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Parameters design optimization of 230 kV corona ring based on electric field analysis and response surface methodology

Hocine Terrab*, Adel Kara

Electrical Engineering Department, Faculty of Technology, Ferhat Abbas University, Setif, Algeria

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ABSTRACT

Ageing of composite insulator in field is mainly affected by the corona discharge activity caused by high electric stress near the end fittings. In order to control the electric field stress on the insulator surface below to the accepted limits, new approach to analyze the corona ring effect on the E-field stress is presented in this paper. The effect of geometrical corona ring parameters on the E-field is studied using the finite element and the design of experiment methods. The analysis of variance is used to evaluate the main and the interaction effects of the studied parameters. The relationship between the E-field and the geometrical parameters (ring projection from end, ring radius and ring tube thickness) is modeled and optimized by the response surface methodology. Results show how much the E-field is influenced by the ring tube thickness. Finally, an attempt based on the obtained model is done to estimate the ring parameters to control the E-field lower to the maximum recommended threshold. The proposed methodology gives an efficient fast working tool to examine a complex geometry of corona rings without extra high computational effort, which reduces the time involved during computational analysis.

1. Introduction

Ceramic insulators have been used for over a hundred years. Although these materials have been proven themselves resistant to environmental ageing, their pollution performance has typically been relatively poor due to their hydrophilic surfaces. During recent decades, composite insulators have been increasingly used in modern transmission systems. This is mainly due to the various advantages offered by polymeric insulators compared to ceramic insulators like light weight, pollution performance and vandalism resistance. However, polymeric insulators suffer from aging especially under high electric stress and harsh environmental conditions. The aging is mainly caused by different factors that influence simultaneously such as acid rain, salty contamination deposit, corona discharges, arcing and UV radiation [1–7].

When the E-field exceeds the ionization threshold of air, Corona occurs and it leads to energy loss, radio interference, for composite insulators, it can degrade the used polymeric materials and continuous discharges can lead to erosion of the material which in-turn can damage the insulating material resulting in failure. Results from both natural and artificial aging tests show a clear trend for reduced hydrophobicity on sheath sections where the E-field exceeds approximately 0.3–0.4 kV/mm (Fig. 1) [8]. Therefore, electric field must always be controlled in the most vulnerable areas of these types of insulators [9].

The E-field repartition on the insulator surface depends mainly on the applied voltage, insulator design, material characteristics, tower design [10,11] for this reason, different measures could be adopted to reduce the E-field stress along the insulators to avoid corona occurrence on the surface, among them the installation of corona rings [12–16].

Nowadays, corona rings are recommended on both ends of insulators string at voltages above 345 kV and only at the HV side in the voltage range between 230 and 345 kV. For voltages below 230 kV, corona rings are seldom used depending on some installation requirements [17]. However, recent investigation has found that these failures could often be attributed to high E-field occurring near or on the high-voltage end fittings. Such findings suggest that, contrary to common practice, it might be necessary to consider application of corona rings on polymeric line insulators even at system voltage below 161 kV [18,19].

The major problem is the fact that no specific standards for the corona design is available, each manufacturer makes their own recommendations for the use of corona rings; therefore, several techniques have been adopted to optimize the corona ring parameters [20–22].

* Corresponding author.
E-mail address: terrab.hocine@yahoo.fr (H. Terrab).

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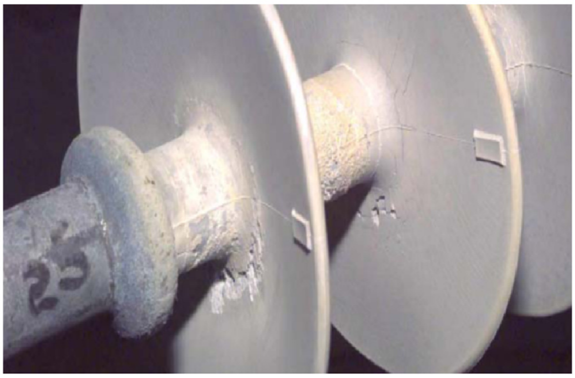

Fig. 1. Observed deterioration close to the high voltage flange after five years of accelerated aging [8].

Numerical methods are adopted for power system analysis such it is economical and efficient way to evaluate the complex phenomena. Recently, finite element method (FEM) has been widely employed in high voltage engineering and numerous models have been developed for outdoor insulators [10,14,15,21,22]. However, FEM analysis for a complex 3-dimensional problem are very time consuming, which results in a very long run-time in case of iterative optimization. Therefore, using the design of experiments methodology (DOE) is the better way to obtain the maximum of information with minimum of experiments to be carried out without influencing the quality of the results [23–26]. Using mathematical processing of design of experiment data enables a rather accurate evaluation of multi-factor effects and interactions.

In this paper, the E-field on the surface of 230 kV composite insulator with and without corona rings is studied by FEM. The effect of corona ring parameters namely ring projection from end, ring tube thickness and ring radius are analyzed using the DOE methodology and the analysis of variance (ANOVA). Then, optimization attempt based on response surface methodology (RSM) is performed to reduce E-field below the critical value of corona discharge initiation; the optimized parameters are then verified by FEM. This study presents a lot of advantages because it reduces the gain of time and labor involved during composite insulator design optimization.

2. Material and methods

2.1. Design of experiment methodology

In the modeling of complex nonlinear phenomena in high voltage engineering such as breakdown and flashover phenomena, there is no general method to reach optimal design or for conducting experiment given specific requirements, except varying the parameters step by step. This strategy, called one factor at a time (OFAT) method consists of choosing a beginning point for each factor, and then successively varying each factor over its range with the other factors held constant at the baseline level. The major disadvantage of the OFAT strategy is that can be time-consuming if a big number of runs is needed. Moreover, it fails to consider any possible interaction between the factors. An interaction is the failure of one factor to produce the same effect on the response at different levels of another factor. The experimental design methodology is a systematic and efficient method that can resolve this inconvenient by making possible to determine the number of experiments to be achieved according to a well defined objective by studying several factors simultaneously. The main advantages of DOE are:

- The reduction of experiments number to obtain the optimal solution by studying several factors simultaneously.
- Increasing the accuracy of the obtained results.
- Taking into account interactions effect between factors.
- A statistical analysis can be carried out at the end of the method in order to check if the factor effects or the model coefficients are statistically significant or not. A statistical hypothesis test is used to make decisions.

The development of an accurate mathematical model with good quality with minimum efforts depends on the way in which intervals of input factors are selected. This method can be used as follows [25,26]:

- Recognition of and statement of the problem.
- Selection of the response variable.
- Choice of factors, levels, and ranges.
- Choice of experimental design.
- Performing the experiment.
- Statistical analysis of the data.
- Conclusions and recommendations.

In this paper, we opted for the Taguichi design, which allows using Response Surfaces Modeling, which is usually considered in the context of experimental design as a statistical method for modeling and optimizing of problems in which different variables affect a response of interest. The first step in RSM is to determine a suitable approximation for the actual functional relationship between the response variable y and a set of independent variables. Consequently, the mathematical model relating response Y to the different factors is as follows:

$$Y = a_0 + \sum_{i=1}^{3} a_i X_i + \sum_{i=1}^{3} a_{ii} X_i^2 + \sum_{i<j}^{3} a_{ij} X_i X_j \quad (1)$$

Where, Y represents the wanted response. a_0 is constant. a_i,a_{ii} and a_{ij} are the coefficients of linear, quadratic and cross-product terms respectively. X_i represents the coded factors related to the considered parameters. The variance analysis is employed then to summarize the significance test of the model coefficients. Then, main effects, interactions effects and normal probability plots related to the analysis of variance are represented.

The goodness of fit of the quadratic model is evaluated using the coefficients of determination (R^2), which shows the ratio of the explained variation to the total variation and is a measure of the degree of fit, when R^2 approaches to unity, the obtained model is better.

The main effects plot displays the means for each group within a categorical variable. When the line is parallel to the x-axis, there is no main effect present. The response mean is the same across all factor levels. When the line is not horizontal, there is a main effect present. The response mean is not the same across all factor levels. The steeper the slope of the line, the higher the magnitude of the main effect.

The interaction effects plots show how the relationship between one categorical factor and a continuous response depends on the value of the second categorical factor. This plot displays means for the levels of one factor on the x-axis and a separate line for each level of another factor. Parallel lines indicate the absence of interaction. Nonparallel lines indicate the presence of interaction effect, the more non-parallel the lines are, the greater the importance of the interaction.

Normal probability plots are used to detect non normality of data. Points that approximately follow a straight line indicate that the residuals are normally distributed. The test of Anderson–Darling (AD) is used to evaluate the distribution fit of data. The null hypothesis indicates that the data follow a normal distribution, and the alternative hypothesis indicates that the data do not follow a normal distribution. The P-value represents a prob-

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