Development of a Deep Learning Software for Visual Analysis of High Voltage Insulators

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***Abstract*— Silicone rubber insulators have been favoured over conventional insulators to be adopted on high voltage power systems due to their hydrophobic properties and better performance in polluted environments. However, dry-bands and discharges can still be initiated on the polluted surfaces of polymeric insulators causing surface degradation and lifetime reduction. This paper presents a new procedure that identifies and assesses location and frequency of electrical stresses such as discharges and partial arcs on high voltage insulator surface analyzing visual recordings. The procedure is based on image analysis and deep learning techniques to be fully automatic and to minimize user intervention. Also, a MATLAB GUI was developed to provide a fast and user-friendly control of all steps of the analysis and its results.**

***Keywords*— High-voltage, polluted insulators, deep learning, CNN and dry-bands.**

I. Introduction

The performance of outdoor insulators in high voltage (HV) systems can be compromised by environmental and physical factors but the main issue that affects insulators is pollution. When pollutants are present the insulation strength becomes weaker. Pollution can originate from different sources such as sea salt, ashes, smog, smoke and bird droppings. At first, the pollutant deposits on the surface of the insulator and a pollution layer appears Then, with light rain or fog, the polluted surface is dampened which makes it more conductive. The increase of conductivity leads to a leakage current that results in the formation of dry bands. With further increase, partial arcs and discharges may appear through the dry bands and the insulator surface.

Compared to previous technology, glass and porcelain insulators, Silicone Rubber (SiR) insulators are widely selected in HV systems due to their good performance in such polluted environments. Nevertheless, under highly polluted environments, SiR insulators can still suffer damage due to the consistent discharges and dry-bands, on the surface of the insulator, which can cause a reduction of the hydrophobic property of the SiR. This can eventually cause tracking and erosion on the surface by partial arcs, possibly leading to a full flashover and significantly limiting the insulator lifetime [1, 2].

This research aims to develop a new computer algorithm to assess statistical data of electrical stress on HV SiR insulators analysing visual image recordings [3]. Furthermore, one of the main objectives of this research is to achieve a high level of autonomous image analysis of the SiR insulator. Visual images recorded during laboratory tests or on live systems can provide very useful information on location and characteristics of discharges and partial arcs. However, manual analysis can be time consuming requiring continuous interaction of the users. The challenge is to identify the shape of the insulator in different energised situation. It is assumed that the insulator design can be different for a series of tests, can have different shed diameters or simply different number of sheds, or the test set-up might not be perfect, and insulators can be not perfectly aligned with the desired position. The analysis can start only after the insulator has been detected and all the key parts of the insulator have been identified and selected. Only after this step, the location of sparks can be correctly identified and assigned. The use of image processing and artificial intelligence (AI), specifically deep learning, have been adopted in this work to significantly augment the process of the image analysis, improving the precision of the location and significantly reducing the user intervention. This new procedure offers an interesting analysis tool for post processing laboratory test results and insulator monitoring on live systems. The current version procedure is optimized for its use in high voltage laboratory and future work will focus on adapting the procedure to take into account the increased interferences present on live systems.

II. Test setup and Methodology

Several 11kV silicone rubber 4-shed insulators were tested at Cardiff University's high voltage laboratory under pollution and fog conditions. Suitable voltage levels above the nominal insulator's ratings were applied in order to monitor the insulators under stress conditions. All the visual recordings are then post-processed and analysed using the new procedure proposed in this paper. The outcome helps in identifying any difference in the location and intensity of discharge events among the different designs.

A. Laboratory Test setup

The laboratory test procedure adopted was developed at Cardiff University in previous studies [4]. Firstly, the insulator is artificially polluted according to a modified procedure of BS EN 62217 standard [5], based on sodium chloride, kaolin and a wetting agent, Triton X-100. The insulator is then placed in a fog chamber where two pairs of water sprays supply a uniform fog to the insulator at a 3 ℓ per hour rate. The chamber's door has a small opening that will allow the camera to record the insulator area during the test. A HV transformer can provide up to 75kV which delivers the high voltage to the insulator through a programmable control unit. In this test, a ramp voltage increasing at a rate of 4kV per minute was adopted. The data acquisition interface (DAQ) is programmed in LabVIEW which measures and records the magnitudes and shape of the applied voltage and insulator leakage current. After the desired response has been achieved (flashover, or only discharges) the data can be collected from the high definition digital camera with a frame resolution of 1440x1080 pixels. The camera adopted in this series of tests has an interlaced refresh rate. The presence of interlaced frames requires a pre-processing step of converting the frames into a non-interlaced video to avoid the presence of null row data in the visual matrix data. The resulting frame rate is reduced to 25 fps. Then, the camera files can be imported in MATLAB where the visual analysis is performed.

B. Visual Analysis Methodology

The post processing analysis aims to locate any discharge event recorded over the insulator surface during the laboratory test or an inspection on live systems. An important preliminary step is the correct identification of the insulator position and selected areas as trunks and sheds. The procedure is divided into 3 sequential parts, *Image Acquisition*, *Image Processing* and finally *Image Analysis*. A block diagram, as shown in Fig. 1, illustrates the steps required for the analysis of each insulator.

Image Acquisition is applied to the camera recording the video and the extraction of all frames of recorded video and associated timestamps. The video files are transferred to the pc via a USB cable. However, in future, the transfer will be set up via wireless connection to achieve an almost real time processing. The procedure takes advantage of the capability of MATLAB to acquire video files using internal and third-party drivers available on the system. The video recording is processed to extract features such as number of frames, frame rate, time length and timestamp of first frame and resolution of the frame. Each individual frame is then uploaded onto the memory of the computer as an RGB matrix, three matrices of size equal to the frame resolution and each associated with one of the colours Red (R), Green(G) and Blue (B); each cell value represent the brightness of the pixel for the associated colour with a range between 0 to 255.

The next step is the *Image processing*, a core element of this analysis as it will prepare the images accordingly and make it possible to extract the right features for the analysis of the insulator. It consists of three sub-procedures:

- insulator presence in the frame,
- evaluation of its axis direction and its angle with a vertical line,

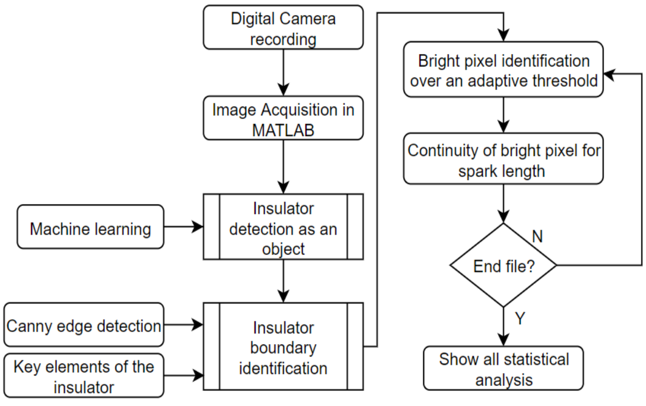


Fig. 1: Block diagram of the insulator analysis

- identification of insulator's main parts and area definition.

When the images have been processed, the *Image Analysis* will aim to evaluate the presence of brighter pixels indicating a spark event and its position on the insulator. An adaptive threshold is required to identify brighter pixel, since the light conditions in the visual recordings can vary significantly. The overall statistics, counting the number of sparks, their extension, their frequency of occurrence and their location according to selected areas, enables the comparison between insulators with different designs.

III. Image Processing: Insulator Detection Procedure

A. Computerised identification of the position of the insulator.

One of the main tasks in the analysis of the insulator is the automatic identification of the presence and the position of the insulator on the frame. The computerised identification of the insulator will focus on the insulator and its close surroundings, ignoring the background and other objects. This will allow a faster and more accurate sparks analysis as it reduces the number of pixels to analyse and it also eliminates the risk of analysing noise in the background. Object detection is a computer vision technique that locates the object of interest in images or video. With object detection techniques based on AI, the object can be located and classified by training predictive models [6].

Object detection techniques can vary but, in general, there are three main categories: Deep Learning, Machine Learning and computer vision techniques. Deep learning uses convolutional neural networks (CNNs) to teach the necessary features of object detection, examples are R-CNN and You-Only-Look-Once (YOLO v2). Machine Learning operates by extracting features before training a classifier to identify objects. Well known approaches are aggregate channel features (ACF) and the Viola-Jones algorithm. Finally, classical computer vision is used when the user knows exactly which features will work well for the specific object. Techniques include template matching, image segmentation and blob analysis, or feature extraction and matching [7, 6].

Training a predictive model from scratch is not a trivial task since it requires thousands to a million of labelled images to be collected and processed, requiring days or weeks to complete the training. Furthermore, intense computation power is required, hence, a Graphical Processing Unit (GPU) is necessary to optimize the calculation time [8]. For this reason, training the neural network from scratch is not recommended for tasks such as identifying the location of the insulator. Instead, Transfer Learning will be used as it uses an existing pretrained CNN as an automatic feature extractor from images. The pretrained network already contains a set of different features, and this knowledge can be used for identifying an insulator in the frame. Transfer Learning techniques takes the trained network and retrains it for a new specific object classification using only hundreds of images.

The pretrained network GoogLeNet was selected as the best candidate for this project because of its high accuracy , reduced memory requirement and faster than other available

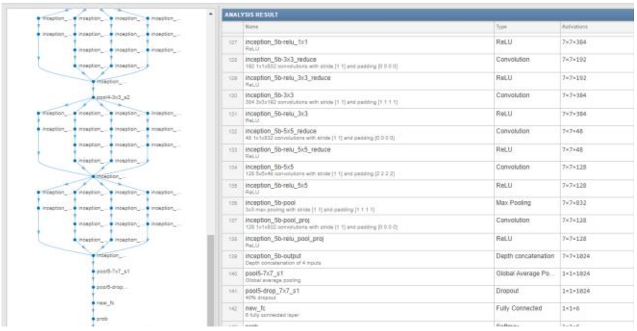


Fig. 2: GoogleNet layer visualisation and the new final output layer with the 6 classes definition.

networks (Squeezenet and AlexNet). Once downloaded, it has been imported in the MATLAB environment. Using Matlab Deep Learning Toolbox, it is possible to visualize and inspect the network architecture. In the first element of the Layers property of the network, the required input image size (for the selected network was 244-by-244-by-3, as number of RGB pixel matrix dimensions). In order to apply the Transfer Learning for the application of identifying an insulator, a collection of insulator pictures was prepared. This data store contains 90 images of 6 different object types, insulator, torch, hat, cup, playing cards and a screwdriver. Since the goal is a different classification to be performed by the pretrained network GoogLeNet, the last two layers need to be replaced, as shown in Fig. 2. The in-between layers will not be changed and will extract all the necessary features for processing the images. The selected layers are replaced with a fully connected layer with 6 outputs which represents the 6 different classes (insulator, hat, cup, cards, torch, screwdriver) and a final output layer, which will classify output classes, will be replaced with a new one excluding the class labels. In addition, some key parameters of the training as the Initial Learn Rate, the number of epochs to train for, mini-batch size and validation data have been selected after some trial and error tests.

To test the new training network, the validation images had to be classified and to evaluate the confidence of classification. The confidence test performed on 6 sample images randomly selected with predicted labels and the probabilities of the images having those labels is shown in Fig. 3.

B. *Automatic identification of insulators tilted angle*

The insulator image needs to be in a straight vertical position in order to identify the trunks, terminals and sheds areas and to estimate the spark's vertical height correctly. A

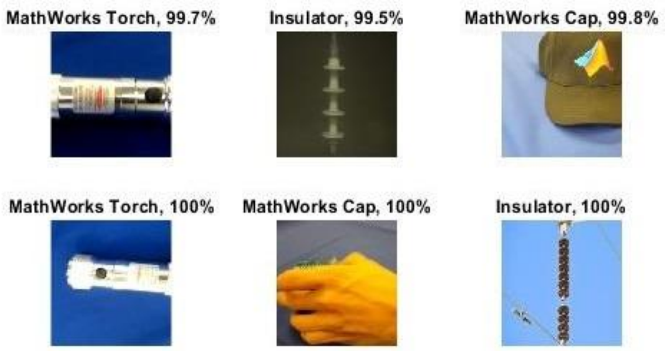


Fig. 3: Validated images with the predicted labels and percentage of confidence

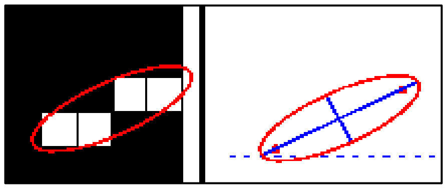


Fig. 4: Graphical example of the "Orientation" property

tilted image of the insulator provides incorrect measurements of the spark's height due to difficulties in correctly identifying the axis direction. However, due to the nature of the test set-up, the insulator might not always be in perfect straight alignment but it can be in a tilted position. To accomplish the vertical orientation of the insulator, the image is processed and relative features, that will help with this task, are extracted using MATLAB's command "regionprops", a powerful function that returns measurements of a binary image for the set of properties, about each 8-connected component. Properties of "regionprops" return Area, Centroid, Boundingbox, Perimeter and more. However, the property "Orientation" proves to be a more useful one. The Orientation property calculates the angle between the x-axis and the major axis of the ellipse that is created from the black and white pixels. Fig. 4 illustrates a binary image (left) and the ellipse with its axis (right). The angle is calculated through the major blue axis and the horizontal dotted line. The value that appears is in degrees with a range from -90 to 90 degrees [9]. This will provide the horizontal alignment, hence, by adding to 90 degrees, the angle value will ensure the vertical alignment of the insulator. "Regionprops" only work with binary images. For this reason, the image needs to be first pre-processed and then the Orientation property applied. The rotating algorithm has been tested for various angles and different insulator designs. An example of the application of the rotation algorithm on an image of a non fully vertically-aligned 11kV insulator is shown in Fig . 5. The resulting image of the insulator appears to be successfully vertically-aligned.

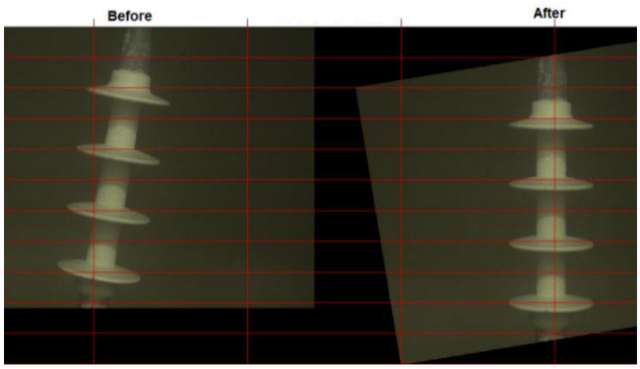
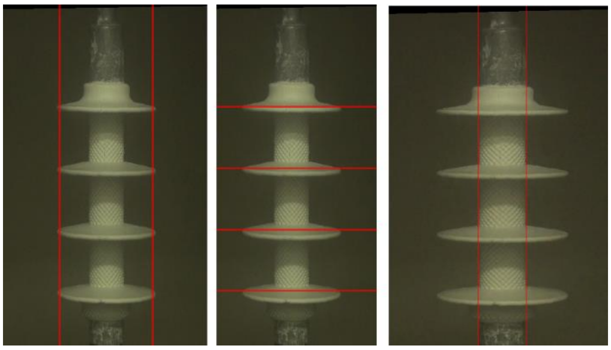


Fig. 5: Example of application of the rotation algorithm on an image of a not fully vertically aligned insulator.

C. *Automatic identification of insulators main parts*

The key feature of the analysis is to identify the insulators main parts such as the trunks, terminals and the sheds, since this allows the segmentation of the insulator into smaller selected areas that give more in-depth details about the spark's frequency and location. The division of the insulator in zones allows classifying the location of the spark and identifying any specific area more prone to experience a high spark frequency. This is beneficial, as it



a) b) c)

Fig. 6: Red line tracing: shed's diameter (left), location of sheds (centre), trunk area (right).

can provide a useful feedback about the insulator's design. The process begins pre-processing the image transforming it into a binarized image of the insulator. The image processing ensures that only the insulator exists in the image and all the unnecessary information, as other objects, and noise are removed. Then, any identified insulator part is traced using red horizontal and vertical segments over the original RBG image, to confirm to the user the correct execution of this procedure.

1) Identification of the shed's diameter and location

The identification of the shed's diameter is obtained using the horizontal binary image of the insulator. The horizontal orientation of the insulator helps to identify the maximum and minimum points of the insulator boundaries and then the highest and lowest coordinates with white pixels (Fig. 6.a). By knowing that the sheds are all aligned, two different for-loops can be used to check the image for the outer pixels. Then, the detected minimum and the maximum coordinates are the left and right shed parts of the insulator, respectively. However, a second check aims to identify the two horizontal coordinates within the almost the same vertical height to confirm the horizontal alignment of the shed and to count the number of sheds present on the image (Fig 6.b). The shed diameter is then evaluated as the average length of the multiple pair of horizontal coordinates (Fig. 6c). The calculated shed length is in pixel units. Then, using the diameter width provided by the user, a pixel to millimetre scale is calculated.

Once the outer coordinates of the sheds are obtained, it is possible to evaluate the vertical axis position as the middle point. If the insulator profile uses an alternate profile, e.g. large and short sheds, the shed procedure will be repeated after the vertical axis identification.

2) Identification of trunk's width

After all the sheds are identified, the midpoint between two consecutive sheds can be easily found and the vertical midpoint row does not contain any sheds. A simple for-loop checks when the insulator trunk starts and when it stops. A "flag" has been used as an indicator to act as a signal for this function. When the first white pixel comes across, it will indicate the beginning of the trunk, that is when the flag will turn 1, and the first black pixel after that will reveal that the trunk's width has been completed and turns the flag back to 0. The number of trunks present is simply evaluated assigning the upper and the lower areas as special terminal zones, the remaining number is the central trunk number.

IV. Spark identification

A discharge in the recordings indicates that an electric stress is present on the insulator surface and suggests the presence of dry-bands on the pollution layer. These discharges can be identified in the visual video as very bright pixels, usually with a yellow or red glow for partial arcs and blueish glow for corona discharges. However, this procedure is not aiming to distinguish these two events. Besides, the proposed procedure could be simply applied to recordings generated by Ultra Violet (UV) cameras; the UV camera recordings consists of the superposition of a visual image with the UV detection as a very bright pixel superimposed. When the visual recordings are converted into grayscale, the sparks tend to have a very high value in comparison with the insulator surface. In fact, in this series of tests, the sparks are associated with brightness level above 190, where 0 is fully black and 255 is fully white. These indoor tests are performed in a fog chamber with presence of fog, therefore the brightest object is the insulator when no spark is present. In this series of tests, the initial frames have no spark since the voltage is still below 1 kV. Therefore, the threshold can then be set averaging the maximum brightness in the first 10 frames and multiplying by a coefficient. This is the value that will determine the spark threshold in all the frames and any pixel associate with a higher value is classified as a discharge.

A. Vertical spark length calculation

It is useful to evaluate the vertical extension of discharge, in order to evaluate the percentage of creepage length short-circuited by them and consequently follow the dynamic changes of the pollution layer resistance [10]. The estimate can be obtained by counting all bright pixels across the vertical length of the insulator, noting that sparks that exist in the same row are taken into account only once. A nested loop allows the index to go through all the rows of the matrix in the binary image.

Partial discharges deteriorate the material of the SiR insulator. The extent size of the discharges are associated with higher value of leakage current and, consequently, more damage on the insulator surface [11]. For this reason, it is important to track the continuity of each spark. Taking advantage of the "regionprops" function and its property "BoundingBox", all continuous areas are detected and visualized by a red box. The vertical height is then retrieved as an output from the function. All the calculated dimensions are then converted into millimetres using the conversion factor previously obtained.

B. Localised spark activity

Similarly to the previous sub-procedure, the localized spark activity are identified and the frequency of occurrence is calculated. The identification of the main parts of the insulators and their associated areas can be drawn as boxes of known coordinates. Every discharge identified within each box contributes to the frequency of occurrence for that area. This number offers an easy way to find weak spots of the insulator and it may provide valuable feedback on the insulator's design.

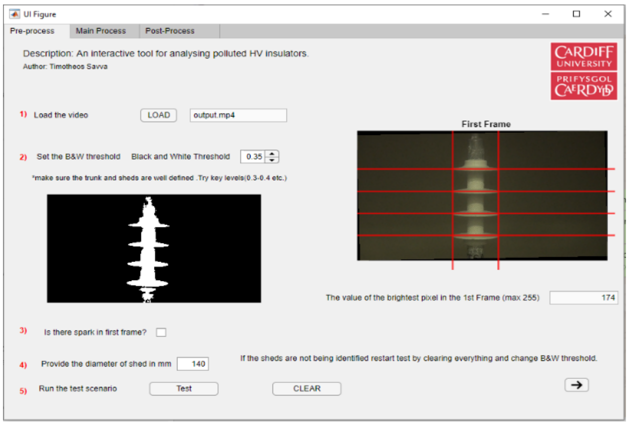


Fig. 7: First tab of the user interface.

V. APP DEVELOPMENT

Following the successful development of the algorithms, a Graphical User Interface (GUI) was developed to include all algorithms produced previously (Fig.7).

The GUI's goal is to be user-friendly, self-explanatory, robust and a tool that can be used in the future. These aims were taken into account and by using MATLAB's App Designer, a GUI was developed from scratch. The GUI integrates the visual components with the programming scripts to create a tool that can be used in further studies by engineers. By packaging the new MATLAB app into a single file, it can be easily shared with other MATLAB users. Furthermore, using the MATLAB platform, users will be able to update the app when any future modifications take place [12].

The User Interface (UI) that has been developed contains 3 tabs, the *Pre-Process* tab, the *Main Process* tab and the *Post-Process* tab. The *Pre-Process* step allows the user to upload the video file that contains the insulator test recording (Fig. 7). Then, an adaptive threshold field allows the user to select the most appropriate binary value that works better for each insulator. A quick analysis on the first frame is completed each time the threshold value is modified and then the result plotted; in this way, the user can estimate the correct identification of the main parts of the insulator before the full process begins.

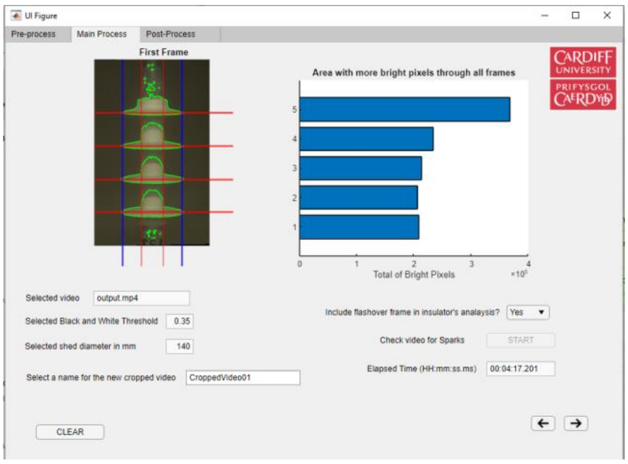


Fig. 8: Main Process tab of the UI showing insulator geometry (in green) and areas (red and blue lines) identification.

In the second tab, *Main Process*, the full analysis, Image Processing and Image Analysis, is computed. Before

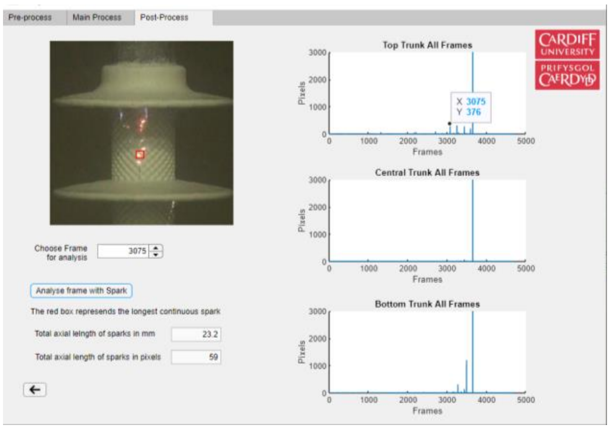


Fig. 9: Post-Process tab of the UI.

the process is started, the user can select to modify the default value of the shed diameter and the file name of the resulting cropped video.

The first datum is used to calculate the pixel to millimetre scale and the actual length of sparks, as mentioned in Section III. The second input offers the possibility to save a video without any part of the frame not pertinent with the insulator and its close surroundings, offering a smaller video size maintaining the native resolution. Once the analysis is completed, the insulator image of the first frame is plotted on the screen, including the boundaries of the insulator (in green colour) and its geometry (red and blue lines), as shown in Fig. 8. On the righthand side of the image, a plot represents the corresponding sum of bright pixels detected in each of the corresponding areas.

In addition, the Post-Processing window offers the inspection of the spark distribution over time on the trunk areas (or the terminal areas), and it is equal to three in the example shown in Fig. 8. The three plots display the number of bright pixels detected on each frame for the top, centre and bottom trunk. The user can inspect the sparks on the desired frame, selecting directly the individual bar in the plot (frame 3075 in the example of Fig. 9), and the corresponding trunk area is visualized on the right side of the window. An additional feature allows the sparks from the selected frame to visualize all important computed results such as the location of the longest continuous spark on the image (in red) and the total axial length of discharges in millimeters and pixels. Finally, all the generated figures can be exported as images using the MATLAB interactive tool.

VI. RESULTS AND DISCUSSION

The full analysis procedure with the Graphical User Interface has been adopted on videos recorded during several test series performed at the Cardiff University High Voltage laboratory. As previously described, the tests were performed on artificially polluted insulators placed inside a clean fog chamber and energized using a ramp voltage shape. The equivalent salt deposit density for this series of test was 0.64 mg/cm^2 and the fog rate was set to 3 ℓ/hr. This type of test applies an increasing electrical stress on the insulator surface and determines an increasing number of discharges over time. The post-process results of one of the tests is shown in Fig 10.

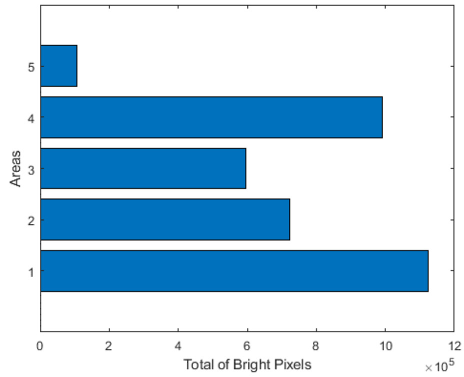
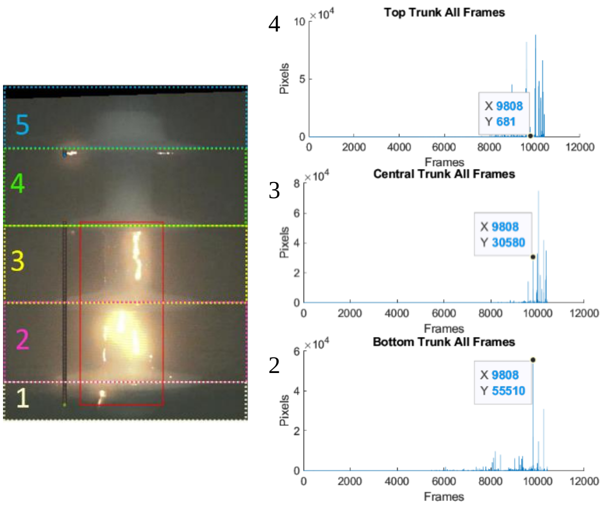


Fig. 10: Total count of bright pixel over the entire test; 11 kV insulator artificially polluted (0.64 mg/cm^2) and fog rate 3 l/h.

The total count of bright pixels over the entire test grouped by 5 selected areas. It is noticeable that areas 1 and 4 contain the majority of discharges.

This result is extremely useful, indicating to the researcher where to check for possible surface erosion or damage. In addition, the capabilities of the developed procedure permits to explore how this damage is applied at a specific time; by selecting any point on the graph, the corresponding frame is visualized (N=9808 Fig.11a) with a red square indicating the spark extension and the magnitude per area over the time (Fig.11b).

The output of the procedure is a very good indication of discharge activity on the insulator surface under electric stress, and any test comparison of different geometries may lead to design improvement. However, it is important to note that the test set up and applied stress conditions need to be the same for the results to be comparable. This procedure, if applied with a different voltage set up, for instance constant voltage, can be simply applied considering a fixed time period of the recording.



a) Specific frame with identified sparks

b) the spark-pixel count per frame per trunk areas

Fig. 11: Example of output results.

VII. Conclusions

The computerised procedure, proposed in this research work, can perform statistical analysis of discharges caused by electrical stress on HV SiR insulators based on visual image recordings. The procedure takes advantage of deep learning techniques to reduce significantly the user input and improves significantly the speed and the accuracy of the analysis. This is very important in series of tests involving flashover due to the need of high number of tests to achieve correct and valid statistical results. The possibility of obtaining useful information about location, frequency of occurrence and extension of spark is a valuable tool for insulator designers and users. Future work will focus on the application of this procedure to robotised devices with micro GPU board able to localize the insulator autonomously and to process in real time any discharges on live systems.

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