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A method to enhance the predictive maintenance of ZnO arresters in energy systems

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ABSTRACT

Leakage current and temperature are common features of zinc oxide (ZnO) arrester degradation in power systems; however, for substation engineers, these key features often bring difficulties in grasping the operating conditions of ZnO arresters because of insufficient maintenance references. Therefore, in this study, the aim is to propose a systematic method to facilitate the realization of predictive maintenance of ZnO arresters in energy systems. The method begins with the feature extraction of ZnO arresters by using on-line resistive current monitoring and infrared radiation (IR) image inspection. A regression model based on the temperature difference, the total leakage current, and the resistive leakage current is then formulated to assist in the insulation diagnosis. This approach is useful to observe the insulation condition, thereby benefiting the predictive maintenance of ZnO arresters. In order to validate the effectiveness of the method, it has been applied to inspect several ZnO arresters installed in a 345 kV substation in Taiwan. Results show that this proposed method performs more effectively than published techniques.

Introduction

Surge arresters are an essential part for the secure operation of power systems. The two primary types of arresters are silicon carbide (SiC) with series gaps and zinc oxide (ZnO) without series gaps. Because ZnO arresters are capable of absorbing high non-linear energy, they are more reliable than SiC arresters and are frequently used in modern power systems [1].

Arresters are usually installed together with power equipment to protect against lightning and switching surges. However, because these arresters contain no gap, they would induce a leakage current that flows through the arrester when a working voltage is applied. The analysis indicated that the leakage currents can be decomposed into a large capacitive current component and a small resistive current one. Normally, the magnitudes of both components are several hundred microamperes and several tens of microamperes [2–4]. Research has shown that the resistive leakage currents often increase in conjunction with insulation degradation. The ZnO material becomes heated when leakage currents increase due to any abnormal condition. Once this generated heat exceeds the dissipation capability of ZnO, a thermal runaway process would immediately take place. This also implies that the leakage current monitoring and thermal inspection serve as effective diagnostic methods for in-service ZnO arresters. Numerous published studies have examined this topic. A wireless passive surface acoustic wave temperature sensor was suggested for measuring the temperature [5]. The resistive current measurement and the influence of harmonics on the measurement were discussed [6,7]. Various diagnostic methods were also mutually compared [8]. The thermal characteristics and thermal stability computation of arresters was used for the protection and maintenance design [9–11]. Some approaches based on the advancement of computational intelligence were also successively developed [12,13]. Previous research revealed that the diagnosis of surge arresters is typically conducted by current measurement or infrared (IR) image inspection, which was considered feasible but lack a concise judging criterion for convenient applications. A further investigation is therefore crucially required.

The study made in this research is aimed to propose a hybrid method combining the leakage current measurement with IR imaging in order to assist the predictive maintenance of ZnO arresters. This approach is proposed based on a regression method that models the relationship between the maximum temperature difference and the resistive leakage current. Through the comprehension of the maximum temperature difference at a specific resistive leakage current, the degradation of the arrester can be early informed once the temperature difference is greater than the predetermined threshold.

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It is note that for a 345 kV system in Taiwan, the arrester is usually formed by a series of three or four sections. Degradation may occur in any section of the arrester, yet the identical leakage currents at each section are incapable of serving as useful discriminator for fault identification. Furthermore, since the maximum surface temperatures seldom differ in a significant manner, which also imply that those existing methods may be ineffective to find the location of abnormal sections. Therefore, the study proposes to utilize the information retrieved from on-line resistive leakage current and IR image inspection, by which the temperature difference, the total leakage current and the resistive leakage current are all collected to analyze, hence enhancing the predictive maintenance capability of arrester. This proposed approach has been effectively applied to real case, by which all abnormal arresters are correctly identified without mismatch. Test results support the feasibility of this method for the application that is investigated.

This paper is organized as follows: Section 'Paradigm and methodology' presents the paradigm and methodology; Section 'Field testing and results' shows the validation of the proposed method; Section 'Discussion' details the findings; and lastly, Section 'Conclusions' offers a conclusion.

Paradigm and methodology

As stated before, the degradation of metal oxide surge arrester in service could occur due to the operating voltage, the impulse currents, and the chemical reactions. The degradation in arrester elements may cause the increment of leakage current, resulting in excessive heat and unexpected aging. The temperature of arrestor column is often a primary basis to justify the operating condition. Yet, because stray capacitances existed in both high and low voltage electrodes which results in an uneven voltage distribution across the arresters, the power loss of arrester elements may not be in proportion to the temperature. Therefore, rather than adopt the maximum temperature, the paper has proposed a temperature difference-based regression analysis for the predictive maintenance of ZnO arresters in this study. Previously, regression analysis is commonly recognized as a useful tool to understand the relations among the variables of concern within the model. This approach allows selected independent variables to be used for forecasting the responses of independent variables. In this equipment maintenance study, a linear regression model developed with Eviews software [14] is employed to determine relationships among maximum temperature difference, total leakage current, and resistive leakage current. The software offers reliable solutions for forecasting applications that have been widely adopted in the field of high-voltage engineering, with satisfactory results [15–18].

Fig. 1 shows the temperature data of a real ZnO arrester that was recorded by the thermal image, where the [1]red line stands for the higher temperature and yellow line the lower temperature measured at different time. This study uses a 69 kV ZnO arrester as a specimen to develop a regression model for the diagnosis of ZnO arresters. The leakage currents and temperatures of ZnO arresters are individually acquired by an online resistive current monitoring system and an IR thermal image [20–22]. Both signals were sampled at one sample per minute over a two-hour period. For the model formulation, the study uses the resistive leakage current and total leakage current as independent variables, whereas the maximum temperature difference is deemed as a dependent variable. A multiple regression model can be therefore expressed as

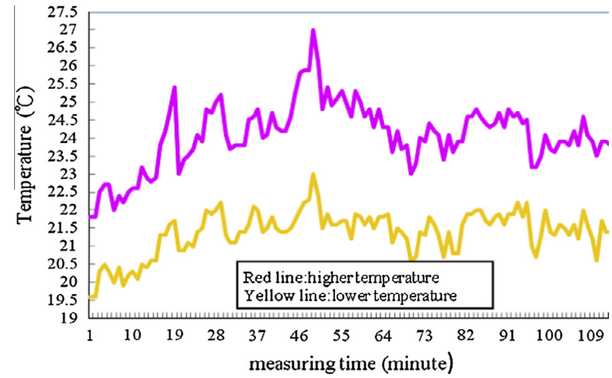

Fig. 1. Temperature inspection of a real ZnO arrester.

$$Y_i = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \varepsilon_i \quad (1)$$

where Y_i is the maximum ZnO temperature difference, X_1 is the resistive leakage current variable, X_2 is the total leakage current variable, $\beta_1$is the coefficient of the resistive leakage current, β_2 is the coefficient of the total leakage current, β_0 is the Y-intercept, and I is the random error. The coefficients in (1) are determined by the least-squares method, whereas the p-value test provides a measure of interdependence among these variables. A smaller p-value represents a greater dependency. Note that the dependent variable is closely related to a specific independent variable when its p-value is less than 0.05, indicating that both variables come with a significant positive correlation. Greater details on statistical theory can be found in [19]. The developed regression model is investigated as follows.

In this model, the dependent variable is maximum temperature difference (Y), and the independent variables are resistive leakage current (X_1) and total leakage current (X_2). Table 1 shows the regression analysis results of these variables. The values of the coefficients $\beta 1$, $\beta 2$, and $\beta 0$ are 0.022669, 0.000540, and −0.388186, respectively. The regression equation can be hence derived as

$$Y = 0.022669X_1 + 0.000540X_2 - 0.388186 \quad (2)$$

The degree of correlation (p = .0008) between Y and X_1 is significantly less than the threshold (p = .05), implying hat Y and X_1 have a significant positive correlation [23–24]. It is worth mentioning here that X_2 is also related to Y because their correlative degree (p = .3742) indicates that X_2 is negligible in this study.

The analysis and discussion shows that the maximum temperature difference (Y) on the IR inspection is significantly relevant to the resistive leakage current (X_1) of the arrester. A statistical model based on this key variable (X_1) is presented to understand its significance. The model is convenient for further applications because it requires only one variable.

Table 2 shows the results of the second regression model. The values of the coefficients $\beta 1$ and $\beta 0$ are 0.024050 and −0.043203, respectively. The regression function equation can be expressed as

$$Y = 0.024050X_1 - 0.043203 \quad (3)$$

Table 1
Result of regression Model I.

	Max. temperature difference (Y)	p-value
Resistive leakage current (X_1)	0.022669 (3.435263)	.0008
Total leakage current (X_2)	0.000540 (0.892118)	.3742
Y-intercept	−0.388186 (−0.346089)	.7299

[1] For interpretation of color in Figs. 1 and 2, the reader is referred to the web version of this article.