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Non-linear high impedance fault distance estimation in power distribution systems: A continually online-trained neural network approach

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ABSTRACT

This paper presents a new methodology for high impedance fault (HIF) location in overhead power distribution systems. A polynomial function was used to model the voltage at fault point as function of the fault current. Additionally, a continuously trained neural network after the occurrence of HIF was used. This neural network is used to estimate unknown parameters present in the equations that model the feeder during an HIF. The proposed algorithm uses measurements of voltage and current taken only at the substation together with the feeder parameters. A typical 13.8 kV distribution system is used to test and validate the proposed scheme. The performance of the method was evaluated according to the fault current amplitude and the system load level. In addition, a comparative analysis with a state-of-the-art method was also performed. The HIF distance estimation errors remained below 1% in 86% of the tested cases. The maximum error obtained was 2.3%. Hence, such good performance along with the simplicity of the method and low cost of implementation, make this methodology suitable for real distribution feeder.

1. Introduction

In most electric power distributors, fault location is performed from the visual inspection of the affected zone. This methodology is inefficient, mainly due the presence of lateral branches. Therefore, the interruption time is high in the distribution systems.

Furthermore, HIFs may occur in distribution systems. These faults occur when a live conductor of a feeder, in general of a 15 kV class, breaks and goes into contact with high impedance surfaces such as stones, sand or asphalt. Due to the relative low voltage and elevated impedance, this type of fault generates currents with low amplitudes. In most cases, these values are lower than the feeder load current. Thus, such fact imposed by the nature of this fault may lead to its non-detection by conventional protection systems such as overcurrent relays and fuses, which endangers the lives of population and the integrity of material goods.

Therefore, with the objective of increasing the reliability and the safety of distribution networks, several studies have been published in recent years attempting to solve the problem of HIF detection in distribution systems. According to Ref. [1], 225 studies regarding HIF detection in distribution systems were published between the years of 1960 and 2008. However, despite the great amount of algorithms that were proposed, few studies had the goal of determining the fault point. Hence, when an HIF is detected by some detection algorithm, the whole system must be shut down in order for the maintenance crews to run through the entire length of the feeder to find the HIF point. This procedure prolong the recovery time and harm consumers and the utility's quality indicators. Moreover, the non-actuation of the system fuses for this kind of fault increases even more the recovery time because the crews do not have this information in order to reduce search space.

Thus, an accurate HIF location tool could improve reliability indicators commonly used by electric power utilities and help utility personnel to expedite service restoration and reconfiguration process in order to reduce outage time.

The available literature on HIF location is reduced in terms of distribution systems. Moreover, most studies have suggested the installation of remote measurement equipment or fault indicators throughout the feeder length [2–5] in order to obtain more information that may help solve the problem. This type of solution is expensive and impracticable for the reality of power utilities due to the great numbers of feeders.

Furthermore, research has made use of the high frequency components presented in HIF [2,6–9]. These components are

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manipulated by using mathematical tools such as Wavelet Transform. This tool enables the determination of the range of frequencies and identifies the typical features that help in identifying the fault point. This methodology shows promising results however its application may generate high computational and financial costs due to high frequency sampling.

Additionally, Artificial Neural Networks (ANNs) are also studied HIF location in Ref. [10] due to their robustness and generalization capacity. However, different HIF characteristics are possible in different situation, such as, soil type, humidity level, feeder voltage, fault distance, etc. Because of the difficulty in obtaining real data corresponding to HIF, these different characteristics are previously generated by computational simulations and, afterwards, are used for ANN training. Given this reason, at the moment an HIF is detected, the same characteristics used in the training are extracted and become inputs of an ANN that generates an estimate for the fault point as an output. Nevertheless, despite the number of advantages, the need of prior training an ANN may be an obstacle to be used in feeders of great size since several cases must be simulated in order to assure satisfactory results by the ANN. Moreover, if the network topology changes, some ANN-based methodologies will require new training patterns thus demanding new computational simulations.

Algorithms based on apparent impedance were also adapted for HIF location. In Ref. [11], a time domain methodology was proposed, which determines the voltage at the fault point through an HIF model based on two diodes in anti-parallel. The mathematical description was used to model the feeder during an HIF in function of the fault distance. Thus, the unknown parameters of the equations proposed in Ref. [11] were estimated through a least square algorithm together with application of Newton's Method. Nonetheless, despite the innovative aspect, such a method was evaluated in a system with a length of only 1500 m, which is smaller than most real feeders, and it presented errors in the fault location process with values above 10% in some cases.

In Ref. [12], the HIF model based on two diodes in anti-parallel is also used to equate the voltage at the fault point. However, differently from Ref. [11], the equation proposed by Ref. [12] is developed in the frequency domain and uses the weighted least squares method to determine the unknown equation parameters. Similarly to Ref. [11], the method proposed in Ref. [12] was validated in a small system of 2 km. However, one case was tested in a larger real system. Although in this case the fault current has characteristics similar to an HIF, the fault current was higher than 600 A. This current is higher than that considered in the literature as being the HIF current. In addition, the method proposed in Ref. [12] requires empirical adjustments of thresholds to select the correct values for the distance of the fault. Thus, similar to other methods in the frequency domain, the method proposed in Ref. [12] requires a high sampling frequency (23 kHz in 60 Hz) not compatible with most relays.

In conclusion, given the reduced literature about the subject and the limitations presented in the previous papers, this paper aims to present a new HIF location tool. A simple and economic technique based on solving the current and voltage equations directly in the time domain to find the HIF distance is proposed. The methodology presented uses an ANN to solve these equations. However, unlike the other methods proposed in the literature, the proposed ANN requires no previous training since it is continually trained online. In addition, the method requires no empirical adjustments of thresholds, uses a sampling frequency that is compatible with the most actual relay, considers the feeder capacitances and requires no installation of additional measurement equipment.

The proposed method was evaluated in an unbalanced test system with 24 km length, containing single-phase and three-phase lateral branches. In the test system, line-to-ground high impedance faults were simulated at the different nodes of the system. The performance of the proposed algorithm was analyzed for three cases. The influence of the fault current amplitude and the feeder loading are the first and second case, respectively. The third case is a comparative analysis between the proposed algorithm and another state-of-the-art method.

The remainder of this paper is structured as follows: Section 2 presents a review about HIFs and the proposed model for the voltage at the fault point during a HIF, Section 3 the proposed analytical method for HIF location and Section 4 the tests performed to validate the method. The conclusions of this work are finally presented in Section 5.

2. High impedance faults

The main feature of HIFs is the low amplitude of the fault current due to the high contact impedance of some surfaces such as asphalt, stones and sand. This low fault current makes traditional protection systems not operate in this fault type. An HIF does not behave as a linear resistance; instead, it tends to present a nonlinear behavior of V × I at the fault point due to the existence of electric arcs and modification in surface conditions. Another specific feature of HIF is the buildup and shoulder steps. The buildup is the period in which the fault current increases due to cable accommodation in the ground. The shoulders steps refers to the period where the fault current amplitude remains constant within the buildup period.

In Ref. [13], practical experiences were performed with HIF. In these experiments, a conductor energized at 13.8 kV is brought into contact with different high impedance surfaces. Through these experiments it has been found that for some surfaces the fault current is less than 20 A (sand, asphalt and gravel). These currents are lower than the load currents of typical distribution feeders [13]. Because of this, traditional protection devices do not act for this type of fault and the cable will remain energized compromising human security.

There are two widely accepted models for HIFs simulation in the literature, which are the models proposed in Refs. [14] and [15]. The two models present similar results; however, unlike model [14], model [15] is unable to represent all the HIF characteristics as buildup and shoulder stages. In addition, the model proposed in Ref. [14] was validated through field tests performed on a 22.9 kV system and in Ref. [13] the same model was validated on a 13.8 kV system. Thus, it can one may consider that this model presents satisfactory results for these voltage levels. For these reasons, the model proposed in Ref. [14] was used in the algorithm proposed in this paper.

The model proposed in Ref. [14] consists of two variable resistances in series. The first one (R_1) models the growing feature of the current during the settling time of the conductor in the soil (buildup stage). The second one (R_2), models the typical asymmetry of the electric arc and is present in all fault current cycles.

In consequence, the voltage at the fault point (v_F) is given by Eq. (1).

$$v_F(t) = v_{R_1}(t) + v_{R_2}(t) \quad (1)$$

where: $v_F(t)$ is the instantaneous voltage at the fault point, $v_{R_1}(t)$ and $v_{R_2}(t)$ are the instantaneous voltage on the resistors R_1 and R_2, respectively.

2.1. R_1 control

The R_1 resistance emulates the buildup period. The buildup period depends on several factors, including the soil type, humidity level and feeder voltage. Nevertheless, the tests reported in Refs. [13,14,16] show that the duration time of this stage is approximately 30 cycles. Thus, in order to simplify the proposed