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# Novel capacitive proximity sensors for assessing the aging of composite insulators

Jingpin Jiao*, Liang Li, Bin Wu, Cunfu He

*College of Mechanical Engineering and Applied Electronics Technology, Beijing University of Technology, Beijing 100124, China*

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ABSTRACT

A novel electrode structure consisting of a variable spacing interdigital electrode (VS-IDE) was proposed for assessing of the aging of silicone rubber sheds with variable thickness. A series of numerical simulations and experiments have been carried out to investigate the influences of finger number, unit width, and metallization ratio on the signal strength and penetration depth of sensors with a traditional interdigital electrode structure. According to the relationship between the penetration depth and the unit width, the width of each finger that composed the VS-IDE structure sensor was optimized individually to confine the electric field line within the sheds under test. Experimental results showed that compared to the other sensors, the optimal sensor exhibited high amplitude, high sensitivity, and excellent stability against the effects of environmental humidity. The developed capacitive proximity sensors have been used for assessing of the aging of silicone rubber sheds in composite insulators, and the feasibility of assessing insulation degradation by quantitative capacitive techniques is demonstrated.



## 1. Introduction

In recent years, composite insulators (silicone rubber insulators) have been widely used in power transmission systems because of their excellent attributes, such as being lightweight and high in mechanical strength, and offering excellent resistance to pollution and vandalism. However, the superior performance of composite insulators degrades over time because of high-voltage surge and unfavorable environmental factors, such as high temperatures, pollution, humidity, ultraviolet (UV) radiation, and oxidation. Aging of the composite insulators will lead to electrical property degradation or deterioration of the external insulation, threatening the safety and reliability of the power supply.

A composite insulator consists of a glass fiber-reinforced polymer rod attached with metal end fittings and silicone rubber sheds which cover the rod (as shown in Fig. 1). The silicone rubber sheds are molded into a series of concentric disks to protect the rod from the environment and provide a sufficiently long leakage current path. Because of lengthy direct exposure to a harsh environment, aging is more likely to occur in silicone rubber sheds. It has been reported that the failures due to the aging of silicone rubber sheds in composite insulators have always been a challenge in engineering practice [1,2]. Therefore, it is critically important to detect the deterioration of silicone rubber sheds.

Several methods have been proposed to estimate the aging of silicone rubber insulators [2,3]. These methods include visual inspection [4], UV imaging method [5,6], infrared ray imaging [7], ultrasonic non-destructive testing [8,9], hydrophobicity classification [10], nuclear magnetic resonance (NMR) [11], electric field measurement method [12], and leakage current measurement [13]. Extensive research has been conducted on assessment of aging of insulators using above methods; however, it has been found that these methods have limitations in measurement precision, reliability, and engineering practicality [14,15].

For capacitive sensing techniques the most common electrode structures are the planar parallel plate electrodes and the co-planar electrodes (called capacitive proximity sensors). The working principle of capacitive proximity sensors are based on the fringing effect of the electric field. Compared to the traditional parallel-plate capacitor, capacitive proximity sensors have unique features, such as one-side access (the other side can be open to the ambient), easy control of signal strength by changing its dimensions, multiple physical effects in the same structure (electric, magnetic, acoustic), and a wide frequency spectrum of use. Therefore, they have been widely used in many fields, such as material property monitoring, humidity sensing, electrical insulation properties sensing, chemical sensing, and bio-sensing.

* Corresponding author.
*E-mail address:* jiaojp@bjut.edu.cn (J. Jiao).

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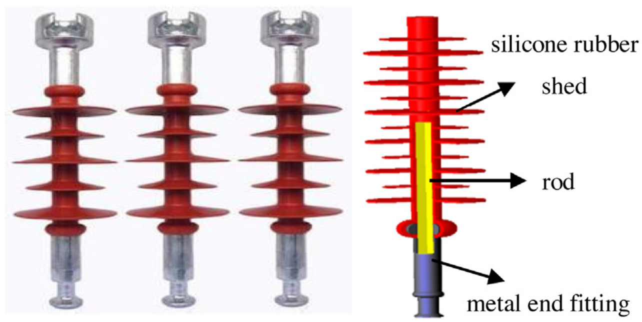


**Fig. 1.** Structure of composite insulator.

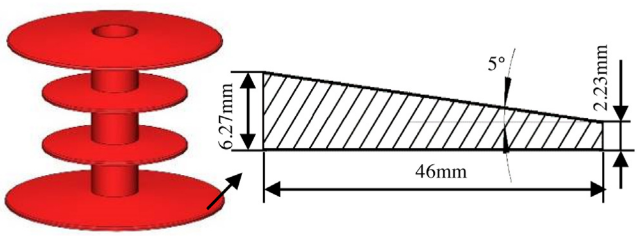


**Fig. 2.** 3D model of the composite insulator and the cross-sectional drawing of silicone rubber shed.

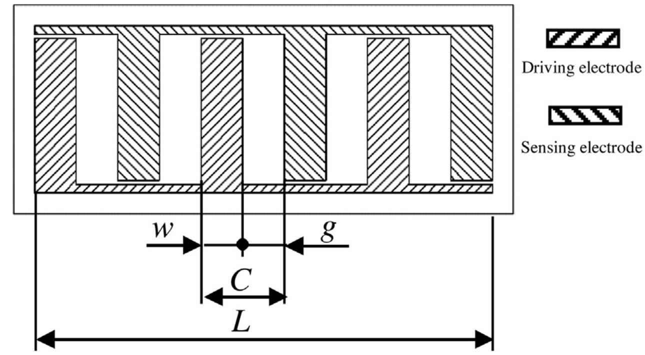


**Fig. 3.** Fundamental parameters of interdigitated electrode structure.

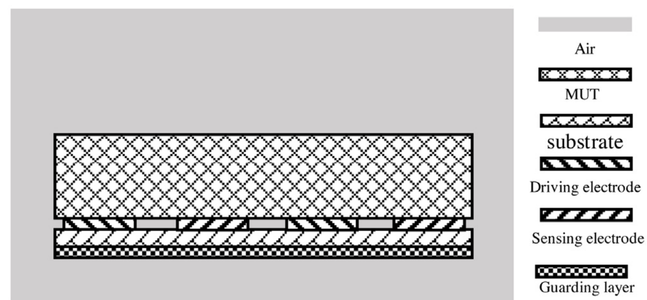


**Fig. 4.** 2D finite element model of proximity interdigital sensor.

Capacitive proximity sensing techniques have been widely used for nondestructive evaluation (NDE) of low-conductivity materials [16–21]. Based on detecting the local variation of the dielectric properties of materials under testing, capacitive sensing techniques have been used for structure-healthy monitoring (SHM) of the concrete slab retrofitted with composites [18,19]. EI-Dakhakhn et al. [20] applied the proximity capacitive technique for unfilled cells detection in grouted masonry constructions. A concentric coplanar capacitive sensor was developed for the quantitative characterization of material properties for multi-layered dielectrics [21], and the effectiveness of the proposed method for water intrusion detection in random structures was experimentally validated.

The outside insulation layer of the electric cables is also typically low-conductivity material. Research has applied capacitive sensing techniques to characterize cable insulation properties. Chen and Bowler [22] designed a capacitive probe for evaluation of wiring insulation permittivity, and experiments demonstrated the feasibility of assessing wiring insulation degradation status by quantitative capacitive techniques. Proximity-coupled interdigital sensors are introduced to detect insulation damage in power system cables, and the measurement results confirm that the proximity capacitive technique is sensitive to the presence of holes and water trees in a power line cable [23]. To detect aircraft wire aging damage, Sheldon and Bowler [24] developed an interdigital capacitive sensor and experimentally verified the capacitance variation resulted from aircraft fluid immersion.

Research indicates that the patterns and parameters of electrodes have great influence on capacitive sensor performances, such as signal strength, penetration depth, sensitivity, and noise-to-signal ratio, all of which affect the detecting capability of capacitive proximity sensors. Many efforts have been devoted to improving the performance of capacitive proximity sensors [25–27]. Several sensor patterns including square-shaped, maze, spiral, and comb patterns were investigated, and it was demonstrated that complex sensor patterns can increase the effective electrode area and then improve sensor signal and sensitivity [25]. To improve signal strength and sensitivity, Rivadeneyra et al. [28] designed a serpentine structure which is a combination of meandering and interdigitated electrodes. A capacitive sensor of interdigital electrode structure with increased height was fabricated for humidity measurement [29]. Compared to the traditional interdigital electrode sensor, the proposed sensor showed higher sensitivity owe to the horizontal electric field lines confined in the polyimide sensing layer. Syaifudin et al. [30,31] investigated the influence of electrode configuration on performance of capacitive proximity sensors and found that the optimal number of negative electrodes between two adjacent positive electrodes can improve the sensitivity for chemical detection. For water detection in an automatic windshield system, a few petal-like electrode structures were designed [32].

The silicone rubber sheds are made of high-temperature vulcanization silicone rubber (HTVSR), a typical dielectric material [33]. Aged silicone rubber may lead to fracture of the molecular chains and produce large numbers of free radicals, changing the permittivity (dielectric constant). Capacitive sensing, however, is ideally suited for characterization of dielectric materials due to the closely relationship between the measured capacitance and the relative permittivity (dielectric constant) of the material. To ensure the self-cleaning ability of the composite insulators under contaminated conditions, the umbrella skirt structure is designed to be an inclined plane with a certain angle, whose thickness decreases gradually from near the fiberglass-reinforced resin rod to the edge of the umbrella skirt.

In this paper, the capacitive proximity sensing method is applied to assess the insulation degradation of silicone rubber sheds in a composite insulator. The influence of finger number, unit width, and metallization ratio on the performance of capacitive proximity sensors was investigated by simulation and experiments. Capacitive proximity sensors with variable spacing interdigital electrode (VS-IDE) structure were designed for nondestructive testing of thickness gradient samples. The proposed sensors are experimentally measured and used to assess the aging of silicone rubber sheds in a composite insulator.