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Partial discharge location using a hybrid transformer winding model with morphology-based noise removal☆

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ABSTRACT

This paper employs a hybrid model of a power transformer winding for accurate partial discharge (PD) location. The hybrid model greatly reduces the computation complexity of the multi-conductor transmission line (MTL) model, yet retains the ability to accurately represent a winding. Having obtained the transfer functions of the hybrid model, PD signals can be calculated from both line-end and neutral-end at a set of detecting points. Subsequently, the pairs of the calculated signals are compared and a PD is located at the point where the minimum normalized Euclidean distance or *F*-ratio of the two signals is detected. In order to enhance computation efficiency a two-round technique, which includes a coarse round and a precise round, is developed and a guideline for section division is given. The influence of noise introduced by measurement devices has also been considered. To reduce the noise meanwhile preserve the feature waveforms, an adaptive morphological filter is employed. Simulation studies have shown that it is accurate and feasible to perform PD location using the hybrid model even with the presence of Gaussian noise.

1. Introduction

PDs in transformers usually lead to gradual degradation of insulation and when transformers are approaching the end of their operating life, critical levels of PDs may result in a full breakdown of insulation [1,2]. Hence, these PDs need to be located as soon as possible so that maintenance can be taken in time. Yet it is not a simple task as a PD may occur at any point inside a transformer. Besides, it is very difficult to record the signal as they are very short pulses of durations from tens of nanoseconds to 5 μs [3].

A considerable amount of research has been carried out for PD location, which can be classified into two categories: acoustic methods and electrical methods [5]. The acoustic method is simple but with low sensitivity. More works are devoted to electrical methods, which involve the assessment of transfer functions. They describe the impact of the location of PD affecting the currents measured at the terminals of a winding. Papers [5,6] use the position of the zeros in the transfer function of the measured currents to locate a PD. In [7,8] PD location is achieved based on correlation, which measures the responses at all the nodes of the output side and the one with the maximum correlation value is determined as the location of the PD. In [9] the technique used for PD location is by investigating the transfer functions and the currents from the line-end and the neutral-end. The basic principle is that the PD signals occurring within the winding and calculated from both ends using the terminal currents and transfer functions should be identical. The transfer functions are calculated from all possible PD locations and the line-end and neutral-end currents are measured. The PD signals can therefore be calculated from the currents and the transfer functions. These schemes have been tested on the lumped parameter model [10,7] and the MTL model [11,9]. In this paper the location scheme used in [9] has been adopted and the transfer functions are calculated using the hybrid model developed by the authors [12,13]. The idea of combining the lumped parameter model and the MTL model to describe a transformer winding was adopted in [14]. Each turn of a winding is considered as a segment and represented by integrated parameters, the calculation of which is based on the lumped parameter model. Subsequently, the MTL formulation is employed for PD location. The major drawback is that the accuracy of a lumped parameter model is dependent on the parameter calculation methods employed; an inaccurate calculation method may easily lead to a large deviation of model outputs from actual frequency responses. Therefore, another hybrid model [12], which is built in a different manner, is adopted in this paper. This hybrid model considers signal propagation along a single winding disc, views each disc as a transmission line, and applies traveling wave equations for all

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discs in a matrix form of MTL model. As stated in [15], if the winding model used for PD study is valid in the frequency bandwidth of the PD measuring system, satisfactory PD location results can be achieved. The hybrid model is efficient in computation and accurate in representing a transformer winding.

In practice, the line-end and neutral-end currents are obtained from measurement. The measurement devices usually bring noise to the measured currents, which may have a negative impact on accurate PD location. To minimize the influence of noise, an adaptive morphological filter is used to smooth out the measured currents beforehand. Morphological operators are known for their ability to preserve shape information of a signal and their computation efficiency. In this paper, basic morphological operators are combined and the progressive umbra-filling (PUF) procedure [16] is adopted to design an adaptive morphological filter, which is used to tidy up the line-end and neutral-end currents before they are compared for locating a PD.

2. Hybrid winding model

For the modeling of a transformer winding, two models are usually used – the lumped parameter model and the MTL model. In the former, sections of a winding are lumped together, and the size of a section can be one or a few discs for disc-type windings and one or a few turns for helical type windings. Hence, it is easy to calculate, but its accuracy is determined by the parameter calculation methods employed. The MTL model views every turn of a transformer winding as a transmission line and these lines are parallel with each other and with the ground. This is a rather complex model when the number of turns and discs is large. Hence, a hybrid model is proposed in [12], which bundles the turns of the same disc and views each disc as a transmission line. This model takes advantage of the simplicity of the lumped parameter model and the accuracy of the MTL model.

The equivalent circuit of the hybrid model of a disc-type transformer winding is given in Fig. 1, where C_i and G_i are the ground capacitance and conductance of the ith disc, K_i and g_i are the interturn capacitance and conductance of the ith disc, r_i, L_i and $M_{i(i+1)}$ denote the resistance, self and mutual inductance, $C_{di(i+1)}$ and $G_{di(i+1)}$ are the interdisc capacitance and conductance between the ith and $(i+1)$th discs, Z_{in} and Z_{out} are the impedance of measurement cables, l is the conductor length of a disc, x denotes the distance from the left terminal of each disc towards the right terminal, and n is the total number of discs in the winding. The circuit equations of the hybrid model can be expressed in the following form [13,17]:

$$\begin{bmatrix} U_1(s,0) \\ U_2(s,0) \\ \vdots \\ U_n(s,0) \\ U_n(s,l) \end{bmatrix} = \begin{bmatrix} & & \\ & \mathbf{\Omega}(l) & \\ & & \end{bmatrix} \cdot \begin{bmatrix} I_1(s,0) \\ 0 \\ \vdots \\ 0 \\ I_n(s,l) \end{bmatrix} \tag{1}$$

where $U_i(s, x)$ and $I_i(s, x)$ are the Laplace transforms of voltage $u_i(t, x)$ and current $i_i(t, x)$. $\mathbf{\Omega}(l)$ is an $(n+1)\times(n+1)$ matrix containing the electric parameters, which are of per unit conductor length and can be calculated from its geometry parameters following the instruction in [17,18]. The accuracy of the hybrid model has been verified by experiment data in our previous work [13]. A detailed procedure of the building of $\mathbf{\Omega}(l)$ can be found in [17]. The following equations can be obtained from (1):

$$U_1(s,0) = \Omega_{1,1} I_1(s,0) + \Omega_{1,n+1} I_n(s,l) \tag{2}$$

$$U_n(s,l) = \Omega_{n+1,1} I_1(s,0) + \Omega_{n+1,n+1} I_n(s,l). \tag{3}$$

From the equivalent circuit we can also get:

$$U_1(s,0) = -\left(Z_{in} + \frac{1}{j\omega C_b}\right) I_1(s,0) \tag{4}$$

$$U_n(s,l) = Z_{out} I_n(s,l). \tag{5}$$

Thus, the transfer function is given by:

$$H(s) = \frac{U_n(s,l)}{I_1(s,0)} = \frac{Z_{out}\Omega_{n+1,1}}{Z_{out} - \Omega_{n+1,n+1}}. \tag{6}$$

3. Partial discharge modeling

Supposing that a PD, which is denoted by I_{PD}, occurs in the kth disc of a winding, we have $I_{PD} = I_k(s,0) - I_{k-1}(s,l)$. The circuit equation of the hybrid model (1) hence becomes:

$$\begin{bmatrix} U_1(s,0) \\ \vdots \\ U_k(s,0) \\ \vdots \\ U_n(s,l) \end{bmatrix} = \begin{bmatrix} & & \\ & \mathbf{\Omega}(l) & \\ & & \end{bmatrix} \cdot \begin{bmatrix} I_1(s,0) \\ \vdots \\ -I_{PD} \\ \vdots \\ I_n(s,l) \end{bmatrix}. \tag{7}$$

From this equation, we can get:

$$\begin{aligned} H_L(s) &= \frac{I_1(s,0)}{I_{PD}(s)} \\ &= \frac{\Omega_{1,k}(Z_{out} - \Omega_{N,N}) + \Omega_{1,N}\Omega_{N,k}}{\left(Z_{in} + 1/(j\omega C_b) + \Omega_{1,1}\right)(Z_{out} - \Omega_{N,N}) + \Omega_{1,N}\Omega_{N,1}} \end{aligned} \tag{8}$$

$$\begin{aligned} H_N(s) &= \frac{I_n(s,l)}{I_{PD}(s)} \\ &= \frac{\Omega_{1,k}\Omega_{N,1} - \Omega_{N,k}\left(Z_{in} + 1/(j\omega C_b) + \Omega_{1,1}\right)}{\left(Z_{in} + 1/(j\omega C_b) + \Omega_{1,1}\right)(Z_{out} - \Omega_{N,N}) + \Omega_{1,N}\Omega_{N,1}} \end{aligned} \tag{9}$$

where $N = n+1$, and $H_L(s)$ and $H_N(s)$ are the transfer functions from the line-end and the neutral-end, respectively. As different winding models are used, the transfer functions and the above equations are different from the ones proposed in [10,11,9]. Eqs. (8) and (9) indicate that given the measured currents of $I_1(s,0)$ and $I_n(s,l)$, the PD current can be calculated from the line-end and neutral-end, respectively, and the calculated line-end and neutral-end currents, denoted by I_{PDL} and I_{PDN}, should be identical [9]:

$$I_{PDL}(s) = \frac{I_1(s,0)}{H_L(s)} \tag{10}$$

$$I_{PDN}(s) = \frac{I_n(s,l)}{H_N(s)}. \tag{11}$$

This feature can be used to locate a PD in the following way.

- Step 1: Assume a winding consists of M sections and each section contains $r = \lceil n/M \rceil$ discs, where operator $\lceil x \rceil$ rounds scalar x to the nearest integers greater than or equal to x. Assign a string of detecting points at the end of each section.
- Step 2: Assume a PD occurs at the end of the rth disc.
- Step 3: Calculate $H_L(s)$ and $H_N(s)$ using (8) and (9) at the rth disc, then calculate I_{PDL} and I_{PDN} using (10) and (11).