

Electromagnetic Time Reversal for Locating Partial Discharge in Transformers Using Discontinuous Galerkin Time-Domain Method

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Partial discharge (PD) localization is important for monitoring and maintaining power transformers. In this digest, the electromagnetic time reversal (EMTR) technique is applied to locate PD sources. To minimize focusing time and position errors, the maximum electric field intensity criterion and the combination of multiple sensors are used for positioning. In addition, a stable discontinuous Galerkin time-domain (DGTD) method with a new efficient implicit-explicit scheme is proposed for modeling PD in transformers. The lossy terms are discretized using the implicit Crank-Nicolson (CN) scheme while the remaining terms are discretized using the explicit Runge-Kutta (RK) scheme, i.e. the CN-RK scheme, which can avoid the influence of the lossy media in transformers on the time-step size and improve computational efficiency. Numerical results demonstrate that the proposed method can effectively locate PD sources in transformers.

Index Terms—Discontinuous Galerkin time-domain method, electromagnetic time reversal, implicit-explicit, partial discharge, transformer

I. INTRODUCTION

AS ONE of the most expensive and important equipment in the power system, it is essential to locate partial discharge (PD) in power transformers. The localization method based on time difference of arrival (TDOA) is widely used [1]. However, the localization accuracy of the TDOA method is significantly compromised in the case of line-of-sight obstructions, such as the presence of transformer cores and windings [2]. Recently, the electromagnetic time reversal (EMTR) technique has been recognized as an effective means to locate PD sources and is gradually being applied to fault localization in power systems [3]. Therefore, we introduce the EMTR technique for PD localization in transformers. To reduce focusing time and position errors, the maximum electric field intensity criterion and the combination of multiple sensors are employed to achieve precise positioning.

A small amount of literature has been published to preliminarily conduct theoretical analysis and experimental verification of PD localization in transformers [4]. Nevertheless, there is a paucity of research on transformer PD based on the discontinuous Galerkin time-domain (DGTD) method. The DGTD method utilizing unstructured mesh discretization is particularly well-suited to the modeling of PD in transformers. However, the stability of the standard DGTD method with explicit Runge-Kutta (RK) schemes is severely affected by lossy media in the transformer, resulting in an exceedingly small time-step size. Thus, a stable DGTD method with a new efficient implicit-explicit scheme is proposed, using the implicit Crank-Nicolson (CN) scheme for the time marching of the lossy terms, while the explicit RK scheme for the rest. The CN-RK schemes can completely eliminate the restriction of time-step size induced by lossy media and improve computational efficiency compared with implicit-explicit RK schemes [5]. The proposed method can realize accurate localization of PD in transformers.

II. FORMULATIONS

A. Principle of EMTR

By employing the EMTR technique, the divergent transmit signals are refocused to the source based on time-reversal invariance, thereby facilitating the localization of the source position. Steps of the EMTR technique for PD localization are as follows [3]:

- 1) Forward process: The PD signal is emitted by a single source and then received by multiple sensors.
- 2) Time reversal: Perform EMTR transformation on the received signal.
- 3) Backward process: The time-reversed signal is injected into the medium oppositely, and waves will refocus at the source position in time and space.

For convenience, homogeneous Maxwell's equations for the heterogeneous and lossy media in the forward process can be written as

$$\nabla \times \mathbf{E}(\mathbf{r}, t) = -\mu(\mathbf{r}) \frac{\partial(\mathbf{H}(\mathbf{r}, t))}{\partial t} \quad (1)$$

$$\nabla \times \mathbf{H}(\mathbf{r}, t) = \varepsilon(\mathbf{r}) \frac{\partial \mathbf{E}(\mathbf{r}, t)}{\partial t} + \sigma(\mathbf{r}) \mathbf{E}(\mathbf{r}, t) \quad (2)$$

where $\mathbf{E}$ and $\mathbf{H}$ are the electric and magnetic field intensities, respectively. ε , μ , and σ denote the permittivity, permeability, and conductivity, respectively. A EMTR transformation ($t \rightarrow -t$) in (1) and (2) yields

$$\nabla \times \mathbf{E}(\mathbf{r}, -t) = -\mu(\mathbf{r}) \frac{\partial(-\mathbf{H}(\mathbf{r}, -t))}{\partial t} \quad (3)$$

$$\nabla \times (-\mathbf{H}(\mathbf{r}, -t)) = \varepsilon(\mathbf{r}) \frac{\partial \mathbf{E}(\mathbf{r}, -t)}{\partial t} + \sigma(\mathbf{r}) \mathbf{E}(\mathbf{r}, -t). \quad (4)$$

In this digest, the maximum electric field intensity criterion is used to determine the focus position of the PD source in time and space. And multiple sensors are used to improve the accuracy of positioning.

B. Stable DGTD Method with CN–RK Schemes

To model PD in transformers effectively, a stable DGTD method with CN–RK schemes is proposed, which allows explicit advancement. With Galerkin’s spatial testing procedure and the upwind flux, the semi-discrete form of Maxwell’s curl equations can be derived as

$$\frac{\partial \mathbf{H}^k}{\partial t} = N_h(\mathbf{E}, \mathbf{H}) \quad (5)$$

$$\frac{\partial \mathbf{E}^k}{\partial t} = -\frac{\sigma^k}{\varepsilon^k} \mathbf{E}^k + N_e(\mathbf{E}, \mathbf{H}) \quad (6)$$

where $1 \leq k \leq K$, and K is the total number of discrete elements. $N_e(\mathbf{E}, \mathbf{H})$ and $N_h(\mathbf{E}, \mathbf{H})$ denote terms contained the discretized operators associated with curl and the upwind flux [6], respectively.

Since the transformer involves lossy materials, the time-step size of explicit RK schemes is strictly limited. To overcome this bottleneck, the implicit CN scheme is employed to discretize the lossy term of (6). The remaining terms are discretized by the explicit RK scheme. By applying the CN–RK time integration scheme at time step $(n+1)$, the time-domain update is given by

$$\mathbf{U}_1 = \mathbf{E}_n^k, \mathbf{V}_1 = \mathbf{H}_n^k \quad (7)$$

$$\mathbf{U}_i = \mathbf{E}_n^k + \Delta t \sum_{j=1}^{i-1} a_{ij} N_e(\mathbf{U}_j, \mathbf{V}_j), 2 \leq i \leq s \quad (8)$$

$$\mathbf{V}_i = \mathbf{H}_n^k + \Delta t \sum_{j=1}^{i-1} a_{ij} N_h(\mathbf{U}_j, \mathbf{V}_j) \quad (9)$$

$$\mathbf{E}_{n+1}^k = \chi \left(\mathbf{E}_n^k - \Delta t \frac{\sigma^k}{2\varepsilon^k} \mathbf{E}_n^k + \Delta t \sum_{i=1}^s b_i N_e(\mathbf{U}_i, \mathbf{V}_i) \right) \quad (10)$$

$$\mathbf{H}_{n+1}^k = \mathbf{H}_n^k + \Delta t \sum_{i=1}^s b_i N_h(\mathbf{U}_i, \mathbf{V}_i) \quad (11)$$

where $\chi = 2\varepsilon^k / (2\varepsilon^k + \Delta t \sigma^k)$, and Δt is the time-step size. a and b represent the coefficients of the s -stage explicit RK scheme, respectively. The proposed scheme can be theoretically proven to be stable in lossy media.

III. NUMERICAL RESULTS

To verify the validity of the proposed method to locate PD in transformers, we simulate the 3-D three-phase transformer model with five ducts using the DGTD method with CN–RK44 scheme, as shown in Fig. 1(a). Assume that the PD occurs at the upper end of the C-phase winding at (1.00, -0.26, 0.41) m. The PD source is considered to be equivalent to a vertical electric dipole source, and the temporal variation of the electric dipole moment p is $p(t) = 10^{-10} \sin(2\pi f_c(t - 10t_0)) \exp[-((t - 10t_0)/t_0)^2]$, where $t_0 = 1/[\pi(f_h - f_c)]$, $f_c = 1$ GHz, and $f_h = 1.5$ GHz. The sensors receiving the PD signal are located in each of the five ducts.

After performing the EMTR of signals received by sensors, the time-reversed signals are added to the transformer as excitation sources for simulation. Fig. 1(b) illustrates the variation of the maximum electric field intensity of E_z with time in the

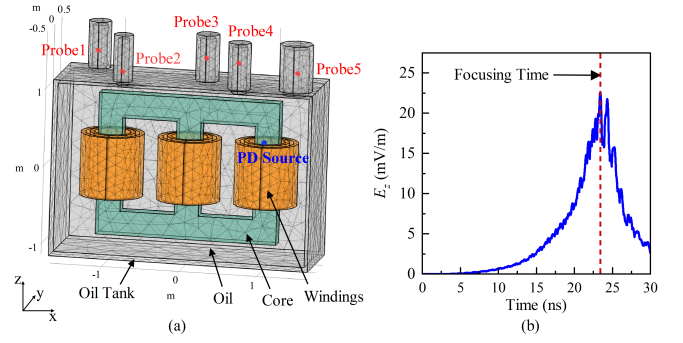


Fig. 1. (a) Transformer model. (b) Time evolution of local maximum electric field intensity of E_z .

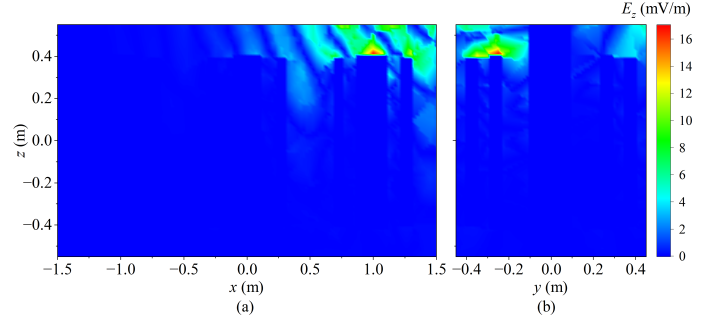


Fig. 2. Local electric field distribution of E_z . (a) Cross-section for $y = -0.26$ m. (b) Cross-section for $x = 1.00$ m.

localized box that just contains the transformer windings. It is observed that the peak time, i.e., the focusing time, is 23.39 ns. The local electric field distribution of E_z near the transformer windings at the focusing time is depicted in Fig. 2. A distinct electric field concentration is visible at the upper end of the winding, with the PD source estimated to be situated at (0.995, -0.235, 0.400) m, a determination that closely approximates the actual PD location. Therefore, the proposed method can effectively and accurately determine the localization of PD in transformers.

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