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Discharge voltage prediction of complex gaps for helicopter live-line work: An approach and its application

Zhibin Qiu[a], Jiangjun Ruan[a], Chao Liu[b], Qi Jin[a], Daochun Huang[a],*

[a] School of Electrical Engineering, Wuhan University, Wuhan, China
[b] Jiangsu Shemar Electric Co. Ltd., Rugao, China

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ABSTRACT

Complex gap discharge voltage is an important parameter to determine the approach path and the minimum air insulation distance for helicopter live-line work (HLLW) by platform method. This paper proposes a novel approach for discharge voltage prediction of complex gaps with a floating object, combining electric field calculation, feature extraction, machine learning and intelligent prediction based on support vector machine (SVM). The methodology is performed by twice electric field calculations and SVM predictions to obtain the withstand voltages of the primary gap and the secondary gap, thus to compute the dielectric strength of the complex gap. A simulation model of the HLLW platform near the 1000 kV UHV AC transmission line is presented for electric field calculations, and some electric field features (EFF) are extracted from the calculation results to parameterize the complex gap configuration. Taking the EFF as input variables, a SVM model is applied to predict the switching impulse discharge voltages of different gap configurations relevant to HLLW. The validity of the proposed methodology is demonstrated through comparison with the experimental results. This study offers a possible way to determine the minimum safe gap distance for HLLW by numerical calculation rather than costly and time-consuming experiments.

1. Introduction

Helicopter live-line work (HLLW) is an important technology for inspection and maintenance of high voltage (HV) transmission lines, which has been successfully applied in several countries [1–6] and performed on transmission lines with the voltage up to 1000 kV [7–10]. With the rapid development of ultra high voltage (UHV) transmission technology, there are more than twenty 1000 kV AC and ± 800 kV DC transmission projects in operation and under construction in China [11]. It is foreseeable that the efficient HLLW will be widely applied on UHV transmission lines in the future.

The two reported methods of HLLW are platform method and suspension or sling method [4], while the former has been used more commonly. For the platform method, a worker sits on an operating platform electrically bonded to a helicopter, and the helicopter flies to the vicinity of the transmission line to position the worker, thus to perform the live-line work such as spacer replacement, stockbridge damper installation, conductor maintenance, etc. In order to ensure the safety of live-line work, it is necessary to determine the safe working distance between the helicopter work platform and the HV energized transmission lines, and also the distance from the grounding electrode.

During the process of entering equipotential, a complex gap is formed by the energized transmission lines, the helicopter work platform and the grounding electrode. The helicopter, work platform and line worker can be viewed as a floating-potential conductor in the vicinity of the transmission lines, which will cause a distortion of the electric field distribution and reduce the dielectric strength of the air gap. There is a lowest discharge location in the air gap, which results in the highest risk level for the live-line work. In order to study the electric field distortion phenomenon and the flashover characteristics of live working complex gap, numerical calculations concerning floating objects have been investigated [6–8,12,13] and experimental researches about complex gap discharge have been carried out worldwide [9,10,14,15].

A three-dimensional (3D) finite element model of the Bell 206 helicopter was established in Refs. [6,12] to analyze the electric field distortion near the 500 kV transmission line in the presence of a floating-potential helicopter. A model of HLLW on 1000 kV UHV transmission lines by platform method was established in Refs. [7,8], and the effect of the approach path on the maximum electric field strength of the line worker was studied by finite element calculation. The electric field distribution around a 750 kV transmission tower with

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* Corresponding author. Permanent address: No. 8, Southern Road of East Lake, Wuhan 430072, Hubei Province, China.
E-mail address: huangdc2009@whu.edu.cn (D. Huang).

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Nomenclature

C	Regularization parameter
EFF	Electric field features
GS	Grid search
HLLW	Helicopter live-line work
HV	High voltage
K-CV	K-fold cross validation
MAPE	Mean absolute percentage error
SVM	Support vector machine
UHV	Ultra high voltage
U_{50}	50% discharge voltage
γ	Kernel parameter

a line worker inside was calculated in Ref. [13] and the results show that there is a close relationship between the 50% discharge voltage (U_{50}) of the complex gap and the electric field distribution, especially the maximum electric field strength. However, even though the electric field distribution considering the floating conductor can be calculated accurately, it is difficult to predict the sparkover voltages of the complex gaps with moving helicopter and line worker. Hence, the determination of the minimum safe gap distance for HLLW of transmission lines still relies on costly and time-consuming experimental studies. On account of this, full scale discharge tests of complex gaps for HLLW on UHV AC transmission line by platform method were carried out in Refs. [9,10] under typical working conditions, and the experimental results provide the minimum phase–ground and phase–phase safe distances for the live-line work. But for different circumstances, experiments should be carried out repeatedly to simulate different working situations.

In order to reveal the discharge mechanism of the complex gap for live-line work and provide an analytical tool to cover the shortage of experimental studies, some researchers try to establish theoretical calculation models to analyze the discharge characteristics of the complex gap with a floating conductor. Based on classical streamer and leader theories, Rizk introduced a mathematical–physical approach to evaluate the critical switching impulse discharge voltages of such gaps, using charge simulation method to determine the floating potential and therefore assess streamer breakdown, leader inception and propagation in the two gaps [14]. A modified model of Rizk's method was proposed in Ref. [15] by introducing a revision coefficient combined with the leader inception model, so as to be appropriate for live working complex gaps on extra high voltage (EHV) and UHV transmission lines. These models considered the complex gap as a primary gap and a secondary gap, and their discharge processes were analyzed successively. Due to the complexity of the complex gap discharge process, Rizk's model and its modified versions are still semi-empirical methods. Whether these models can be generalized to the condition of HLLW has not yet been verified.

In this paper, a novel approach is proposed for discharge voltage prediction of complex gaps with a floating object, which involves electric field calculation by finite element method (FEM), feature extraction, machine learning technique based on support vector machine (SVM), and iterative prediction by golden section search method. The performance of this approach is validated by predicting discharge voltages of complex gaps for HLLW. The major contributions of this paper are given as follows:

(1) This paper proposes a new method to predict the complex gap discharge voltage based on FEM calculation and SVM prediction. The complex gap is divided into gap 1 and gap 2, and some features are extracted from FEM calculation results of the electric field distribution and taken as input parameters of the SVM model, while the final output is the withstand voltage of gap 1 and gap 2. In the premise of model training and parameter optimization, the complex gap discharge voltage can be predicted by twice FEM calculations and SVM predictions. The most significant advantage of this approach lies in the fact that, compared to traditional physical modelling methods based on air discharge theories, it avoids directly studying the complicated discharge process.

(2) The proposed model is applied to predict the switching impulse discharge voltages of the phase–ground complex gaps for HLLW, under simulated working conditions of a UHV AC transmission line. The test data given in Refs. [9,10] are employed to compare with the predicted results. This application case realizes discharge voltage prediction of complex gaps for HLLW for the first time. The major significance lies in that it provides a possibility to obtain the minimum safe gap distance and the complex gap combination by numerical calculations instead of costly full scale tests, which can provide references for HLLW of UHV transmission lines by platform method.

The rest of this paper is organized as follows: Section 2 introduces the proposed approach for complex gap discharge voltage prediction. Section 3 presents details about modelling of HLLW platform. Section 4 describes discharge voltage prediction process and results of complex gaps for HLLW. Section 5 gives a discussion commented on the prediction method and the produced results. Section 6 presents conclusions of this study.

2. Discharge voltage prediction method of complex gaps with a floating object

A complex gap with a floating object can be divided into two serial gaps. Taking a conductor-plane gap with a floating sphere for example, as shown in Fig. 1, it is composed of the gap 1 between the HV conductor and the floating sphere, and the gap 2 between the floating sphere and the grounding plane. The lengths of gap 1 and gap 2 are respectively d_1 and d_2, while the gap spacing between the conductor and the plane is d. The complex gap discharge voltage depends on which gap will breakdown firstly and be determinant for the whole gap breakdown. Therefore, the discharge characteristic of the complex gap is generally different from that without the floating object.

The proposed approach for discharge voltage prediction of such gaps is based on FEM calculation, electric field features (EFF) extraction, and SVM modelling and prediction. FEM calculation of the electric field distribution and EFF extraction are quantitative approaches to characterize the complex gap configurations by some physical or mathematical quantities instead of simple geometric parameters. SVM modelling is applied to establish the multidimensional nonlinear

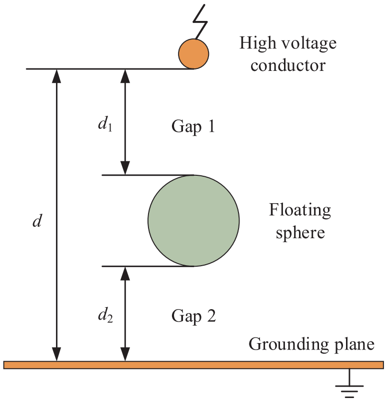

Fig. 1. Schematic diagram of a conductor–plane gap with a floating sphere.