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Acoustic partial discharge localization methodology in power transformers employing the quantum genetic algorithm

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ABSTRACT

Partial discharge (PD) is one of staple reasons resulting in the deterioration of insulation system in power transformers and power faults. If the PD activity can be located at an early stage, preventive maintenance measures can be taken effectively. Therefore, the localization techniques of the PD do play an extraordinarily momentous role to enhance the operating reliability and stability of the system. It is proposed that a methodology based on the quantum genetic algorithm (QGA) adopting acoustic emission (AE) techniques for locating PD in power transformers. Results of the calculating example confirm the localization effectiveness and accurateness of the proposed method are ideal and satisfactory, and that precision of localization is enhanced compared to some other localization algorithms. The acoustic localization methodology based on the QGA is feasible and of suitability for the field applications.

1. Introduction

With the development of modern industries, agricultures and commerces, *etc.* undoubtedly there is a growing tendency, dependence and demand on energy resources and power consumption. Power transformers, especially large power transformers, are one of extremely significant and quite expensive facilities in modern power systems and are one of the biggest concerns of power companies; it is inner electrical insulation systems of power transformers that are extraordinarily principal parts and their structural integrality does play an important and decisive role for the safe and steady operation of power systems [1]. Power transformers in service are under disparately environmental, mechanical, thermal, chemical, and electrical conditions, which are required durability against these stresses experienced during their operations. Degraded insulating property or insulation breakdown of electric equipments during running periods can lead to serious accidents or sudden unscheduled shutdowns, which can cause grave inconveniences and great losses to both the energy utilities and customers. Strenuous avoidance of unexpected failures of power apparatus is of utmost importance for reliable operations of power systems.

Partial discharge (PD) is recognized as one of the major causes resulting in insulation deterioration or breakdown of power transformers [2–9], thus leading to catastrophic failures. It is established that PD is a natural electrical phenomenon that occurs inconspicuously in insulation systems in a wide variety of electric devices when the local electrical field intensity exceeds the dielectric strength and gradually it evolves as time goes by, tending to slowly jeopardize and deteriorate the insulation medium, diminishing its isolation capacity and resulting in the total flaw and insulation breakdown of the isolation system ultimately.

And PD is indicative of some defects within the insulation systems; its early detection and localization can facilitate repair and deter the potentially catastrophic, ultimate costly and unforeseen breakdown [1,10]. Hence, it is extraordinarily meaningful and crucial to study the techniques of the detection and localization of PD both in theory and practice, especially localization techniques, because only recognizing the existence of PD is not of great help unless the source location can be obtained in large power transformers [1].

When PD happens inside the solid, liquid or gas insulation materials, usually it is accompanied by many electrical phenomena, such as electric current pulse with a high frequency and a great energy and electromagnetic radiation, as well as quite a few non-electrical phenomena, such as ultrasonic waves, lights, heat, gas pressure variations and even chemical changes et al. [11–15]. Various detection and localization methods appeared on account of varied physical and chemical phenomena; hence, as a rule detection and localization approaches of PD can be classified into two fundamental types: the electrical type and the non-electrical type; at present, among those used in transformers ultrasonic detection and localization method is the most studied and highlighted all over the world and one of the most widely used

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detection and location methodology [10]. For example, the acoustic emission (AE) method has been used for the detection and localization of one PD source in power transformers in Refs. [1–4,8,9,14,16].

The detection and localization methodology of PD adopting AE techniques is based on the fact that acoustic waves, in the extent of ultrasonic, are emitted when PD occurs in inner insulated media of power transformers [1]. The localization of PD employing AE techniques, which is as a kind of non-destructive testing (NDT) and has many advantages such as powerful capability of locating, being immune to electromagnetic interference (EMI) and high precision, has been paid more and more attention [1,10,17,18].

Algorithms of localization are a key factor that decides the accuracy of localization in the acoustic PD localization [19]. Literature [3,8,9] applies the fundamental GA to the PD localization adopting AE techniques. Ref. [20] researches the application of the self-adaptive optimization algorithm in the ultrasonic localization of PD in transformers, the algorithm combining the steepest decent method and Newton method. In Ref. [15], the AE method is used for the defect diagnosis of gas insulated substations (GIS), which considers the amplitude and time interval of signals that detected by sensors. Furthermore, the neural network method [21,22] and particle swarm optimization (PSO) [14] algorithm are also employed for the acoustic detection and localization of the PD sources.

Global positioning system (GPS) algorithm is utilized to the acoustic localization of PD; the GPS algorithm gives multiple solutions and selection of exact solution from them is still a principal problem [23,24], and calls for the experience on the part of analysts [24].

A non-iterative algorithm is also applied to the acoustic localization of PD [24]; however, this algorithm gives two solutions, and the accurate solution is not always easily recognized from them.

Traditionally the least squares iterative algorithm is applied to acoustic PD localization problem of PD in power transformers; however, the convergence of this algorithm increasingly depends on the selection of initial condition and may not always converge or may converge to some point which is not a feasible solution [1,24,25].

Ref. [26] applies the pattern recognition method to the acoustic localization of PD in an oil-immersed transformer. The method divides the transformer into a large number of 20 mm × 20 mm × 20 mm submodules; the smaller the divided submodules are, the more precise the localization is; however, the data needed to be handled also definitely increase. And the internal dimensions of power transformers, sometimes, are not easily identified. Therefore, the methodology is unsuitable and inconvenient for the field applications and on-line monitoring.

Hence, from what has been discussed above, it is safely concluded that some existing algorithms for the acoustic localization of PD have some imperfections and limitations. Then, it is really needed that applying some new algorithms to the acoustic localization of PD in order to conquer some drawbacks in the current existed algorithms.

The quantum genetic algorithm (QGA) is an improved GA and the QGA overcomes some drawbacks of the fundamental GA. The QGA is applied to the problem of the ultrasonic localization of PD in power transformer; then the acoustic PD localization methodology based the QGA is proposed. Then this PD localization method is applied to localize PD source of the field transformer in service. And the localization results based on the QGA are compared with some current existed algorithms such as the GA and some other intelligent algorithms. The results of the case study of the spot experiment demonstrate that the method based on the QGA is feasible, practical and suitable for field applications and the precision of localization is enhanced, and the localization effectiveness of the method based on the QGA is ideal and satisfactory.

The purposes of this paper are to study and probe into the feasibility and accuracy of acoustic PD localization methodology based the QGA in solving the PD localization problem adopting AE techniques in power transformers.

This paper is organized as follows. Section 2 elaborates the principles, the mathematical model of acoustic PD localization methods and signal processing method of AE signals. Section 3 describes the fundamental GA and QGA. Section 4 contains the analyses and discussions of the case study, and the results of the case study are systematically summarized and analyzed. Concluding remarks follow in Section 5.

2. The principles and mathematical model of acoustic PD localization

2.1. Principles

A PD event is pulse-like in nature and can be deemed to be a small "explosion" or "micro-crack" which leads to the generation of AE pressure waves [1]. Signals of AE elastic waves emitted by the discharging source propagate throughout surrounding insulated media of the transformer when the PD occurs and are detected by piezoelectric sensors mounted on the outside tank wall of the transformer which are sensitive to generated acoustic signals; then AE signals are analyzed; the PD source is located through the solution of the localization equations in the end [1]. This is the fundamental principles of the acoustic PD localization in power transformers.

2.2. Paths of acoustic wave propagation

The focus of acoustic PD measurements is based on the PD source localization, however, of particular importance is the much better knowledge of paths of acoustic mechanical stress wave propagation in power transformers [1].

The standard partial differential equation (PDE) which governs the propagation of an acoustic wave for the isotropic homogeneous medium is given by:

$$\frac{\partial^2 P}{\partial t^2} = v^2 \nabla^2 P = v^2 \left(\frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2} + \frac{\partial^2 P}{\partial z^2} \right) \tag{1}$$

where $P(x,y,z,t)$ is the pressure wave field (Pa) as the function of space and time; x, y and z are the three Cartesian coordinates (m) and t is the time (s); v is the acoustic wave velocity (m/s). The above PDE equation includes three fundamental equations, which are the description of the continuity, the conservation of the momentum and the elasticity of the medium.

Acoustic pressure waves travel to AE sensors via disparate insulated materials. According to the theory of acoustics, the reflection, refraction, deflection and attenuation occur at the boundary surfaces of different media [1].

As shown in Fig. 1, spherical pressure waves produced by the PD source can be regarded as an infinite number of beams originating from the PD source and propagating equivalently in all directions, and each beam reaching at the wall of tank with disparate incidence angle θ. At the PD source, the spherical pressure front includes two types of waves *i.e.* longitudinal and shear (transverse) waves. To be generalized, the AE signals created by the PD of the internal insulation media of transformers arriving at AE sensors installed on the tank wall contain two kinds of propagation routes *i.e.* the direct path (see SA shown in Fig. 1) in the oil with a velocity of 1413 m/s approximately and the mixed (indirect) path (see SBA and SCA, *etc.* shown in Fig. 1) of the oil and tank wall of the