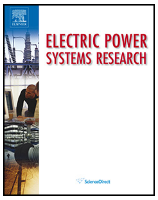
Electric Power Systems Research xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr



# Flashover improvement of polluted high voltage insulators by nonlinear nanofilled hydrophobic coating

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ARTICLE INFO

*Article history:*
Received 15 February 2015
Received in revised form 2 March 2016
Accepted 30 April 2016
Available online xxx

*Keywords:*
Coating
Flashover
High voltage insulators
Nanotechnology

ABSTRACT

In this paper, a model for computing the dry band arcing voltage is proposed and verified by experiments on glass specimens coated with the nanofilled material with different characteristics. Such coating is to increase the dry band arcing voltage which leads to a better flashover performance of high voltage insulators. Then, a simple technique to enhance the flashover performance of high voltage insulators is presented. The proposed technique depends on coating only the insulator metal cap and pin. Studying the effect of RTV silicone rubber for metal cap and pin coating is presented and about 200% (on average) flashover performance improvement is achieved. Enhancing the cap and pin coating with a thin layer of the nonlinear nanofilled material, the flashover performance is improved by about 235% (on average). Finally, a model based on developing Obenaus's model for computing the flashover voltage is proposed. A good agreement between experimental and model results is achieved.

## 1. Introduction

Flashover is an important issue facing the use of glass and porcelain high voltage insulators in polluted areas. The major problem of these insulators is the hydrophilic surface nature which results in forming continuous pollution films over there surfaces in wet conditions [1–6]. Formation of continuous pollution films results in higher leakage currents which lead to formation of dry bands. Partial arcs are developed in these dry regions due to rise in electric field intensity. When the arc propagation criteria [7–11] are valid, the arc propagates and the flashover can occur. To reduce the occurrence of flashover, semiconducting glazed insulators (SGI) are used with porcelain insulators [12–15]. These insulator types allow a leakage current of 0.5–1 mA to flow on SGI surface in order to reduce the dry band arcing activity. In fact, SGI gives a sufficient performance up to certain humidity values. Therefore, hydrphobic coatings are used over insulator surfaces. RTV silicone rubber is one of the most common materials used for this purpose. The application of RTV coating began as a trial during 1970s and was applied widely during 1980s [16]. Now, RTV is used as a coating for pre-coated high voltage insulators. In 1991, the pre-coated insulators were used in Qatar. Usage of 55,000 pre-coated glass insulators were used in 132 kV transmission line of a distance 85 km from Doha to Dukhan [17]. In China, the first time for using RTV pre-coated insulators was done in 1986 as a trial by Tianjin Generating Authority. After success of this trial, the use of RTV pre-coated insulators has found a wide spread in polluted areas [16]. From 2003 to 2011 there were about 25,000 insulators have been used in coastal areas in USA [18]. Also, TERNA, the Italian transmission system operator, applied pre-coated glass insulators for first time to a 380 kV line in 2003 [19]. After this date, TERNA has used pre-coated insulators over a wide range as the number of pre-coated insulators reaches approximately 9500 insulators in 2010 [16]. As shown from the previous statistics, coating of high voltage insulators finds a wide application in the real field. Therefore, this becomes as a motivation for more research in this area.

Recently, application of nanocomposites as coating materials for high voltage insulators has attracted a lot of researchers [20–22]. Zhao et al. [20] developed a super hydrophobic PDMS/nanosilica hybrid coating for improving the ice flashover performance of high voltage insulators. According to this research, a contact angle of 161° was reached with the nanofilled coating material. So that, the ice flashover performance of the nanocomposite coated insulator was improved as compared to RTV silicone rubber coated one. Also, Xu et al. [21] improved the anti-icing performance of RTV silicone rubber coatings on porcelain insulators by adding nanosized carbon black to the RTV silicone rubber coating. According to their research, the high voltage insulator anti-icing performance was improved. Another research by Bai et al. [22] was presented to improve the vacuum flashover performance of a polyamide 1010 insulation by using a semi-conducting $TiO_2$ as a nanofiller with fluorophlogopite as a coating material. According to their research,

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http://dx.doi.org/10.1016/j.epsr.2016.04.025
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Please cite this article in press as: M.E. Ibrahim, et al., Flashover improvement of polluted high voltage insulators by nonlinear nanofilled hydrophobic coating, Electr. Power Syst. Res. (2016), http://dx.doi.org/10.1016/j.epsr.2016.04.025

the flashover voltage was increased by 31% compared to the neat polyamide.

In this paper, dry band arcing and flashover performance of high voltage insulators are improved by developing a nonlinear nanosized carbon black filled hydrophobic coating material. A proposed model for computing the dry band arcing voltage is presented and verified by experiments on glass specimens coated with the nonlinear nanofilled material. Also, a technique for flashover performance improvement is presented. The presented technique is cheap since, the coating is provided only for metal cap and pin. As the cap and pin are vertical elements and the coating is hydrophobic, sufficient dry regions can be formed preventing high leakage currents to pass. Therefore, the flashover performance is expected to be improved. Coating a glass insulator with RTV silicone rubber over the cap and pin is evaluated and about 200% (on average) improvement on the flashover performance is achieved. Evaluation of the nonlinear nanofilled material [23] as a thin layer over RTV coating is performed and about 235% (on average) improvement in the flashover performance is achieved. Finally, development in Obenaus's flashover model to be suitable for coated surfaces is presented. The comparison between experimental and theoretical results gives a sufficient accuracy.

## 2. A proposed model for computing dry band arcing voltage

In this section, a proposed model for computing the sufficient DC applied voltage for dry band arcing initiation is experimentally verified. In the experimental coating, nanosized carbon black (80 nm particle diameter, 850 $m^2$/g BET surface area and 50 Ω cm resistivity) was used as a filler to control the nonlinear characteristics of coating material and to reduce the dry band arcing thereby improving the flashover performance of high voltage insulators. The nonlinear nanofilled hydrophobic coating material consists of silicone rubber, polystyrene and colors [23]. The composition of the base coating material and their percentages from the total weight is 30 wt% silicone rubber, 50 wt% polystyrene and 20 wt% colors. Silicone rubber and polystyrene are dissolved into a carbon tetra chloride solvent $CCl_4$. Nanosized carbon black is added to the solution at different loadings, 1% and 3% are chosen and mixed very well using an ultrasonic homogenizer for 60 min to ensure a good dispersion and to minimize the agglomerations. Finally, the required colors are added to the composite. Silicon rubber is used to give the composite a hydrophobic nature. Also, polystyrene gives a hydrophobic nature and good mechanical properties since it represents a coupling medium. Nanosized carbon black gives the composite good mechanical properties since it acts as coupling bridges between the mixture molecules and controls nonlinear characteristics of the coating material.

Consider a continuous water film in series with a dry band as shown in Fig. 1. Assuming the insulator surface is coated with a nonlinear coating material such as the described before, the voltage equation can be written as [23]:

$$V = k \cdot x \cdot I^{\alpha} + r_p \cdot (L - x) \cdot I \tag{1}$$

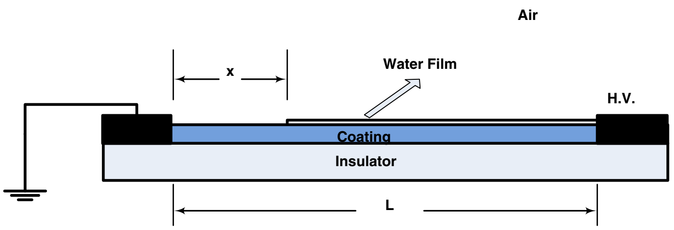

**Fig. 1.** Coated insulator with *x* dry band length and water film of NaCl solution.

where ($k{\cdot}x{\cdot}I^{\alpha}$)is the voltage drop over the dry band region, $k$ (kV/A cm) and $\alpha$ are coating material constants depending on filler loading. The value of $\alpha$ is determined from the experimental results [23] and is found to be 0.057 and independent on filler loading. The values of $k$ are determined experimentally using the experimental results [23] and their values were found to be 10 and 8 at the two different nanosized carbon black loadings 1% and 3%, respectively. $V$ is the applied voltage in kV, $x$ is the dry band length in cm, $I$ is the leakage current in mA, $r_p$ is the water film resistance per unit length in kΩ/cm and $L$ is the length between the two electrodes in cm. Since dry band arcing represents an essential stage before flashover occurrence, the nonlinear characteristics of coating material are used to reduce the electric field intensity over the dry band by allowing the leakage current to pass through the coating material. Electric field intensity over the coating material and hence over the dry band decreases for the lower value of $k$ at the same applied voltage. In other words, for the same value of electric field intensity, a greater applied voltage is required for the lower value of $k$. The important notice here, this occurs only in the nonlinear region.

For occurrence of dry band arcing, the electric field intensity over the dry band should reach a certain value which called the streamer threshold ($E_s$) expressed by [23]:

$$E_s(\mathrm{kV/cm}) = \begin{cases} 8 & \text{for} \quad x \le 2\,\mathrm{cm} \\ -0.43x + 9 & \text{for} \quad 2\,\mathrm{cm} \le 5\,\mathrm{cm} \end{cases} \tag{2}$$

The streamer threshold appears over the dry band region, which has nonlinear characteristics. Therefore, it can be expressed as:

$$E_s = k\,I^{\alpha} \tag{3}$$

Therefore, the current passing at the dry band arcing instant can be calculated by:

$$I = e^{\frac{1}{\alpha}\ln\frac{E_s}{K}} \tag{4}$$

Substituting from Eqs. (3) and (4) into Eq. (1), then the total applied voltage required for dry band arcing occurrence ($V_d$) can be computed from:

$$V_d = E_s X + r_p(L - x)e^{\frac{1}{\alpha}\ln\frac{E_s}{K}} \tag{5}$$

To validate the proposed computation model, an experimental model similar to Fig. 1 was built and the applied voltage was raised slowly until dry band arcing was occurred. This process was repeated five times (a very small deviation was recorded every time) and the average voltage was recorded at six dry band distances. Fig. 2 shows the experimental validation of the proposed

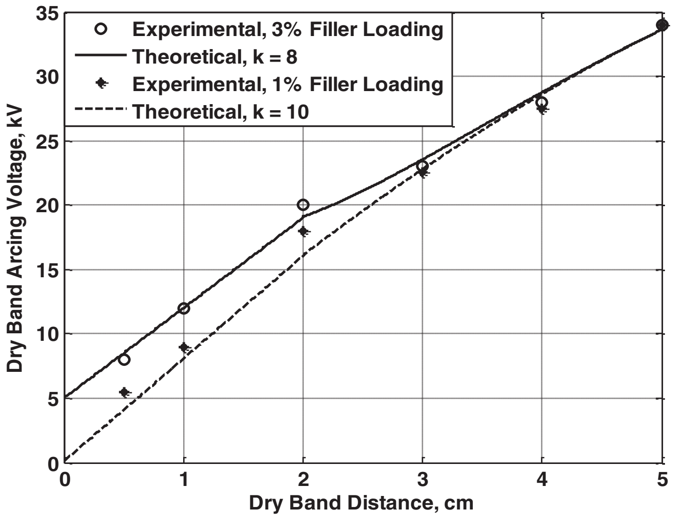

**Fig. 2.** Dry band arcing voltage at different filler loadings (1% and 3%), *L* = 5 cm.

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