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Development and application of software for the analysis of magnetically induced subsequent fault (MISFault)

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ABSTRACT

As an initial electric fault occurs, the fault current would result in a strong magnetic force and torque exerted on the power line conductors. The rotational magnetic torque, in turn, would make the power lines with sags swing and may bring them to close proximity or in contact with one another, causing a subsequent fault. For the analysis of the magnetically induced subsequent fault (MISFault), software has been developed as the end product of a multi-year research project sponsored by Duke Energy Company. The software is capable of predicting the smallest distance between the power line conductors during their swing procedure, from which one can predict the probability of the magnetically induced subsequent fault; and determine the allowed span length range from consideration of eliminating the subsequent fault, which is anticipated to be useful for a utility in long span design. The software has been tested and the accuracy of its computation results has been validated by verifying that the energy conservation law requirement is well satisfied. The MISFault software is being used by Duke Energy Company. It is user friendly and is expected to be useful to a utility for eliminating the magnetically induced subsequent fault.

1. Introduction

When an electric fault occurs, the overhead power line conductors briefly carry a fault current, which is much higher than the current under normal operation conditions, resulting in a much stronger magnetic force and torque exerted on the power line conductors. Under the influence of the magnetic torque, the conductors will start swinging, and they may be brought to close proximity or even contact one another, causing a subsequent fault. The subsequent fault will be closer to the substation/source than the initial fault, and thereby likely to have higher fault current than the initial fault. This subsequent fault condition may be difficult to identify, and will cause reduced service reliability and poor power quality. Being able to predict and eliminate these subsequent faults will be beneficial to a utility. Under the sponsorship of Duke Energy Company, computer simulations of the magnetically induced subsequent fault (MISFault) of three-phase power lines have been formulated for level spans [1], inclined spans [2], and transition spans [3], and for determining the allowed span length range from consideration of eliminating the MISFault [4]. Based on the computer simulations presented in [1–4], we have developed user-friendly computer software for the analysis of MISFault. The MISFault software has been tested and is being used by Duke Energy Company.

In this paper, we first summarize the numerical techniques presented in [1–4], which have been implemented in the computer codes of the MISFault software. Then, we present the modules of the software, and show its main functions using two illustrative examples of its applications.

2. Numerical techniques

The computer simulations previously developed by the authors [1–4] are based on a dynamic analysis tracing the smallest distance between the power line conductors as they are swinging after the initial fault occurs, to determine whether or not they would touch each other causing a subsequent fault. In the computer simulations, use has been made of electromagnetic theory and fundamental laws of mechanics [5,6]. Such developed numerical techniques are summarized in this section for level spans, inclined spans, and transition spans; and for determining the allowed span length range.

An overhead power line with level span is illustrated in Fig. 1, where L is the span length and s is the sag of the conductor. Such a power line is used for three-phase power transmission and distribution. When an initial fault occurs, the three-phase power line conductors carry a high-level fault current, resulting in a strong

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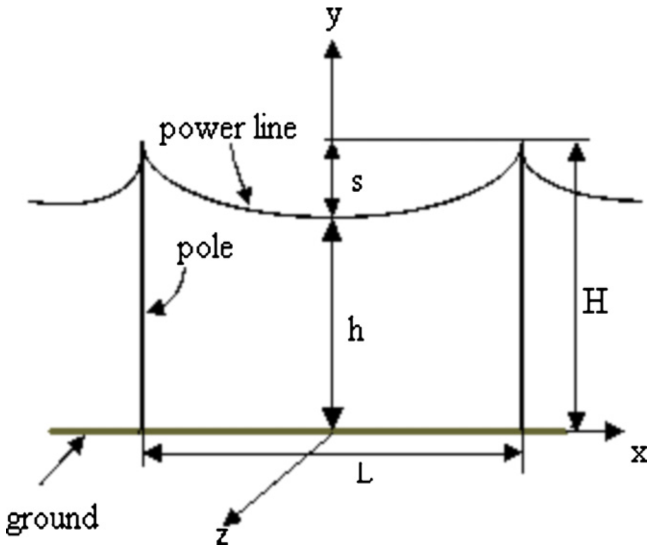

Fig. 1. An overhead power line with level span.

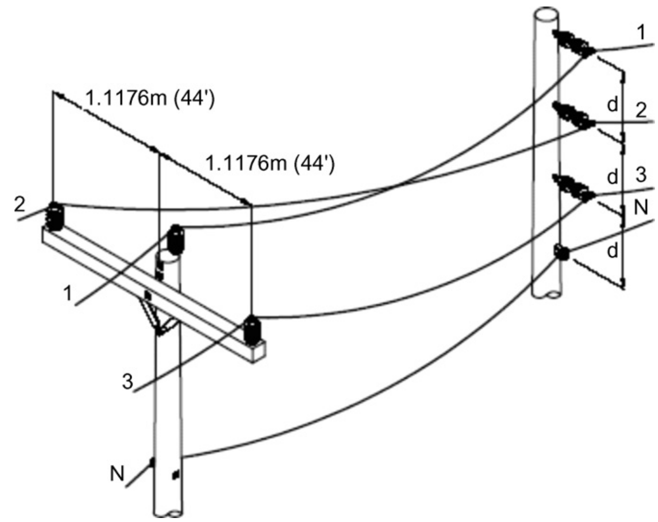

Fig. 3. An example of transition span: a crossarm to vertical construction.

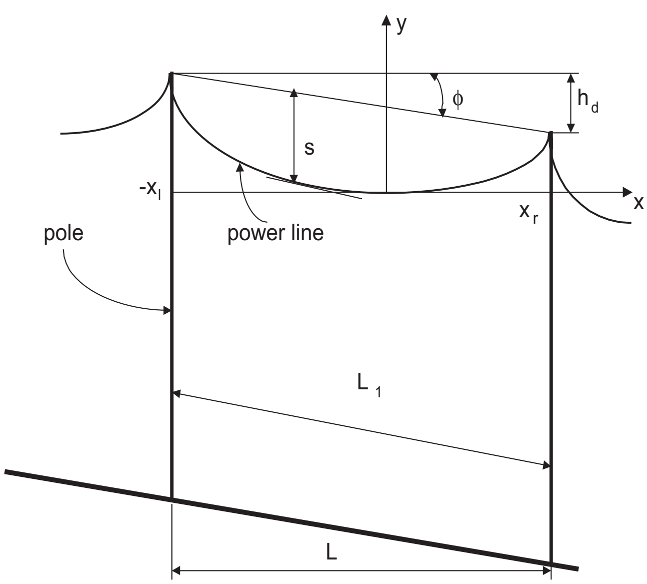

Fig. 2. An inclined span.

magnetic field, and magnetic force and torque exerted on the power lines. Under the influence of the rotational magnetic torque, the power line with sag will start swinging; its swing axis is a line connecting the two supporting points on the two end poles of a span. As presented in [1], for computing the magnetic force and then the torque, the power line conductor is partitioned into N small segments. The torque exerted on it can be determined by

$$\tau_n = \sum_{i=1}^{N} F_{ni} r_i, \tag{1}$$

in which F_{ni} is the vector sum of the magnetic force and the gravity exerted on the ith segment of the conductor, and r_i is the normal distance from the ith segment of the power line conductor to its swinging axis.

The magnetic force $\vec{F}_i(t)$ on the ith segment of the conductor can be calculated by

$$\vec{F}_i(t) = I(t) d\vec{l}_i \times \vec{B}_i(t), \tag{2}$$

where $d\vec{l}_i$ is a length vector along the ith segment, $I(t)$ is the current flowing in the power line conductor, $d\vec{l}_i$ is the differential length vector in the direction of the current flow, and $\vec{B}_i(t)$ is the magnetic flux density produced by the power line currents. Since the magnetic flux density $\vec{B}$ depends on the location of the power lines, which changes as time progresses after the power lines start swinging, $\vec{B}$ must also vary as a function of time t and

$$\vec{B}(t) = \vec{B}_0 \cos(\omega t + \phi_B) \tag{3}$$

in which ω is the angular frequency, $\vec{B}_0$ and ϕ_B are the magnitude and phase angle of the magnetic flux density; they can be calculated using Biot-Savart's law as shown in details in [1]. One notes that both $\vec{B}(t)$ and $I(t)$ appearing in Eq. (2) are functions of time t. Therefore, when the power lines are swinging, the magnetic force and the resulting torque exerted on them must vary as functions of time t as well. To take the time variation into account, a dynamic analysis is developed as the follows. First, we divide the whole swinging procedure into many very short time steps Δt ($\Delta t \ll T = 1/60$ s). Then, starting from $t = 0$ and using a recursive procedure described in [1], we can find out the movement of the power lines and then update the magnetic force and torque at their new locations during each time interval step by step. Finally, their locations and the smallest distance between the power line conductors at any specific moment can be determined, from which we can tell whether or not the conductors would touch each other, causing a subsequent fault.

For power transmission and distribution in mountainous terrain, applications of overhead power lines with inclined spans are required. Fig. 2 illustrates an inclined span of power line, in which h_d is the vertical distance between the supporting points on the two ends of an inclined span. One notes that as the power line conductor of an inclined span swings under the influence of strong magnetic torque caused by an initial fault, the swing axis would be a line through its supporting points. Therefore, for convenience of a dynamic analysis of the power line swing, we set a new (X, Y, Z) coordinate system in such a way that the X-axis is parallel to the swing axis of the power line and a coordinate system transformation is employed, as presented in [2]. After the coordinate system transformation, a dynamic analysis on the power line movement under the influence of the magnetic force and toque can be carried out in a similar way as that described in [1]. But the analysis is carried out in the (X, Y, Z) coordinate system.