To the Evaluation of the Insulation State Based on the Analysis of Partial Discharges

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Abstract. The existing partial discharge models, their diagnostic value, and application area are analyzed in the article. The models are considered from the point of view of their improvement or the possibility of creating new diagnostic methods for electrical equipment based on the characteristics of partial discharges. As an example of the implementation of a new approach to partial discharge modeling, a quasi-deterministic model is considered, which makes it possible to obtain information on the real number of cavities in the insulation of high-voltage equipment.

1. Introduction

It is known that a partial discharge (PD) is a breakdown of gas inclusions, local breakdowns of small volumes of a solid or liquid dielectric, local discharges on the surface of a solid dielectric under the action of a high electric field strength [1]. Partial discharges do not lead to a through-breakdown of the insulation. At the initial stage of development, they are the cause of the slow local degradation of the dielectric. Practice shows that under the influence of a strong electric field, the aging of insulation occurs mainly due to PD [1]. With the development of PD from the initial stage to the critical one, a sharp decrease in the dielectric strength of the insulation is observed, which ultimately can lead to a breakdown. The occurrence of PD always indicates the presence of a local non-uniformity of the dielectric. This is an important factor in terms of identifying defects and subsequently assessing the technical condition of high-voltage equipment.

Specialists in diagnostics pay great attention to the issues of studying the appearance and development of PD [1 - 8]. PD and their manifestations have a set of specific characteristics. Using these characteristics, it is possible to assess not only the state of the insulation of high-voltage equipment, but also to determine the type and location of defects, as well as their number and degree of development.

Currently, the physical processes occurring during the origin and development of PD are being actively investigated in order to develop models that allow in mathematical form to most objectively reflect the laws that determine the physical phenomena accompanying the appearance and development of PD. This subsequently makes it possible to explain the appearance and development of defects, to determine their effect on the general state of insulation [2 - 9]. In the future, such models can be used to create various methods for assessing the state of insulation and diagnostics of electrical equipment.
Most models either have several assumptions (i.e. simplifying physical processes) or have an excessively complex (hard) mathematical explanation. These circumstances prevent the further use of these models for the development of algorithms and methods for diagnosing electrical equipment and assessing of insulation state. This is due to the need to meet the increased requirements for such methods. First of all, they should have a deterministic diagnostic value, make it possible to obtain information sufficient for making decisions on the operation of equipment. This article analyzes typical models from the point of view of their compliance with the requirements, which necessary for the development of effective methods for diagnosing insulation and assessing the technical condition of equipment.

2. Partial discharge model analysis

Today, there are many models describing different stages of the development of a PD. In addition, models describing the PD distribution in an inhomogeneous dielectric [9], the discharge process in a single inclusion [10], the processes of destruction of dielectrics under the action of PD [5, 11-12], the influence of external electromagnetic fields [13, 14] can be distinguished. Models that use the statistical characteristics of PD are of great importance [9,15]. Some models have a specific character and are developed for the analysis of processes in certain types of dielectrics [5, 11].

All these models are focused on solving specific problems and have their own limitations and areas of application. Further, we will consider groups of physical models that differ in the way they display the basic physical properties of PD.

2.1. Models based on the equivalent circuit of the insulation gap

Partial discharge research has been going on for over 80 years. One of the earliest models for investigating PD is the model of a single small cavity located in a uniform electric field based on the analysis of the simplest equivalent circuit (or three-capacitor circuit) [16, 17]. This model in the classical form has the following assumptions: the electric field in the insulating gap must be uniform, the surfaces of the cavity (charge spots), opposite in sign of the charge, must coincide with the equipotential surfaces of the electric field, it is assumed that there is only one cavity in the insulation volume, and the discharge energy is not spent on losses. It follows from this that such a model can be used for an approximate analysis of the PD development process, and the methods based on it are able to detect the most obvious developed defect.

Later, different modifications were developed based on this simplified model. For example, in [6], resistors are introduced to simulate the conductivity of the insulation and the discharge channel. In particular, a time-varying resistor is used in the model to simulate a significant reduction in cavity resistance during PD development.

Multi-capacitive models have also been developed. For example, in [7], the charge spots formed during the discharge on the walls of the cavity are represented in the form of conducting disks. The model considers not only the capacitance of the insulation volumes between the conducting surfaces of the cavity and the sample electrodes, but also the edge capacitance of the insulation pillars and the edge capacitance of the cavity. This representation allows one to obtain the dependence of the apparent discharge on the geometric form of the cavity.

Most models use a parameter such as "apparent partial discharge charge" to assess the technical condition of the insulation. There is no definite consensus regarding the information content of this parameter among researchers of partial discharges, especially for the problems of diagnostics of electrical equipment [4, 8, 18, 19]. Methods for assessing the technical condition based on this parameter, adopted in the standards, are proposed to be revised [7].

Despite the fact that the simplest model of the three-capacitance circuit of the isolation gap is used to describe the methods for assessing the technical condition of electrical equipment, many experts criticize it [2, 8], because it creates the illusion of simplicity in describing the PD process and leaves a number of uncertainties. Unfortunately, this model is not able to fully describe the physical processes
occurring during the development of partial discharges, which ultimately significantly hinders the use of the three-capacitor model as a basis for constructing effective diagnostic methods.

2.2. Electrostatic model
Recently, various researchers [18, 19] have proposed field electrostatic PD models instead of capacitive models. In these models, the concept of induced charge is introduced to quantify the relationship between physical (true) charge and apparent charge. This approach is based on the fact that charge transfer inside the cavity leads to a change in the surface charges on the electrodes during the development of the discharge.

An opinion is expressed in [2, 18] that electrostatic models have a complex description of the physical processes of PD. These models take into account the geometry of the inclusion, its location in the insulation, the surface conductivity of the inclusion wall, and the electric field strength from the settled (induced) charge of the PD. Plasma models are not able to provide information about the actual number of cavities (as well as capacitive models). Some of these models implicitly assume the presence of only one single cavity in which PD occurs. The main assumptions are that the electric field and surface charge distribution in the cavity are uniform.

According to researchers [18, 19], the electrostatic model, the PD model, makes it possible to relate the PD distribution with the defect size and with PD manifestations in the external circuit.

This model predicts measurable PD characteristics such as the initial PD appearance voltage, PD initial delay, apparent charge, statistical characteristics, and the distribution of PD pulses over the AC voltage phase.

Most electrostatic models are analytical and based on the assumption that the electric field and surface charge distribution in the inclusion are uniform. Illias et al in work [4] proposed to calculate the induced charge in the cavity using the finite element method. This approach makes it possible to take into account the distribution of the electric field in the inclusion and to give a more realistic model.

2.3. Plasma models
Plasma models concentrate on an accurate description of the processes occurring during the development of PD in a cavity and are more rigorous models that include as few simplifications as possible. Physical processes such as impact ionization, attachment, recombination, diffusion and charge drift are quantitatively described by the equations of the liquid in these models. Photoionization and the effect of residual charges are taken into account.

Using the equations of the liquid, as well as the Poisson equation, it is possible to obtain the time evolution of the distribution of the charge and the electric field inside the cavity during the development of the discharge. In addition to information about the accumulation of space charge in the gas channel, the subsequent change in the electric field, ion and electron currents, and the accumulation of charge on the electrodes, graphs in the phase space for various types of PDs can be presented [20, 21].

However, the described processes are problematic to observe at the macrolevel and register outside laboratory conditions. In addition, this approach requires large computing power when simulating a set of PDs.

Attempts have been made to simplify the models to reduce the need for computing resources [22]. Photoionization was not taken into account, and free electrons with a high concentration were placed closer to the anode to shorten the avalanche period. However, in these studies, significant differences were observed in the shape of the pulsed current and the distribution of the surface charge in comparison with the experimental results.

2.4. Stochastic models
Stochastic models describe the moments and places of PD occurrence, and other processes in isolation using the theory of probability and statistics.
The model described in [15] proposes to consider the process of PD impulse occurrence as a random process. The main assumptions of this model are:

- the time constants of the change in the electrical quantities accompanying the PD are much less than the period of the change in the electric field,
- each of the PD processes corresponds to its own component in the PD sensor signal, namely, to reversible processes correspond to components that change in time with a change in the external electric field, and to irreversible jumps correspond to impulse components, the average duration of which is less than the period of the electric field change
- the shape of the pulses from all PDs in the investigated dielectric for the period of change in the applied voltage is the same,
- the probability $p$ of the occurrence of a pulse on the interval $dt$ is proportional to the duration of the interval: $p = ndt$, where $n$ is the average number of PD pulses per second,
- the dielectric is in a uniform electric field,
- the probability of occurrence of the $j$-th PD in the interval $(t, (t + dt))$ depends on the time elapsed from the moment of occurrence of the $(j - 1)$-th partial discharge. The durations of the intervals between PDs are assumed to be independent from each other.

It is proposed to use the parameters of the spectral distribution of PD-noise as diagnostic signs in the survey of high-voltage equipment. Nevertheless, it is noted that in order to use this model for diagnostics of high-voltage equipment, it is necessary to improve the mathematical model linking the parameters of the spectral distribution of PD noise with PD parameters and dielectric parameters. At the same time, there is an uncertainty that one and the same spectral distribution can correspond to different fluctuation processes and an adequate choice is ultimately a matter of experiment. This in turn reduces the diagnostic value of this model.

The model described in [9] suggests using the voltage of PD occurrence as a diagnostic parameter. The model has a probabilistic approach in terms of the distribution of the properties of inclusions, namely, the ignition voltage and extinction voltage, in the volume of polymer insulation. At the same time, unlike most of the models discussed above, this model allows the assessment of insulation located in non-uniform electric fields.

The proposed method for calculating the voltage of the occurrence of partial discharges in an non-uniform electric field makes it possible to theoretically substantiate the possibility of using this parameter to assess the state of polymer insulation of high-voltage electrical equipment. The resulting model is consistent with empirical formulas obtained in other studies, and the discrepancies reach no more than 20%.

3. Model of a quasi-determined PD process

One of the most important uncertainties, which are not accepted by modern methods and regulations, is the question of the actual number of defects in the insulation of high-voltage equipment. To answer this question, it is necessary to consider the integral picture as a set of partial discharge pulses in electrical equipment, which are generated by a set of defects - sources of partial discharges, and a series of partial discharges generated by each separately [23]. Under the influence of these two factors, a general picture of reproduced PD signals (or an integral PD pattern) is formed. Consider the integral picture formed by a set of approximately equal partial discharge signals (Figure 1) to clarify the definition of the above uncertainties. As an example, Figure 1 shows a simulated PD pattern. On the Y-axis, the values of the moduli of the pulsed partial discharge currents are plotted in units; on the X-axis, the values of the times of the occurrence of partial discharges are plotted within one period of industrial frequencies.
In [24], a quasi-determinate model is presented. The integral picture of partial discharges is represented as a superposition of PD pulse sequences, where each PD series is associated with a separate PD source using a quasi-deterministic model.

The PD concept adopted in many national and international standards, based on a capacitive insulation equivalent circuit, implicitly assumes that the insulation of high-voltage equipment is in a uniform electric field. This assumption in most cases does not correspond to reality. The model described in [24] takes into account that the electric field can be non-uniform, and this must be taken into account when calculating the electric field strength in the vicinity of the cavity. It is also taken into account that the forced intensity (in the absence of PD) of the electric field inside the inclusion is determined by the shape of the inclusion and the ratio of the dielectric constant of the main insulation and the inner cavity.

It is also stipulated that the discharge ignition voltage on the cavity $U_{fi}$ is determined according to Paschen's law or on the basis of reference data, and the discharge extinction voltage $U_{ei}$ is related to the polarization parameters of the insulation and the current-voltage characteristic (CVC) of the discharge [24]. If we pay attention to the fact that the process of partial discharges is a relaxation (transient) process of charging and discharging insulation through a cavity, one cannot ignore the requirement for the presence of initial conditions for the correct construction of a mathematical model. For this, it is necessary to add the initial condition $U_{0i}$ as one more parameter. The initial condition $U_{0i}$ is a random value and ranges from $-U_{fi}$ to $U_{fi}$.

The voltage across the cavity without the occurrence of PD in it $u_{pd.i}'$ (i.e. if $U_{fi} > U_{mi} + U_{0i}$) is described by the formula:

$$u_{pd.i}'(t) = u_{for.i}(t) + U_{0i}. \quad (1)$$

The voltage across the cavity ceases to be sinusoidal when partial discharges occur (Figure 2).

Figure 1. Integral picture of PD modeled in SimInTech software.

Figure 2 shows the dependence of the voltage on the cavity $u_{pd.i}(t)$ on time for the parameter values: $\{ U_{mi}; U_{fi}; U_{ei}; U_{0i} \} = 100: 80: 50: 40$, and also schematically shows the shape of the PD current pulse. On the X axis in relative units, the values of the ignition voltage $u_{pd.i}(t)$, the partial
discharge current \( i_{pd,i}(t) \) and the set of parameters \{ \( U_{mi}; U_{fi}; U_{ei}; U_{0i} \} \) for the \( i \)-th inclusion. The amplitude of the forced voltage on the cavity \( U_{mi} \) is taken as the base value for other voltage values.

Transient processes of changes in the voltage values on the cavity \( u_{pd,i}(t) \) from \( U_{fi} \) to \( U_{ei} \) and PD current \( i_{pd,i}(t) \) from \( I_{fi} \) to \( I_{ei} \) are observed during the onset and development of PD, where \( I_{fi} \) is the ignition current, \( I_{ei} \) - extinction current. To describe the change in the voltage across the cavity during a partial discharge and a partial discharge current in [24], the nonlinear CVC of a partial discharge and the following formulas were used:

\[
\begin{align*}
    u_{pd,i}(t) &= u_{fi} \cdot \exp\left(-t/\tau\right) \\
    i_{pd,i}(t) &= I_{fi} \cdot \exp\left(-t/\tau\right)
\end{align*}
\]

where \( \tau \) is the PD time constant, which is equal to \( \tau = \rho_i \varepsilon_i \), where \( \rho_i \) and \( \varepsilon_i \) are the resistivity and dielectric conductivity of the medium inside the inclusion, reflecting the presence of polarization losses.

Figure 2 shows that it is possible to algorithmically unambiguously form any correct sequence of PD pulses and determine the time moments of PD occurrence on the cavity using formula (1) and a set of parameters \{ \( U_{mi}; U_{fi}; U_{ei}; U_{0i} \} \). A correct PD pulse sequence is a potentially possible PD pulse sequence from a single PD source.

It is also assumed that: the time of the discharge process of a single PD is significantly less than the period of the operating voltage; values of ignition and extinction voltages do not change during PD; the external electric field is restored to its previous value almost immediately after the discharge is extinguished.

As a result, each cavity can be associated with four parameters \{ \( U_{mi}; U_{fi}; U_{ei}; U_{0i} \} \). The first three parameters contain the size of the cavity and its shape, geometric coordinates, the structure of the working field at a given point of the active part of the high-voltage device, the dielectric properties of the main insulation and cavities, the parameters of polarization insulation, and also indirectly manifest PD CVC properties.

The ability to compose correct sequences according to the model for cavities with different values of the set of parameters \{ \( U_{mi}; U_{fi}; U_{ei}; U_{0i} \} \) (and, consequently, with different cavity parameters and taking into account the stochastic PD component) makes it possible to isolate from the PD integral picture these correct sequences by the enumeration method going from the longest ones, and therefore associated with more dangerous defects, to the shorter ones. Thus, having isolated all the sequences from the integral picture, it can be defragmented (see Figure 3) and each cavity can be described separately.

![Figure 3. The result of differentiating the integral picture of PDs.](image)

4. Conclusion

As a result of considering various models, it can be concluded that there are many models designed to describe a specific aspect in PD processes. There are certain successes in describing the process of destruction of a solid dielectric and the process of PD development in a single cavity. However, none of the existing models can provide comprehensive information about the state of insulation. Therefore, further research in the field of partial discharges is needed. Solving the problem of the number of actually existing cavities (PD sources) in the insulation of high-voltage equipment, with the
subsequent determination of their parameters, is one of the promising areas of PD research. The quasi-deterministic model of the PD sequence provides a theoretical apparatus for answering this question by defragmenting the integral PD pattern.

5. References

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