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Review on Machine Vision based Insulator Inspection Systems for Power Distribution System

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Abstract

In the present world, there is a great necessity to have reliable and quality power distribution, and so there is great scope for research on automation of distribution system. The main objective of this paper is to analyze and comprehend different machine learning and image processing based algorithms to find a practical solution for automated inspection of overhead power line insulators. This method is a relatively new approach for. This paper also highlights the constraints and limitations that are present in the various existing methodologies to achieve the objective. Traditionally the workers who inspect these lines check them in close proximity by going for foot-patrolling and pole-climbing. With an incredible expansion of power distribution network even to remote areas, previously mentioned methods do not seem to be viable. The development of an efficient method of condition monitoring by using image processing followed by machine learning techniques is found to be a suitable method and thus emerging as a feasible option for real-time implementation. The few techniques like artificial neural networks (ANN), Hidden Markov Model (HMM), k-means clustering, Wavelet transform features, S-transform features, and support vector machines (SVM) applied in the domain of condition monitoring of the insulators were presented.

Keywords: Condition monitoring, Defect detection, Image processing, Machine Learning, Classification

1. Introduction

Throughout worldwide, electric power utilities are adopting the computer aided monitoring, management, and control of electric power distribution system [1] more and more, to provide better services to the consumers of electricity. The idea of distribution automation began in the 1970s and the motivation to improve operating performance of distribution systems was derived from the usage of computer and communications technology. Increasing complexity levels in the existing technologies for monitoring, control, communication technologies dictated the improvement in automation of distribution system and the performance and cost of the equipment are also affected. To ensure uninterrupted reliable operation of power distribution system, the performance of insulators under different environmental conditions must be reliable and satisfactory. So, the supplier has to take all the necessary steps to inspect his installations and ensure that their performance complies with the regulations. The other reasons to perform regular inspections [2] of power lines are i. Detection of line defects early reduces power cuts and paves the way for good customer care and advantage over other competitors; ii. Having a photographic record allows the repair teams to know exactly about the repair and maintenance to be done which reduces operational costs; iii. Public are protected by detecting the missing or broken safety features on poles. If a device is found to be the cause of the fault, repair or replacement of the same could be made or recommended for any other required maintenance [3] actions.

If the distribution equipment starts weakening, it can be anticipated that an unpredictable fault is developing in the system may be several days or several months. So, in order to have a reliable power distribution system, it is crucial to monitor distribution, classify and identify the various types of failures before the actual breakdown or breakout of the equipment occurs. The on-line processing to monitor the health of equipment is generally called as condition monitoring [4] (CM). The overhead lines have many items such as insulators, conductors, and fittings, which can be continuously monitored online [5-11]. So, there should be a constant monitoring of the system to trace its progression from healthy to sick status. A mention about health index [12] based on monitoring data is presented by T. Hjartarson, et al. So, the development of transducer technologies, computer technologies and signal processing techniques along with artificial–intelligence (AI) techniques has made it possible to implement CM more effectively on electrical equipment as presented by Y. Han and Y. H. Song [13]. This review aims at comparing and contrasting the reported research that was done based on Image Processing along with Machine Learning Techniques in computing some meaningful information obtained from condition monitoring.

2. Complexities of Automation of Insulator Monitoring

Accurate and reliable techniques to locate or detection of failures, identification, and evaluation of severity, have

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become crucial to in dealing with the maintenance work [4] in the scheduled time and realistic cost. On-site Manual detection is costly, time-consuming, and is an impractical task in case of monitoring the long lines spread over a large distance and difficult terrains. Video surveillance system based on image processing can do that type of monitoring very easily. Use of helicopters has been proposed for video surveillance in the UK to inspect the distribution system. Jones and Earp [15] gave a detailed discussion on the motivation to go for video inspection techniques and the problems that may arise. And there is a mention of wide application of aerial inspection [16] for condition monitoring of overhead lines.

Automatic video surveillance of power lines using a helicopter is not as straightforward and the problems are: i) Pattern recognition applied to target locations[17], ii) Stabilization of the camera in compensation of the helicopter's 6 degree-of-freedom (DOF) movement [18-19], iii) Acquire and maintain the target in the camera's field of view (FOV), iv) Camera's residual sightline motion resulting in image degradation [20], and v) Data analysis system. The inspection process becomes automatic by the use of video surveillance techniques and the depth and coverage improve because it provides a permanent record of the images [14]. But, the inspection of insulators in real-time faces a number of challenges: Image blurring, camera sight control, fast-changing background, and gradual intrusion of tree limbs into the overhead power lines [9]. As an improvement, video surveillance with fixed cameras applied to pedestrian detection [21] seems to be a promising solution for video surveillance of power distribution system [22] insulators. With the fast changing scenario in the availability of cheaper digital cameras with good performance, the mounting of video cameras became cheap. But the manpower becomes very expensive to personally observe and interpret the results. So it was proposed to operate cameras at regular intervals of time to get images of power distribution lines along with insulators, sent for analysis to the control room by the use of remote terminal unit (RTU)s and this method assures promising results.

3. Prior Literature Review

Over the years, there are a number of review papers on condition monitoring of distribution power line inspection [23-27]. In the last few decades, there has been a lot of research conducted in the field of automatic power line inspection. A review paper by Lili Ma, Yang Quan Chen addressed exclusively the inspection with aerial vehicles [25]. A survey paper has been published about the overhead power line inspection which includes automated helicopter-assisted inspection based on inspection with flying and climbing robots [27].

A presentation on a feasibility study about the characterization of emerging insulator failure to predict a fault in the distribution is given by Dabo Zhang et al [2]. A brief outline of overhead line deterioration, available inspection methods, and information about a project being undertaken by the Power and Energy Systems Research Group at the University of Bath who monitored overhead lines on-line is given by R.K. Aggarwal et al. The development of a new two-course sequence to reflect the radical changes that occur or expected to happen in future was recommended by the author in [23]. An automatic video surveillance system using a manned helicopter was proposed to be a promising alternative for traditional inspection methods of power lines in [25] and remotely operated unmanned flying robot was anticipated as the future of overhead power line inspection. B.Avidar [26] gives a brief explanation of the inspection methods in works and focuses on the electronic approach. The concept of an airborne, completely stand and electronic method is also discussed. The most prominent achievements about inspection of power distribution line by mobile robots are presented in [27]. The insufficiency of traditional ways of insulator detection has headed towards a lot of research on automatic on-line detection method. Among the various methods of detection surveyed in [28], the electric field distribution method detects the internal insulation defects live line. An excellent theoretical background to image processing is covered by Gonzalez and Woods [29] and classification based on neural network is given Haykins [30].

Availability of the published literature on automated monitoring of insulators' condition mainly consists of research work done at several academic and research institutions. Academic institutes have published a number of research works. There are some papers published in reported research work mainly focuses on the classification of defects of insulators of power distribution, implemented using various kinds of approaches. However, the authors could not find any review paper on the research work done in the field of condition monitoring and classification of insulators of a distribution system using image processing combined with artificial machine learning techniques. Therefore, this attempt is being done to consolidate the published literature from academia and research institutes on the topic of automatic inspection of the condition of insulators. It then throws a light on various detection and analysis techniques presently being used. The aim of this paper is to compare and contrast the analyses aimed to detect and classify the defected or cracked insulators and thus contribute to the design and deployment of an on-line condition monitoring through the use of machine vision techniques [4].

4. Categories of Insulators and Defects

The insulators used in a transmission line are the devices which are used to contain, support or separate the electrical conductors. They are used for high voltage power distribution networks. The transmission insulators are available in various types and shapes, which include individual or strings of disks, long rods or line posts. There are mainly three types of insulators used for the purpose of the overhead insulator. They are i) Pin Insulator ii) Suspension Insulator and iii) Strain Insulator. There are two more types of electrical insulators which are available mainly for low voltage application and are called Stay Insulator and Shackle Insulator. The insulators are made of glass, polymers, and porcelain. Each model is made up with different tensile strengths, densities and different levels of performance in typical working conditions. Ceramic insulators are generally used in power transmission and distribution lines for a long time. In the recent times, polymeric insulators have become widely useful due to their superior insulation performance, in terms of contamination endurance compared with conventional ceramic insulators[1].

Inspection of defects needs to be done for a wide variety of items. Generally, they depend on i) Size of the item and ii) Level of details required [18]. The types of items to be inspected are: 1) Large scale: sagging spans, broken or slack stay wires, leaning poles, and tree encroachment; 2) Medium scale: equipment fixed on poles, air break switches, high and low voltage fuse units anti-climbing guards, and safety notices; 3) Small scale: chipped or broken insulators, corroded joints on conductors causing discoloration, and traces of arcing on switches or fuse gear [25]. The symptoms related to each problem on overhead lines were identified and quantified in the report of EPRI [24]. Since the 1970s, the focus on cracking of insulators has been observed increasingly, because safety issues related to mechanical factors have declined. Looms has briefed [31] that the damage of pin and cap disc porcelain insulators is mainly due to cement growth, cycling, and corrosion. As per Cherney [32], porcelain suspension insulator failures are due to a volume expansion of the hardened Portland cement grout in the pin hole of the insulator which in turn causes radial cracks in the porcelain suspension insulators shells. When there is sufficiently low surface resistance, there will be an elongation of partial discharges along the insulator profile which eventually results in flashover of insulator [33]. The emerging defects formed in the beginning stages of manufacturing process also are the causes of failure of the insulator.

When image processing techniques are considered for automatic condition monitoring, there is an important problem of the presence of background elements on the images. Usually, for the images taken from the ground, the background is quite easy to remove sky with clouds, because of the high contrast. Still, there may be a situation for aerial images and those taken from the ground, where the background is much more complex like the presence of trees, buildings or roads. Both cases are tackled by some authors [1].

5. Methods of Defect Detection and Classification

As the demand for reliable energy supply is increasing, electric utilities are striving seriously in dropping maintenance costs by adopting proper inspection programs to pinpoint, follow-up and to repair any significant failures at the initial possible stage [26]. The segmentation has been very successful by the use of various types of techniques. The research efforts focus on the automation of power line inspection by considering the approaches that fulfill the various inspection requirements [38]. The wellbeing analysis provides a means to perceive the probability whether the system is becoming a risky state and so indicates the condition of the insulator whether it is good or close to a risky state [9]. There are several techniques used to monitor the condition and classify the insulators and the details as per the literature are listed in Table 1.

Table 1. List of defect detection methods

Defect Detection Method	Analysis done
Aerial inspection using manned helicopter[15]	Produced a basis to theoretically and experimentally specify pointing accuracy of the camera
Modified Hough transform, SVM model[36]	Modified Hough transform and color features are extracted and SVM is used for classification
Combined Hough transform, SVM model[37]	Wavelet transform is used for feature extraction and SVM is used for classification
DOST-ANFIS Combined approach[1]	Discrete orthogonal S-transform is used for detection and ANFIS is used for classification
Combined Wavelet, HMM[34]	Template design, feature extraction using wavelet transform and HMM for well-being analysis of insulators
Wavelet-SVM Combined approach[9]	Wavelet features are extracted and SVM is used for classification
DOST-SVM Combined approach[35]	Discrete orthogonal S-transform is used for detection and SVM is used for classification
Wiener filtering, FCM, Connected component labeling[39]	Insulator image is segmented based on the improved FCM algorithm and contour of insulator is labeled by using connected component labeling algorithm
LBP-HF, SVM Combined approach[50]	Rotation invariant LBP-HF features are used for detection and SVM is used for classification

The ultimate objective of the insulator detection system is to categorize defects into good or defective classes. There are a number of features that are to be extracted from interested regions. Ideally, different combinations of these features are required to uniquely match with the features of various types of defective insulators. Several varieties of available machine learning algorithms can be applied for the classification of insulators. Subhadra Mishra et al [40] gave a review of machine learning techniques applied to agriculture field. The various types of classification algorithms and the features extracted are shown in Table 2 below. The matching generally is done using adaptive, supervised or unsupervised learning methods.

Table 2. Defect classification methods

Method of Classification	Features extracted
SVM[36]	RGB color features
SVM[37]	Statistical features
HMM[34]	Statistical features
ANFIS[1]	DOST features
ANFIS & SVM[35]	Mean, Variance
SVM[50]	Statistical features
SVM[50]	Statistical features

6. Automatic Inspection System

Enactment of electricity Act 2003 of India has been pressurizing the power distribution utility to make a nice plan to achieve Distribution Automation without further delay [41]. The Distribution Automation System (DAS) was defined by Institute of Electrical and Electronic Engineers (IEEE) as a system which facilitates an electric utility to coordinate, monitor and operate the distribution components remotely, from remote locations in a real time mode [42]. The DAS involves the collection of data and analyzes the information to make, implement the control decisions and to achieve the desired result [43]. The Distribution Control Centre (DCC) is the location from where control decisions are initiated. In day to day operation and maintenance of power distribution network, Power Distribution Automation is a developing field and is very useful [22]. The automation system can be designed using the available resources like computer systems, control systems, and metering systems. The tools such as computers and Remote Terminal Units (RTUs) are used for automation which uses utilities to control distribution systems and enhance efficiency, reliability, and quality of electric service [44]. The following are the key elements of the automatic inspection system of distribution system insulators.

6.1 Image acquisition and processing

Traditionally the crews are sent out by the utilities either on foot or in vehicles to drive the lines, with frequent stops to send the linemen to climb the towers for closer inspection. An alternative approach is to train inspectors who fly aboard the helicopters in inspecting the lines with binoculars and cameras, record the data in a log book as the helicopter hovers over and around power lines [19]. As a promising alternative, a helicopter with automatic video surveillance system was suggested [25] but the difficulty comes because of rotation of the camera in its gimbals and the translational motion of the helicopter [20]. An innovative approach using RTUs as well as surface vehicular patrolling (SVP) was validated by different researchers. With the availability of both high-resolution video cameras and communication networks for mass use, an arrangement of intelligent RTUs fitted with the required equipment can send the images of the insulators to the control room at regular interval for further analysis. Since the overhead distribution networks in India mostly run parallel to the roads, SVP approach seems to be a viable alternative to the aerial inspection method using helicopters, which is not only costly and also there is the possibility of danger.

6.2 Extraction of images pertaining to insulators

Traditional approaches to automatic power line inspection [45] are based on human observation and can be performed simply from the ground, with climbing, using bucket truck methods or an airborne platform [46]. To reduce the inspection and maintenance costs, new approaches based on machine vision techniques with analysis of video sequences recorded during the patrol have been introduced. This resulted in the increased robustness of the power system and also is helpful in the automated documentation. Usage of machine learning techniques is adaptable to the DSA and thus emerges as a viable option for real-time implementation. The insulator monitoring system described is depicted in the block diagram shown in Fig 1. The salient features are: (i) image acquisition containing poles as well as insulators, (ii) extraction of image pertaining to insulators and (iii) condition monitoring of insulators using different machine learning techniques.

The power distribution system crosses mountains and forests. Therefore, keeping in view all possible situations, plain background and complex background images have been considered as test cases to extract insulator images using color features and wavelet features by some authors. To simplify the task of acquiring the images containing only insulators, image segmentation has been successfully done using proven techniques such as Canny edge detection, Hough transform in conjunction with SVM [37]. In each bounding box, the insulator's presence was detected by extracting some features like color features [33] and extracted features from the bounding boxes were supplied to an SVM classifier and presence of insulator was detected.

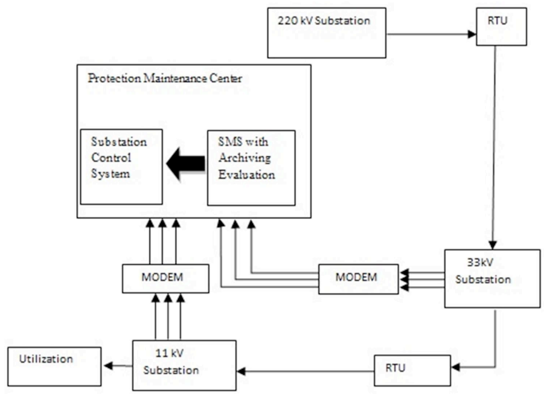

Fig. 1. Insulator monitoring system

7. Discussion on defect detection methods

The insulators of a power distribution system are monitored using a defect detection and classification in three steps procedure: Segmentation localizes candidate defects or regions of Interest (RoI), feature extraction from ROIs and lastly, good or defective classification. In the case of minor cracks on the insulators, the detection alone is a very useful tool to identify the defect and perfect level of classification is achieved with ease.

7.1 Spatial domain methods

There is plenty of literature available for automatic detection of electric towers and few references for extraction and classification of insulators. Dutta et al [47] have taken aerial imagery using Unmanned Aerial Vehicle (UAV) with varying natural and complex surroundings to detect line faults using a novel morphological operator, and a robust image space heuristics to locate and extract power lines completely. Martinez et al [48] presents an approach focusing on autonomous detection in real-time, electric towers localization and tracking using a strategy to train a two-class multilayer perceptron (MLP) neural network and applied over sliding windows for each camera frame until a tower is detected. Electric towers, as well as the insulators, are extracted by V.S.Murthy et al [36] by converting the color images first into gray scaled images and then Canny edge detection which is followed by the modified Hough transform. It was used to isolate features of a particular shape within an image and segmentation is realized by applying edge detection and thresholding methods. It is also used as a tool for edge linking too. In another technique, K-means clustering has been used to locate the proper bounding boxes containing the insulators. From the bounding boxes, features like mean, standard deviation were extracted and successfully tested for automatic insulator extraction from the plain background and complex background [1] as well. Fuzzy C-Means algorithm (FCM) as proposed by Bo Wen Wang, Quan Gu [39] is used to recognize transmission line insulators. To filtrate and recover image in pre-processing, the improved Wiener filter algorithm was used and then, improved FCM was used to segment the insulator. Finally, the contour of the insulator is labeled by using connected component labeling algorithm. Some efficient algorithms such as template design and mean shift tracking have successfully tracked the poles in the streaming video for the subsequent process of identifying insulators [34]. Among the clustering methods used to segment the object of interest, the K-Means algorithm involves more error cluster pixels, whereas FCM algorithm involves less. The algorithm using FCM [39] have a good segmentation effect, effectively reducing the number of error cluster pixels. Local binary pattern (LBP) is a type of spatial domain based feature used widely for classification in the field of computer vision. Trinh Thi Phan et al [49] used the features extracted from Local Binary Pattern (LBP) for mobile product image searching. And its extended version, Local binary pattern Histogram Fourier (LBP-HF) is a rotation invariant feature and is used by P.S.Prasad et al [50] for distinguishing between healthy and risky insulators.

7.2 Frequency domain methods

In the reported research on condition monitoring of the insulators, the degree of damage of an insulator affects the distribution system in different ways and so the defect of insulators have been categorized into either three states namely good, marginal and risk states or two states, good and risky. To understand the condition of insulators from the acquired images, the adopted features extracted by authors used families of wavelet transform [37] as well as discrete orthogonal S-transform (DOST). The wavelet transform has been in wide use in damage detection of the beam as described by Naresh Jalswal et al [51]. If the object's size is small or there is low contrast, generally they are to be examined at high resolutions. If their size is large or contrast is high, a coarse view is needed. If both small and large objects, as well as low and high contrast objects, are simultaneously present, it is beneficial to study them at several resolutions. This concept is the fundamental motivation for multi-resolution analysis [30] (MRA) . The wavelet transform [52] has the natural ability in capturing even small cracks on the insulator using MRA along with a classifying technique like SVM to discern the health of the insulator. The DOST is used in finding the condition [53] of the insulator from the extracted images [54]. It gives a spatial frequency representation like DWT. It also has an additional benefit that phase properties of the ST and FT are maintained and retains the ability to collapse exactly back to the Fourier domain [55].

8. Defect Classification Systems

Once the detection of the insulator is done, classification of defects has to be performed to identify and subsequently replace the faulty insulators hence preventing heavy damages. The intelligent techniques such as SVM, HMM (Hidden Markov Model) and ANFIS (Adaptive Neuro-Fuzzy Inference System) needs such features to perform the task of automated condition monitoring of the insulator efficiently. SVM operates on structural risk minimization principle in minimizing an upper bound based on the generalization error, and deals with only two parameters, for classification, and it has been chosen for effective, faster insulator condition monitoring for automation purposes by various researchers [1]. ANFIS is an adaptive network which is similar to adaptive network simulator of fuzzy controllers and it is equivalent to an FIS. Back propagation gradient descent and least square method for non-linear and linear parameters are used to adjust the parameters for a given input or output data set [8]. A comprehensive review of common machine learning techniques like ANN, SVM, and GMM along with HMM that are used in automatic speech recognition is given in [56] .

8.1 Support vector machine (SVM)

SVM is a set of supervised learning algorithm which can be used for classification and regression [57]. It is found as a very effective technique for general purpose supervised pattern recognition as proposed by Vapnik et al [58]. It is a binary non-linear classifier employed to predict whether an input value belongs a class 1 or a class 2 and is generally used to classify an object into a defective or good one. To classify the insulators, SVMs can be used to separate the given set of labeled data with a hyperplane with the maximum margin. As most of the practical classification problems are non-linear, the SVMs use kernel functions that automatically realize a non-linear mapping to a feature space. Shape recognition of tire marking points [59] is a recent application for SVM. It is also used widely in the medical field as Kiranmayee et al [60] used for MRI brain image classification.

SVM is also extended to solve multiclass separation problem which uses one-versus-all and one-versus-one techniques. Multiclass problem solution using SVM has been reported in [36]. A few binary classifiers have to be trained for a multiclass classification problem. The performance of SVM classification is strongly related to the choice of the kernel function. There are a number of kernel functions available: linear kernel function, radial basis function, polynomial kernel function et al. Among them, Radial Basis Function (RBF) is the most popular one. The linear kernel is a special case of RBF [61]. The features extracted from DOST, along with SVM and ANFIS [1] were used to estimate the condition of the insulator.

8.2 Hidden Markov Model (HMM)

HMMs were used for face detection and recognition and they were motivated because they are partially invariant to variations in scaling and also the structure of images [62-64]. HMM is a statistical Markov model consisting of a Markov chain with a finite number of states, a state transition probability matrix, and an initial state probability distribution. Although the states are unobservable but the output, which is dependent on the state is visible and drawn as per a probability distribution [65]. Application of HMMs is done in many fields where the goal is to recover a data sequence that is not observable immediately whereas some other data are available that depend on the sequence. It is being used in several fields including facial expression recognition [66] (FER) with improved accuracy than existing methods. An algorithm given in [34] utilizes hidden Markov models to determine the health condition of insulators. Since insulators on poles possess a lot of variations in terms of features, and also requires scaling, HMM has been employed by the authors. HMM has been used for well-being analysis to segregate a good insulator from a bad one using Baum-Welch algorithm.

8.3 Adaptive neuro-fuzzy inference system (ANFIS)

For a given input or output data set, the ANFIS adjusts all the required parameters. It uses a method of back propagation gradient descent for non-linear parameters and least square type of method for linear parameters [67]. The neuro-adaptive learning techniques provide a methodology for the fuzzy modeling procedure to extract information about a data set. This, in turn, is used to compute the parameters required for membership functions that needed for the FIS to rightly correlate input or output data in the fuzzy domain.

8.4 Comparative analysis

The comparative study done by Murthy et al [34] establishes that HMM approach performs more efficiently in comparison to SVM due to its accuracy of insulator damages, which leads to quicker maintenance and restoration of power supply compared to the use of SVM. It is also shown that FIS, with its inherent ability, computes the health of insulators in terms of the degree to which the insulators are in good, marginal or risky states. A comparison between the methods, DOST-ANFIS and DOST-SVM was done by Reddy et al [1] incorporating the complex background images and results prove the effectiveness of the proposed techniques in dealing with different possibilities of complex backgrounds. They would otherwise lead to wrong conclusions about the condition of insulators.

9. Scope for future work

There are several tools both in the spatial and frequency domains like several extensions local binary pattern (LBP), curvelet transform, contourlet transform etc., which can be used for feature extraction. Deep belief networks (DBNs) which is a representative method of deep learning [68] and Extreme Learning Machine (ELM) can also be used for classification. The newly emerged machine learning theory, deep learning may be applied for better classification which outperformed the other state-of-the-art classification methods. The various techniques proposed by the different authors did not consider any of the non-visual defects such as internal cracks, high partial discharge activities, and high leakage current. Thermal cameras would be a viable option to take these aspects into consideration. The geographical inference system (GIS) may be used to obtain spatial coordinates for distribution system planning and automation. Once the images sent by the RTUs are obtained, the GIS-aided insulator monitoring would reduce the existing problems by assigning unique identification numbers to RTUs for subsequent image processing and proper monitoring of the insulators.

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