ONLINE DETECTION OF SNOW COVERAGE AND SWING ANGLES OF ELECTRICAL INSULATORS ON POWER TRANSMISSION LINES USING VIDEOS

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ABSTRACT
A potential fatal problem for electrical power delivery through power lines in Northern countries is when snow or ice accumulates on electrical insulators. This could lead to snow or ice-induced outages and voltage collapse, causing huge economic loss. Further, large swing angles due to wind may cause short circuits. This paper presents a novel video surveillance system for detecting snow coverage on electric insulators and swing angles of insulators using videos from a remote outdoor 420 kV power transmission line. To the best of our knowledge, it is the first insulator snow surveillance system based on automatic image analysis techniques. We propose using hybrid techniques by combining histograms, boundaries and template cross-correlations for analyzing a broad range of scenarios caused by changing weather and lighting conditions. Experiments on videos captured during several month periods have shown promising and valuable estimation results. For image pixels related to snow on insulators, our system has yielded an average detection rate of 93% for good quality images and 67.6% for poor quality images, and a corresponding average false alarm of 9% and 18.1%.

Index Terms — electric insulator surveillance, snow detection, ice detection, swing angle, insulator image analysis.

1. INTRODUCTION
Northern countries, e.g. Scandinavian, north Canada, Russia and China often encounter snow and ice during cold winter or in high areas. One of the problems for electrical power delivery through power lines is when snow or ice accumulates on electrical insulators. When the accumulated snow melts and freezes or in case of freezing rain, long ice bars hanging down along the edge of insulators could be formed. Also, the coverage of snow on insulators could be thick. When the ice or snow melts, a conducting layer is formed on the insulator or on the outside of the ice, and short circuit or flashover may occur. This may lead to ice-induced outages and voltage collapse, causing huge economic loss for the power company and the related users. For example, Norwegian power companies have observed ice-induced outages especially during 1987 and 1993. In Sweden, it has recently caused a number of large blackouts. In Canada it has led to large problems and sever blackout in the end of 1990’s. Because snow and ice related outages happen during severe weather conditions, very little information and knowledge are available about the process of ice and snow accretion finally leading to flash over. Further, when upgrading power lines, ice performance is one of the important aspects of the insulation selection process. A better understanding of insulator’s sensitivities to snow and ice would be useful to help improving future design. In Norwegian environment, classical freezing rain rarely occurs. Hence, it is unlikely that rain would lead to outages in their networks. However, it is assumed that accretions from wet snow (possibly in combination with heavy rime icing) that occur regularly could result in ice accretions with electrical properties similar to those of freezing rain. Efforts have made for arranging surveillance cameras along these power lines as they are often located in very remote locations. The captured videos from the cameras are then transferred through the Internet to the corresponding utilities or power companies where the situations are monitored by humans. It is desirable that one automatically monitor and detect possible snow/ice accretions on electrical insulators. Further, once the snow/ice on the insulator are detected, automatic analysis shall be followed to estimate the percentage of snow/ice coverage related to the distance between two neighboring shells of an insulator. The analysis results can be fed to network operators if the snow/ice coverage reaches a risk level, and necessary intervention can then be taken before short circuits occur.

Motivated by the above issues, this paper proposes a full automatic image analysis system for detection and analysis of snow/ice coverage on electrical insulators of power lines using images captured by visual cameras in a remote outdoor laboratory test bed [1, 2]. Although many other techniques can be found (e.g.[3]), to the best of our knowledge, this is the first successful insulators snow and ice surveillance system that is entirely based on automatic image analysis. As a by-product, such results may provide power system experts with a better understanding of snow/ice bridging phenomena hence possible improvement in future insulator design [2].

2. SETTINGS OF WEB-BASED SURVEILLANCE
The measurements are performed for insulators on a 420 kV power transmission line that is set for remote outdoor tests. Basic components installed in the system include: (a) visual cameras and lamps; (b) a weather station; (c) a communication system between the remote test site and network operator; (d) a web-based database; (e) a real-time automatic image analysis system. Measurements (including videos) are done in the remote site (where 230 V supply is not available) in a fix time interval (10 minutes) and during severe conditions such as low temperatures and darkness, where the power is only sufficient for heating the lamps and cameras. Armadillo cameras are used, with schneider/xenoplan lens of 1.9/35 mm, heating is used to avoid moisture on the lens. For the lighting, three halogen beams with pen beams are used, each being an effective 75 Watt, equipped with an internal heating to avoid moisture on the glass. Weather and wind conditions are also recorded. The communication system is established between the remote site and the power network operator, where measured data are transferred from the test site to the database and stored, which are accessible via a web interface immediately after the measurement. Real-time image analysis is performed for each newly captured image and the results are displayed and stored in the system. Other data, such as voltage, power, current, reports and results of analysis, can be added to the database. See [1, 2] for the details of the system.

3. COMPLEX OUTDOOR IMAGE SCENARIOS
Despite rigid insulators and stationary cameras, automatic detection and analysis of snow coverage is non-trivial. Since images were captured from natural scenes, not only lighting conditions and background may change abruptly (e.g. sunshine, cloudy, foggy, drizzle, raining and snow; moving clouds, unexpected moving objects e.g. airplanes or birds within camera views), but also cameras are often slightly moved due to strong wind (causing insulator positions in images drifting with time), see example scenarios in Fig.2. Among them, some events that significantly impact the image analysis are:
- strong wind: may cause camera movement hence the insulator position in the image can drift;
- dark weather: may lead to low visibility or low contrast in images;
- cloudy weather: may lead to non-uniform fast changing background;
- foggy weather: may lead to low visibility / severely blurred images;
- dark night: images may vary significantly, depending on the snow, reflection of lighting and camera incident angle.
- strong sun: depending on the incident angle of camera, images may contain bright regions due to the reflection from the insulator.

4. REGISTRATION FOR EXTRACTING ROI
To limit the computation in insulator image analysis, a small region containing the insulator (or, the region of interest - ROI) is extracted. Observing insulator’s positions in images drift with time mostly due to minor camera movement but also from the swing of insulator, image registration is required for extracting ROI. Since the image size of insulator remains a constant, it is used as a priori information. Separate processing methods are applied to daytime and nighttime images due to significantly different nature of these images. 

Nighttime images: Under the lighting condition of current system setting, only the central axis of insulator images is most visible (see Fig.3(a)). Hence, a histogram-based accumulation method is proposed. Since histograms from night images contain a narrow sharp peak, a binary image $B$ is generated by thresholding the histogram. To determine the ROI, vertical and horizontal accumulations are performed respectively by $a_v(i) = \sum_{j=1}^{N} B(i, j)$, $a_h(j) = \sum_{i=1}^{M} B(i, j)$. The vertical accumulated curve $a_v(i)$ usually shows one narrow peak (see Fig.3(c)) related to the central axis of insulator. This peak position is assigned to the x-coordinate center of the ROI. The horizontal accumulated curve $a_h(j)$ usually shows two large peaks (see Fig.3(d)), corresponding to the top and bottom frame where an insulator is fixed. The valley region between the two peaks in $a_h(j)$ is related to the insulator, the center position in this valley is hence assigned as the y-coordinate center of the ROI. The width and height for the ROI are then assigned according the pre-determined values (fixed constants for each type of insulator in respect to its camera setting). This results in the ROI (see Fig.3(e)).
We propose to use a priori information (a pre-stored template) and cross-correlations. The template $E_T$, containing broadened outer boundaries (width $w = 7$ in our tests) of insulator from an ideal image, is stored beforehand. For each new image frame, a binary edge image $E$ is created from a simple edge detector. The following normalized cross-correlations are then computed,

$$
\rho(u, v) = \frac{\sum_{x, y} E(x - u - v, y) E_T(x, y)}{\sqrt{\sum_{x, y} E(x, y)^2 \sum_{x, y} E_T(x, y)^2}}
$$

(1)

where $u, v \in R_E$ are the lags for cross-correlation, the range of $u, v$ is within the size of image $E$. The reason of using broadened boundaries in the template is to avoid sensitivity in the correlation when edges and boundaries from two images are slightly shifted. The best position is found by $(u^*, v^*) = \text{argmax}_{u, v} \rho(u, v)$. The extracted ROI is then further refined by applying horizontal and vertical accumulations (in the similar way as for the nighttime images). Tests of these methods over 3 months of continuously measured images (in 10 minute interval) have resulted in about 88.5% of success for extracting ROIs.

5. A HYBRID METHOD FOR SNOW DETECTION

Once a ROI image is successfully extracted, detection of snow and subsequently analysis of snow (or, ice) coverage will be performed. Noting that snow (or, ice) scenarios can vary significantly (see Fig.4(a)-(e)), the following prior information is exploited:

- An insulator is a rigid object, its size and shell edges and outer boundaries are fixed and known. These may be changed if an insulator is covered by something, e.g. snow or ice.
- There exist some intensity difference between the snow/ice and the insulator/background.
- The intensity differences between snow, shells (or, background) cause extra edge curves on the top half of insulator shells.

Further, based on observations we assume that snow is only accumulated on the top or along the side of insulator’s shells.

![Fig. 4. Variety of scenarios of: snow on insulator and swing of insulator. From the left to right: (a)(b) snow; (c) melting snow; (d)(e) Rim frost; (f); night image of insulator with almost no wind. (g) night image of insulator with a relatively large swing (measured wind speed 10.4m/sec).](image)

5.1. Detect and Analyze Snow Regions

To determine the snow (or ice) regions from images with a range scenarios, we propose a method based jointly on boundary and context analysis by the steps (a)-(d) described below.

(a) Detect extra regions: Observing that snow may generate extra image edges and regions, an edge detector is first applied to the median filtered ROI image, followed by edge closing. The median filter is used for obtaining a ROI image with a smoother background, hence less edge noise. Each enclosed area surrounded by edge curves forms a region.

(b) Find extra regions above the shells: Snow on insulator shells, and other changes (e.g. local clouds, illuminations, reflections) could generate new extra regions. Using the prior information of standard shell positions and the ‘ellips’ shell shape regions as the reference, these extra regions (including split regions) can be found and require further analysis. Since snow/ice is more likely to accumulate on the top and/or side part of insulator shells, only extra regions related to these locations are considered and analyzed.

(c) Tighten the width of ROI: To further limit the areas, a ROI is narrowed down by tightening the width determined by two parallel lines touching the outer sides of shells (using extremal left/right points of shells). These extremal points are detected either from the outer boundaries or from the silhouette of insulator shells (see Section 6). To make the boundary or silhouette estimate more robust, cross-correlations with a pre-stored template (containing broadened outer boundaries or silhouette) from the ideal insulator can be applied.

(d) Compare the intensities: Region analysis is then performed by comparing the range of intensity values in each extra region with those of the shell and of the background. Decision on snow area is then made by combining the comparison results and the prior knowledge of snow intensity.

5.2. Compute the snow coverage

Once snow regions are determined, a narrow-width vertical bar (see red bar in Fig.5) parallel to the vertical center axis of insulator, is then placed and swept from the left to the right side of the insulator. For each area under the sweeping bar, the heights of detected snow regions are accumulated, and then compared with the total length of insulator shells under analysis, resulting in the percentage of snow coverage. Further, the maximum snow coverage between any two neighboring shells is computed.

6. ESTIMATE SWING ANGLES

Due to the camera view angle, the angle of insulator in an image does not have to be $0^\circ$ with respect to the vertical image axis (see example scenarios in Fig.4(f)). The swing angle is hence defined as the relative angle, computed from the difference between the absolute insulator angle in the given image and the reference insulator angle in an image captured when no wind is present. Since computing a relative angle is straightforward, only the method for estimating the absolute angle is described. The proposed method is based on using the estimated outer boundaries or estimated silhouette of insulator shells. The basic idea is very similar to the cross-correlation used in Section 4, where the edges from the ROI is correlated with a template containing the broadened outer boundaries (or silhouette) of insulator. However, instead of translating the template, the template is now rotated in order to find the maximum correlation with the insulator in the ROI, using orientation-based cross-correlations

$$
\rho(0, 0, \theta_k) = \frac{\sum_{i,j} E(i,j) E_T(i,j; \theta_k)}{\sqrt{(\sum_{i,j} E^2(i,j)) \sum_{i,j} E_T^2(i,j; \theta_k)}}
$$

where $\theta_k = k\Delta\theta_k$ is the rotation angle of the template ($\Delta\theta_k = 0.25^\circ$, $\theta_k \in [0^\circ, 1.5^\circ]$ used...
in our tests), and $\theta_k \in [0, \theta_1]$. The best angle is found from $\theta^* = \arg \max_{\theta_k} \rho(0, 0, \theta_k)$. The original thin outer boundaries (or boundaries of silhouette) from the template at matched positions are then assigned as the outer boundaries for the given ROI image.

Once shell outer boundaries are found, two parallel vertical lines are determined by shifting lines to touching the outer most (extremal) points on shell boundaries or silhouette. The central axis is then determined from the middle of these two outer lines. From the central axis, the absolute angle is computed. For dark/night images, the central axis is directly estimated through the vertical accumulations $a_v$ of ROI image.

7. EXPERIMENTAL RESULTS AND EVALUATION

Test Results: The proposed system is implemented in MATLAB then converted to C programs with a graphical user interface (GUI) as shown in Fig.5, and tested using images measured from one winter period.

![Fig. 5. GUI for the insulator surveillance system.](image)

Fig.6 (left) shows 5 examples of several good and not so good results from snow analysis. It is observed that detection results are significantly affected by the variety of background scenarios, also, they are affected by the setting of camera view angle and image resolution for an insulator of concern. For example, the camera setting for the insulator (b) generates better images as compared with those for insulator (c) (not so good view angle) and for insulator (a) (too low resolution).

![Fig. 6. Left part: automatic analysis results, containing 5 results where the detected snow regions are visually enhanced: the first 3 insulators: good results from images with 1 clear and 2 dark background; the next 2 insulators: not so good results where only partial snow areas are detected from images with cloudy and dark background. Right part: Semi-automatic analysis of snow ground truth for shells 2 and 3. From left to right, top to bottom in each column: Selecting a shell (inside green box) from ROI, a selected shell, closed edge curves after modification, resulted ground truth snow region.](image)

Ground Truth: To estimate the ‘ground truth’ of insulator snow regions, a semi-automatic assisted analysis is provided (see 2nd column function bottoms and insulator image in the righthand side of GUI). and in right part of Fig.6). In semi-automatic analysis, each shell is extracted and analyzed separately, allowing e.g. manually select thresholds for histogram, edge closing. This process is repeated for all shells, as shown in Fig.6(right part).

Evaluation: The performance of automatic analysis results are evaluated for insulator type (b) by using the corresponding insulator snow ‘ground truth’ (generated from the above semi-automatic way) as the reference.

Our preliminary evaluation show that: For good quality images, the average detection rate is about 93% with false alarm rate about 9%, (defined by the correctly and falsely detected pixels related to the snow, respectively). However, it is noticed that the average performance is significantly dragged down by poor quality images with low visibility, very weak edges and dark snow. The average detection rate is dropped to 61.03% for bright background images and 74.22% for dark background images. Meanwhile, the average false alarm also increased to 21.5% for bright background, and 18.13% for dark background. The highest snow coverage during that period was 14.73%.

8. CONCLUSION

The proposed insulator video surveillance system for automatically detecting and estimating insulator snow (or, ice) coverage and insulator swing angles, has been tested. Our test results on one year (winter season) measurements showed that the proposed hybrid method is relatively robust for a broad range of complex images, with an average detection rate ranging from 93% to 67.6% and averaging false alarms from 9% to 18.1% depending on image quality. Such results, though far from ideal, are encouraging since this implies a new approach entirely based on image analysis, can be a rather promising choice for insulator snow surveillance. Further improvement shall be made by exploiting temporal information in videos and by improving the settings of image capture system. The system has also increased the interest for a long term research, as our test results have demonstrated that automatically monitoring ice and snow phenomena, previously considered as not feasible, is now possible.

9. REFERENCES

[1] WAP project website: http://wap.stri.se