Investigation of electrical tree stress using colour techniques

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ABSTRACT

Treeing is one of the serious problems which cause deterioration and breakdown of electrical insulation materials. The attempts to characterise this phenomenon varied from experimental to analytical approaches. The results of both approaches 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 is employed. The relationship between the induced strain, associated with the electrical tree, and the change of colour parameters, represented by indicators named hue, saturation and value, is presented. The images are created by relative retardation orthogonal components of the polarised white light used to illuminate the specimens in the microscope. Image-editing software is used to analyse the tree colours, whereas MATLAB program is written to determine the colour mapping of examined image. The variation of each colour parameter is linked with the tree distribution and introduced as an indicator of stress at each examined point. Therefore, the contribution of the present paper can be summarised as an introduction of a new tool to characterise the stress in insulation materials by converting a treeed 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 the presence of 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 originates at a local point of high field stress and propagates 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 smart dielectric materials for the next generation of electrical insulation will require smart 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 that growth with the fractal dimension of the tree [9]. Another group of researchers has assumed that protrusions, contaminants, and micro-voids cause enhancement of local electrical fields and, consequently, initiation of trees [10]. Nevertheless, a complete understanding of the treeing process, using experimental and theoretical tools is always essential for the high voltage engineering industry [11,12].

Although electrical trees were 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 on 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, in the present paper, an image of a sample electrical tree, grown in a polyester resin matrix is analysed 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 their 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 the variety of conditions affecting their perception and interpretation. Among these conditions are differences in light source, observer, object size, background, and direction [14].

A colour model is a method of describing each part of the image as a combination of multiple components. Colour pixels usually contain Red, Green and Blue (RGB) values. This model is most widely used since it has a convenient mapping to hardware. Display hardware allows for independent control of the contribution of each of the RGB colours. However, the RGB model lacks intuitive appeal. Given a colour, it proves hard to estimate its correct RGB values, which indicates 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 for the classification of red, yellow, blue, and other colours. Mixing primary colours produces other colors 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 easier for people to understand because it uses colour in the way 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 CMY model, which is widely used in printers, it is worth remembering the following facts. Firstly, Cyan is negative of Red. Magenta is negative on Green and Yellow is negative on Blue. Secondly, the colour image consists of 3 channels for three colours, each for one colour. Thirdly, Red, Green and Blue are the main colour components of this model, whereas all other colours are produced by the proportional ratio of these three colours only. This means that 0 represents black and as the value increases the colour intensity increases [20].

3. EXPERIMENTS ON COMPOSITE INSULATION

Specimens of composite insulation are fabricated at room temperature using a polyester resin matrix (resin C) with a layer of reinforcing material, cast midway between the electrodes. All specimens are exposed to an AC voltage of $4kV_{rms}$ for a period of 240 hours (10 days). However, voltage is only applied after the completion of the curing process to avoid any source of strain influence prior to the test. A settling down period is necessary to enable the strain patterns, arising from the casting process, to gain

The RGB colour model is not an especially intuitive model for creating colours in code. Although it is possible to guess the combination of values to use 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 efficient as HSV, and it is mainly used in display monitoring.

Closely allied to the concept of a colour model is the concept of a colour space, which is a set of component values allowable in a colour model. In other words, a colour space is an implementation of a colour model that generates real colours.

more stability. Since the curing process affects the insulation characteristics, the fresh specimens need at least 10 days for relaxation under dry conditions [21].

The tree image is observed within the specimen via a circular polariscope, consisting of a microscope fitted with the quarter wave and polarising plates. The optical system is 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.

![Figure 1. Experimental and electrical tree monitoring setup.](image-url)
4. DIGITALISATION OF TREE IMAGE

The digital representation of an electrical tree image requires a precise determination of all colour components contained in the tree region. This can be achieved by conducting an overall measure of such components 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 one of the free-to-download software packages, which has 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 version of the software has the capability of faster refresh on-screen magnifier and better handling of colour wheel drawing than previous releases.

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 big 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 2a shows a complete area of the tree image, whereas Figure 2b 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.

![Figure 2a](image1.png) ![Figure 2b](image2.png)

Figure 2. (a) Complete area of three images and (b) Net of squares overlaid on the treed area.

5. RESULTS

To study the relationship between the colour values in the squares of Figure 2b and the tree distribution in the studied image, three matrices are formed. Each matrix has 34 rows and 42 columns to specify one of the colour parameters: hue, saturation, or value. Therefore, each element of the matrix determines one colour characteristic in a certain position on the treed area. The horizontal and vertical measurements have started from the top left corner of Figure 1b \((x = 0, y = 0)\). In all subsequent figures, the \(x\) and \(y\) axes are given in units, which refer here to as squares.

Figure 3 below 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, it 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).
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 $xy$ 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 clearly 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 clearly 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, a complete understanding of this mapping can only be achieved when all colour parameters are considered together.
As the tree growth starts from the tip of the H.V. electrode and ends at the opposite earth electrode, it would be useful 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 examined image, whereas Figures 10 and 11 show the same relationships but for colour saturation and value, respectively.

![Figure 9. Variation of hue mean value along the examined image.](image)

![Figure 10. Variation of colour saturation mean value along the examined image.](image)

![Figure 11. Variation of mean colour value along the examined image.](image)

6. 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 the fact that the colour of the tree channels and branches that have been formed under lower stress appears lighter than those formed at higher stress. Trees which take a long time to cause breakdown are usually dark in colour compared with those having 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, for each insulation point, defined by an xy coordinate, there is a specific stress value.

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 the changes in the outer appearance and colours of that point. To study the
transformation process, which might occur to the internal structure of the material from one state to another, various types of experiments and analytical tests are needed. This task is not only complicated, but it is also expensive and time-consuming. Alternatively, it is more useful 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 region. 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 ColourManía 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 grabbing tool is moved to the adjacent non-branched square, the above HSV values become 338, 24 and 254, respectively. This means that the changes in HSV values are 3.15%, 65.7% and 12.8%, respectively. It is clear that a significant change has occurred in the colour saturation or vividness of the dominant colour. The change 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% which means that 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 small difference in stress level. Consequently, the hue is not significantly affected by this level of stress discrepancy, but other colour characteristics can be more sensitive to these changes in stress.

Hue mapping, shown in Figures 3 and 4, is useful to illustrate the spectrum of colour variations in the examined tree image. They also illustrate a set of 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, which are free of tree branches, have shown an unchanged hue but with a reasonable difference from that of treed squares. Secondly, the hue change band is not wide, which means that the number of colours existing 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 which have 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 difference in values 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. In the lower set of rows, the colour saturation starts to decrease significantly. The contour plotting indicates that the largest area is the middle one, 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 the saturation they have.

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, and, 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 one and, consequently, the highest in colour value. If the latter area is the less stressed one, it is possible to use the colour value as a measure of stress. This can be proved by inspecting the colour values in a row of squares, which contains treed and non-treed areas. In one of these rows, there was a series of colour values 250, 254, 254, 254, 253, 254, 254, 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 are in good agreement with that 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, an orange, or another 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, curing process, the barriers in composites and the material construction [23-24], and also other research [25-27]. Nevertheless, the analysis of strain patterns development from a sequence of images captured periodically can be a universal approach and a 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 covering 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.

7. CONCLUSION

An electrical treeing phenomenon in dielectrics can 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 HSV model. The variation of matrix elements is linked to the stress changes in each position of the image. Among all colour parameters, the most sensitive one to the stress changes is the colour saturation or vividness, whereas the last one was 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 in the examined image. The higher magnitudes of colour saturation were evident in the tree zone, whereas the colour brightness has shown a decrease with the tree growth. The contour plots of colour parameters mapping are significant assistance to identify 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 TO 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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