transformers, cables, current transformers, voltage transformers and capacitors [1]. The interest in composites over traditional dielectrics is a result of improved knowledge of the properties of such materials. Among these properties are tolerability, high dielectric strength, corrosion withstand ability and high strength-to-weight ratio. However, these characteristics depend very strongly on electrical stress, which can be developed under abnormal conditions such as moisture, impurities, voids, and protrusions [2-4]. The treeing phenomenon is an ageing problem usually caused by voltage stresses increasing under abnormal conditions. During treeing, the damage originated at a local point of high field stress and propagated over time until enough insulation is breached and breakdown occurs.

The new trends in treeing studies try to use the current smart technologies in innovative test platforms, smart modelling and advanced analysis and monitoring. The new approaches to implementing innovative dielectric materials for the next generation of electrical insulation will require intelligent techniques of treeing analysis, autonomous functions, self-healing, and self-reporting. Despite these approaches, the interest in previous works was mainly directed toward characterising electrical trees and determining the weight of each condition affecting this phenomenon. Some researchers have focused on the damage of the resin surrounding the tree structure as a function of local electrostatic energy dissipation by partial discharges [5-8]. Others have focused on the growth and behaviour of trees as a function of applied voltage, and they have matched the development with the fractal dimension of the tree [9]. Another group of researchers has assumed that protrusions, contaminants, and micro-voids cause the enhancement of local electrical fields and, consequently, the initiation of trees [10]. Nevertheless, using experimental and theoretical tools to understand the treeing process is always essential for the high-voltage engineering industry [11,12].

Although electrical trees have been extensively studied in the last three decades, their effect is still a hot topic, and there is wide room for future research works in this field [13]. The main concern should not be limited to the characterisation of the tree development but should be extended to cover the stress monitoring associated with tree growth. The previous experiments, which were conducted to create conditions similar to that governing the growth mode of electrical trees, have only focused on the tree dimensions rather than the structure of the tree itself.

This paper looks at the problem from a different angle and considers that it is more helpful to concentrate on the differences between the defective and healthy insulation material of the treed region rather than restricting the interest on the damage itself. This means that the change in the insulating material during the tree growth should not be described only by the physical variation and external appearance, but it could also be specified through the colour change of the internal strain of tree images. Therefore, the present paper analyses an image of a sample electrical tree grown in a polyester resin matrix using colour coding techniques. The change in the colour parameters monitored for a specific area in the treed region is used to differentiate between one state of the examined material and the other.

2. UNDERSTANDING COLOUR MODES

Colour is an important part of people's daily life, regardless of age, sex, and culture. Although it has a major role in taking decisions, many people have insufficient knowledge about the colour structure, its techniques, and associated characteristics. Therefore, it is necessary to correctly specify the changes in these colours resulting from various conditions affecting their perception and interpretation. These conditions are differences in light source, observer, object size, background, and direction [14].

A colour model describes each image part as a combination of multiple components. Colour pixels usually contain Red, Green and Blue (RGB) values. This model is most widely used since it conveniently maps to hardware, and display hardware allows for independent control of the contribution of each of the RGB colours. However, the RGB model lacks intuitive appeal. It is hard to estimate its correct RGB values, indicating that such a system does not match well with perceptual properties [15].

When colours are classified, they can be expressed in terms of their hue (colour), lightness (brightness) and saturation (vividness). Hue is the term used in the world of colour to classify red, yellow, blue, and other colours. Mixing primary colours produces different colons, and the continuum of these hues results in the colour wheel [16-18]. Hue is also employed to describe a dimension of colour as experienced by the users of such colour. On the other hand, colours can be separated into bright and dark when their lightness capabilities are compared with hue. Finally, saturation characterises the vividness of colours or the dominance of hue for different objects. The colour model containing these properties is known as Hue, Saturation and Value (HSV) colour model.

HSV model is a cylindrical colour model that remaps the RGB primary colours into dimensions (hue, saturation, and value) that are easier for humans to understand. It uses colour in the way humans perceive them. This representation is more accessible for people to understand because it uses colour in how humans perceive them. These dimensions are strongly interdependent, which means that if the value dimension of colour is set to 0%, the amount of hue and saturation does not matter as the colour will be black. This model of colour representation does not use primary colours directly, and since the cone represents the HSV model, the hue illustrates different colours in different angle ranges. HSV model is used in histogram equalisation and converting grayscale images to RGB colour images. This colour model does not use primary colours directly. Since the cone represents the HSV model, the hue represents different colours in different angle ranges [19].

To understand the CYM model, widely used in printers, it is worth remembering the following facts. Firstly, cyan is negative of red. Magenta is negative on the green, and yellow is negative on the blue. Secondly, the colour image consists of 3 channels for three colours, each for one. Thirdly, red, green, and blue are the primary colour components of this model, whereas all other colours are produced by the proportional ratio of these three colours only. It means that 0 represents black, and as the value increases, the colour intensity increases [20].

The RGB colour model is not intuitive for creating colours in code. Although it is possible to guess the combination of values for some colours, such as yellow (produced by equal amounts of red and green), less pure colours are much harder to guess in this colour model. Because people do not think about colours as mixes of red, green, and blue lights, they do not find answers to many questions concerning obtaining some colours, such as dark purple or the complementary colour of cyan. Therefore, the concept RGB colour model is not as efficient as HSV and is mainly used in display monitoring.

Closely allied to the concept of a colour model is the idea of a colour space, a set of component values allowable in a colour model. In other words, a colour space implements a colour model that generates actual colours.

3. MATERIAL AND METHOD

3.1. Experiments On Composite Insulation

Specimens of composite insulation were fabricated at room temperature using a polyester resin matrix (resin C) with a layer of reinforcing material cast midway between the electrodes. All specimens were exposed to an AC voltage of $4kV_{rms}$ for 240 hours (10 days). However, a voltage was only applied after the curing process to avoid any source of strain influence before the test. A settling-down period was necessary to enable the strain patterns arising from the casting process to gain more stability. Since the curing process affected the insulation characteristics, the fresh specimens needed at least ten days for relaxation under dry conditions [21].

The tree image was observed within the specimen via a circular polariscope, consisting of a microscope fitted with the quarter wave and polarising plates. The optical system was adjusted to a standard magnification level during all stages of strain development to minimise errors due to the influence of magnification. Figure 1 illustrates the experimental setup of insulation specimens and the microscope used to observe the electrical tree images.

3.2. Digitalisation of Tree Image

The digital representation of an electrical tree image requires a precise determination of all colour components contained in the treed region. This could be achieved by conducting an overall measure of such elements of the optically examined insulation area. These components are combined to form pixels agreeing with a colour model. The pixels, with the constituent colour component measurements, represent the considered image's digital representation. The current understanding of a treed image is not limited to the tree itself, but it extends to include the area bounded by the tree branches. Therefore, the obtained values of colour parameters vary according to the location of measured points of tree images.

The current model, employed to characterise the colours contained in the tree image, can be constructed using a simple program with a few lines of ready-to-apply instructions. Alternatively, it is possible to apply specialised software to analyse the colour model embedded in the tree image. ColourMania 2.7 is a free-to-download software package with an intuitive interface, eyedropper, and screen magnifier. The colour modes include RGB and HSV values, brightness adjustment and a colour display in different formats. This software version has the capability of a faster refresh on-screen magnifier and better handling of colour wheel drawing than previous releases.

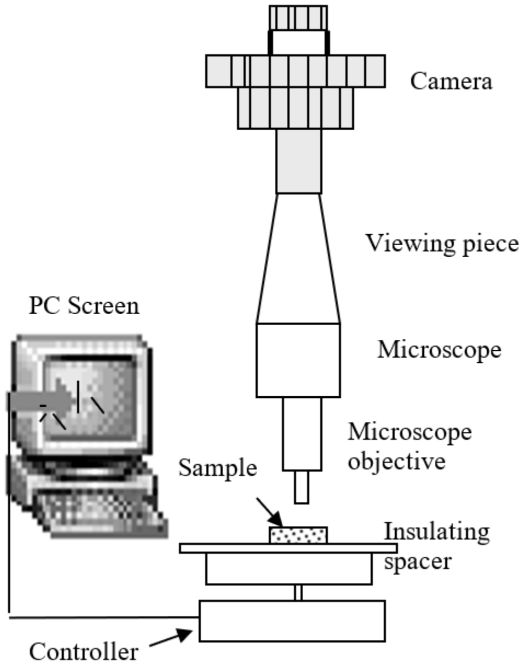
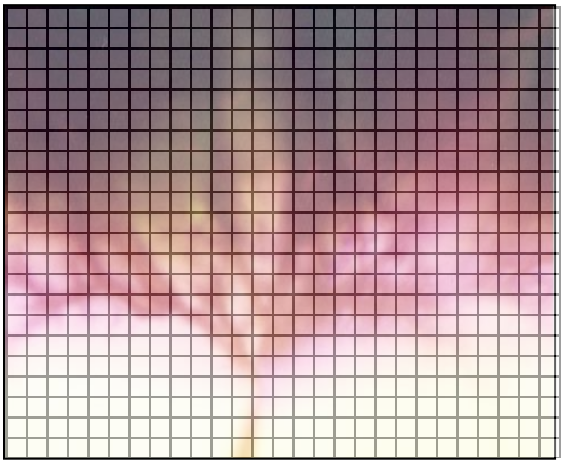


Figure 1. Experimental and electrical tree monitoring setup.

To determine the colour characteristics of the tree image, the picture of such an image is overlaid by a net of identical squares with equal areas. The dimensions of squares should be correctly selected to satisfy a high degree of accuracy without consuming a large size of computer memory or causing a slow computational time. A wrong selection of relatively large squares can significantly affect the accuracy of the colour values prevailing in each square. Therefore, the smallest grid settings of horizontal and vertical spacing available in Microsoft office are used in the current study. The width and length of the sample picture (8.84cm x 6.96cm) were divided into 1428 squares (42 x 34 divisions). Each square has a dimension of 2.1mm x 2.1 mm and an area of 4.41 mm2. A set of three values (HSV) of colour characteristics for each square is recorded. The colour parameters are captured at the same positions. Figure 2(a) shows a complete area of the tree image, whereas Figure 2(b) illustrates the same image but overlaid by a net of identical squares. The shown tree is produced to be a sample for applying this technique.

(a) **The complete area of three images**



(b) **Net of squares overlaid on the treed area**

Figure 2. Tree images

4. RESULTS

Three matrices have been formed to study the relationship between the colour values in the squares of Figure 2b and the tree distribution in the studied image. Each matrix has 34 rows and 42 columns to specify one of the colour parameters: hue, saturation, or value. Therefore, each matrix element determines one colour characteristic in a certain position on the treed area. The horizontal and vertical measurements started from the top left corner of Figure 2b ($x = 0$, $y = 0$). In all subsequent figures, the x and y axes are given in units, referred to as squares. Figure 3 shows the surface plotting of the hue map over the examined insulation area, whereas an interesting type of this mapping is given by plotting this relationship in the contour form, as shown in Figure 4. In all considered figures, it is worth matching the tree located in the image and the shape of the plotting. To correctly understand such figures, it is worth remembering that hue is related to the colour wheel and, therefore, can vary from 0 to 360 degrees. However, the colour hue in the last few rows of the image, where no branches exist, is a relatively stable value (60 degrees).

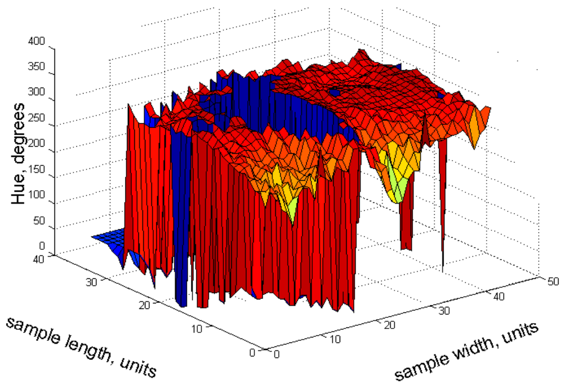


Figure 3. Surface plotting of hue map over the examined insulation area.

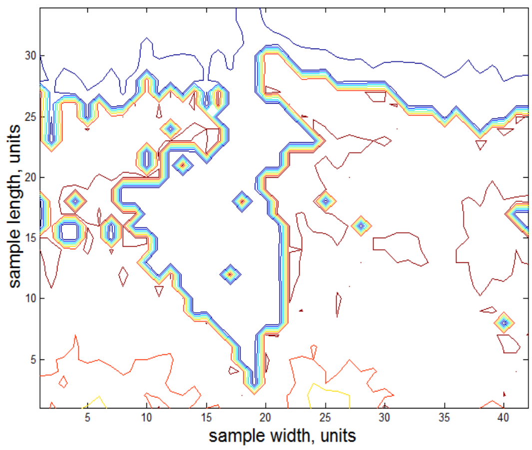


Figure 4. Contour form of hue mapping over insulation area.

The mapping of colour saturation is given in Figure 5, whereas Figure 6 illustrates the same relationship but in the contour form. Each plotting is given as a function of *x-y* coordination of points on the treed region. Unlike the hue, the degree of colour saturation, which characterises the dominance of the hue in a selected point, is given as a percentage value. The highest saturation is shown in the middle of the treed image, which indicates the level of the vividness of dominating colours in that part of the image. As in the case of hue mapping, the saturation shows a high degree of stability in the last few rows of the treed image below the branching area. Except for a pin-tip area, the saturation is low (6 to 16%).

The third element in the HSV model is the colour value, defining the brightness (lightness) of examined points of the image. Figure 7 illustrates the surface plotting form of the colour value variation, whereas Figure 8 shows the contour plotting of Figure 7 described above. The colour value is theoretically varied from 0 to 255 pixels. However, the maximum value measured in this image is 254 pixels. The highest colour values are shown in the last five rows of the depicted image, which are brighter than all areas of the image. This fact is simply illustrated by the contour plot, in which the darkest areas occupy the upper rows of the image and the lightest are distributed on the lower ones.

By inspecting individual squares in each row of the examined image, it is easy to find that the colour value (lightness) is significantly changed when a piece of a tree is contained in that square. If the adjacent squares are empty of tree branches, the lightness is increased and consequently, the colour values are improved. Nevertheless, this mapping can only be understood entirely when all colour parameters are considered together.

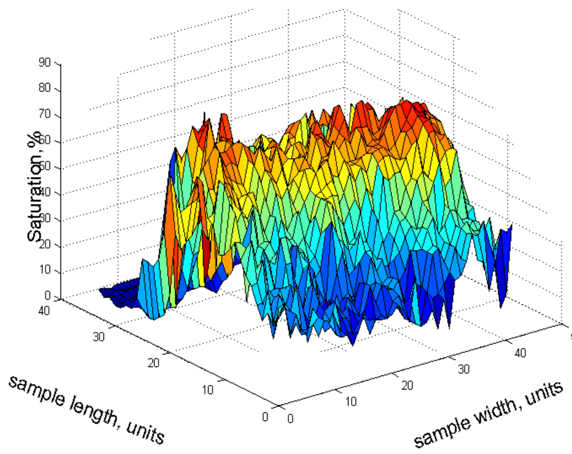


Figure 5. Surface plotting of saturation mapping over the examined insulation area.

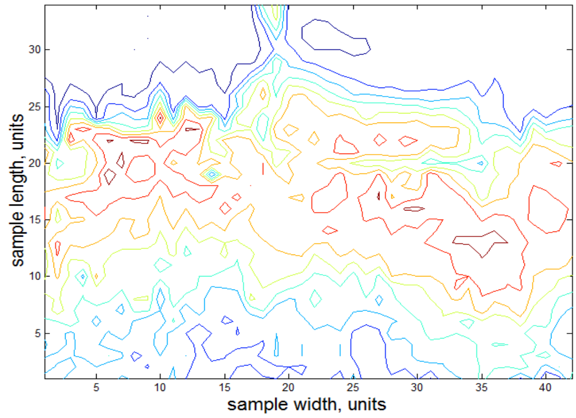


Figure 6. Contour form of saturation mapping of examined insulation area.

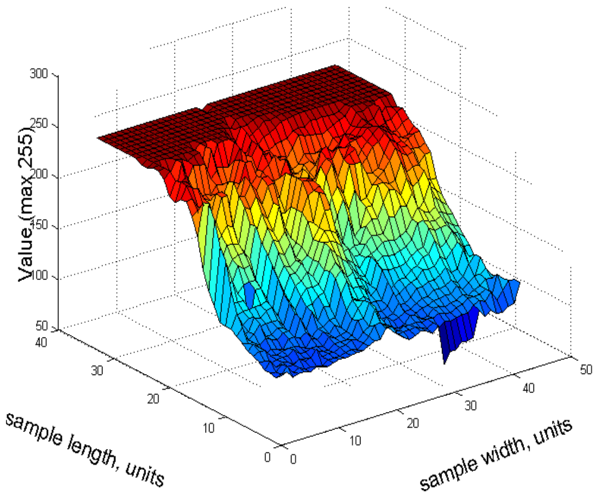


Figure 7. Surface plotting form of the colour value variation.

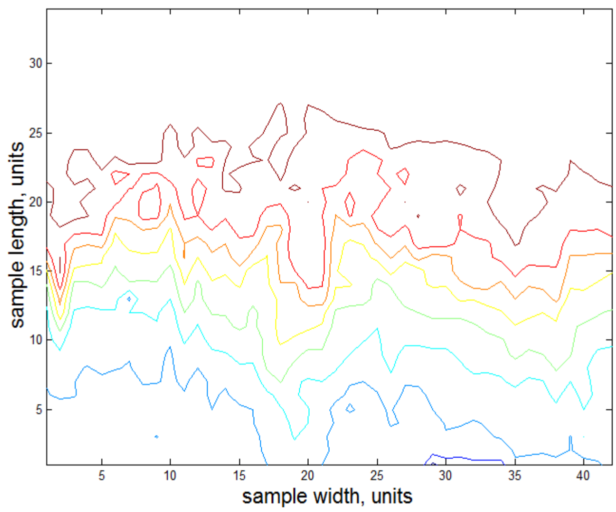


Figure 8. Contour form of colour value mapping over insulation area.

As the tree growth starts from the tip of the H.V. electrode and ends at the opposite earth electrode, it would be helpful to match the tree growth direction with the average change in hue, saturation, and value of the image colours. To achieve this goal, mean values of colour parameters in each row are determined along the vertical direction of the examined image. Figure 9 illustrates the variation of hue mean value along the analysed image, whereas Figures 10 and 11 show the same relationships but for colour saturation and value, respectively.

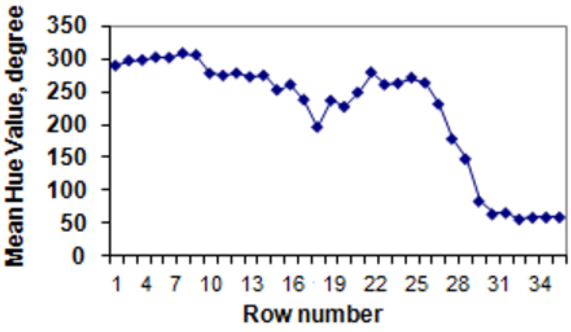


Figure 9. Variation of hue means value along the examined image.

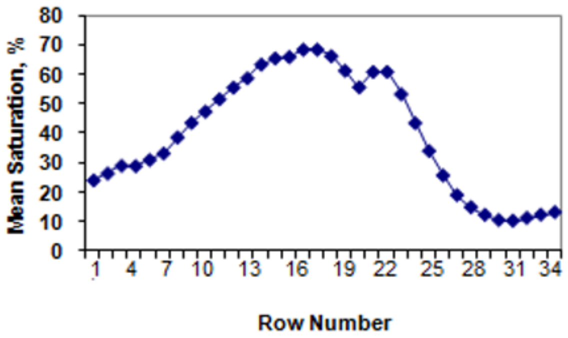


Figure 10. Variation of colour saturation means value along the examined image.

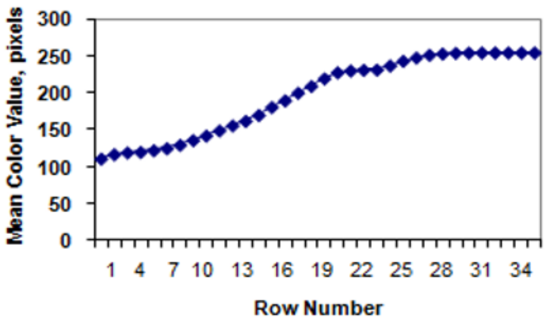


Figure 11. Variation of mean colour value along the examined image.

5. DISCUSSION

Treeing is one of the electric field effects that the insulation material may experience when it is exposed to excessive voltage for enough time. The treeing process does not occur as one continuous process but in several consecutive stages. Therefore, the same tree image may contain several areas stressed to different degrees. This explains that the colour of the tree channels and branches formed under lower stress appears lighter than those formed at higher stress. Trees that take a long time to cause breakdown are usually dark in colour compared with those with lower life. Therefore, if the space occupied by the tree itself is considered the most stressed area, the proximity of a point to that tree can be used as an indicator of a relative strain at that point. In other words, there is a specific stress value for each insulation point, defined by an *x-y* coordinate.

When an insulation point is stressed, the effect is not restricted to the internal structure and physical integrity of the material itself but extends to include changes in that point's outer appearance and colours. Various experiments and analytical tests are needed to study the transformation process, which might occur to the material's internal structure from one state to another. This task is not only complicated, but it is also expensive and time-consuming. Alternatively, it is more beneficial to examine the material state by its colour characteristics in that state. It was found in previous works that the internal strain is strongly related to the colours of a stressed treed region [23-24]. This means that all variations in the colour characteristics can be linked to the development of stress in the examined treed area.

On the other hand, if it is assumed that the tree stem and branches are the most stressed points in the examined image, then the stress in the interfacial area can be correlated to the difference in the colour characteristics of both branched and non-branched areas. Therefore, the horizontal and vertical growths of trees are precisely described by the abrupt variations in the colour model characteristics when the grabbing tool provided by the ColourMania 2.7 software is moved from one point to another. For example, in a square occupied by a piece of a tree branch, the HSV values are 349, 70 and 225, respectively. However, when the gapping tool is moved to the adjacent non-branched square, the above HSV values become 338, 24 and 254, respectively. This means the changes in HSV values are 3.15%, 65.7% and 12.8%, respectively.

A significant change has occurred in the colour saturation or vividness of the dominant colour. The difference in the colour value indicates that the brightness of the non-branched square is relatively higher than the treed square. However, the hue is only changed by 3.15%, meaning there is no significant variation in the colour dimensions or movement in the colour wheel. From the stress point of view, it is expected that the two above adjacent squares must have a slight difference in stress level. Consequently, the hue is not significantly affected by this stress discrepancy, but other colour characteristics can be more sensitive to these changes in stress.

Hue mapping, shown in Figures 3 and 4, is helpful in illustrating the spectrum of colour variations in the examined tree image. They also demonstrate useful information such as the sizes of areas bounded by the same value of hue, areas of low stress and the gradual change of colour values in the examined image. The following findings are worth mentioning here. Firstly, the hue change is relatively small in general. However, the last rows, free of tree branches, have shown an unchanged hue but with a reasonable difference from treed squares. Secondly, the hue change band is not exhaustive, so the number of colours in the examined image is limited. The angle of the hue wheel movement is restricted due to the dominance of purple-like colour in the image. Thirdly, the colour contours, shown in Figure 4, define the areas with the same hue. Although it is difficult to have exact matching between the tree boundaries and the contours, it is easy to notice the impact of tree dimensions on the depicted hue map. Therefore, it is useful to observe the common change in hue along the vertical direction of tree growth, as shown in Figure 9. The hue oscillation around a fixed band of values is noticed in the intensively treed region. The band of this oscillation starts to increase as the pin tip (tree inception point) is approached.

Figures 5 and 6 illustrate the colour saturation mapping on the examined image. In the first few top rows of Figure 2b, the differences in saturation level are small, and the saturation itself is low. By moving down, the saturation starts to grow with a noticeable value difference in the same row of squares. In this zone, the tree branches are slightly separated by non-branched areas. This arrangement causes some differences in the vividness of adjacent squares. The colour saturation starts to decrease significantly in the lower set of rows. The contour plotting indicates that the largest area is in the middle, where the tree frame occupies this zone. These findings agree with the results shown in Figure 10, where the common trend of saturation changes from pin to plane electrodes. Therefore, the colour saturation sensitivity to stress variation can be efficiently applied in the branched area. The lower value of the difference in colour saturation means that the stress level is almost similar—the farthest the points from the tree frame, the lowest their saturation.

The colour value mapping shown in Figures 7 and 8 can be used to characterise the stress from the brightness point of view. This is the easiest colour parameter to analyse. The top rows shown in Figure 2b are the darkest ones; therefore, they are expected to have the lowest colour values. The brightness is improved in the next lower set of rows. The area below the tree frame was the brightest and, consequently, the highest colour value. If the latter area is less stressed, it is possible to use the colour value to measure stress. This can be proved by inspecting the colour values in a row of squares containing treed and non-treed areas. In one of these rows, there was a series of colour values 250, 254, 254, 254, 253, 254, 254, 253, 254, 228, 254, 231, 253, 254, 254 pixels. The abrupt change in colour value from 254 to 228 or 231 pixels agrees with the transformation from a non-treed square to a treed square. The contour plot illustrates the gradual change of colour values in the examined image. The highest brightness is noticed in the last zone of the sample, below the tree image. This zone is free of colour contours compared with the upper dark zone.

Figure 11 determines the general trend of colour brightness change along the vertical line of tree growth. The results obtained from this relationship agree with those obtained from the surface and contour plots. One of the interesting features of this relationship is the small standard deviation among the colour values in the same row. The maximum percentage of this standard deviation is 4.66%, compared with 47.3% and 12% for colour hue and saturation, respectively. The standard deviation values refer to the colour characteristics uniformity of the various colour modes.

The investigation of colour's role in the assessment of insulation stress is not limited to composite specimens, but it can be extended to cover single-dielectric materials such as polyester resin, polyethylene, or any polymeric material. Nevertheless, in most strain patterns observed in previous work, the tip of the H.V. pin electrode is usually surrounded by a purple, orange, or red-related colour [22]. For different specimens and conditions, the colour parameters of an image, characterising a strain pattern, can exhibit a specific mode of change. This could be attributed to several factors, such as the type of material, the curing process, the barriers in composites and the material construction [23-24], and other research [25-27]. Nevertheless, the analysis of strain patterns development from a sequence of images captured periodically can be a universal and more effective measure than the tree growth criterion. Therefore, the valuable application of such an approach implies that the relationship between colour characteristics and strain patterns is not limited to searching for the colour changes from one condition to another but extends to cover the variations of such patterns in different composites.

In the cast specimen, the adhesion of the reinforcement to the resin affects the whole area adjacent to that barrier. The stronger the adhesion of the composite components, the higher the complexity of the strain colour map developed near the barrier. Nevertheless, the current approach can be used to set a new measure for the mechanical impact of various degradation mechanisms of insulating materials, including water absorption and water trees.

6. CONCLUSION

An electrical treeing phenomenon in dielectrics could be characterised by colour modes depicted in the treed image. The differential stress in a treed image is related to the variations in the colour parameters specified by hue, saturation, and value. The mapping of these parameters on the examined image was obtained by setting three matrices for the HSV model. The variation of matrix elements was linked to the stress changes in each position of the image. Among all colour parameters, the most sensitive one to the stress changes is colour saturation or vividness, whereas the last is the colour hue. The scope of change for colour parameters is varied. Parameter hue has shown a limited range of change due to the limited colours dominating the examined image. The higher magnitudes of colour saturation are evident in the tree zone, whereas the colour brightness decreases with the tree growth. The contour plots of colour parameters mapping assist in identifying the boundaries of the stressed areas. Finally, the standard deviations of colour parameters are calculated for each row of matrices to specify the uniformity of colour changes and stress variations.

CONFLICTS OF INTEREST

The author declares no competing financial interests or personal relationships that could have appeared to impact the work reported in this paper.

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