The Problem of the Partial Discharge Sources Enumeration in the HV Devices Insulation

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***Abstract*—The partial discharge (PD) is defined in the international standard IEC 60270:2000 as a localized electrical discharge. The IEC definition is largely academic and it isn't oriented to practical purpose. It should be noted that the PD investigation is aimed to search for the (potential) defects that are PD sources and assess their dangers. The traditional PD conception is analyzed from this point of view. It is shown that if the theory of the apparent charge is useful for case of single discharge it is not useful in general for common case of the set of discharges.**

***Index Terms*—high voltage device, insulation, partial discharge, defect, PD source, PD set**

I. Traditional Conception of the Partial Discharges

General principles of the partial discharge measurements as a part of high-voltage test techniques states in the International Standard IEC 60270:2000 and other publications [1]-[3]. The partial discharge is defined as a phenomenon of "localized electrical discharge that only partially bridges the insulation between conductors and which can or cannot occur adjacent to a conductor" (definition 3.1). The definition is largely academic. It is not constructively because it isn't oriented to practical purpose. It should be noted that the partial discharge (PD) investigation is aimed to estimate of the high voltage (HV) device technical condition, or more accurately the aim is search for the (potential) defects that are PD sources and assess their dangers. Let us analyze the traditional PD conception from this point of view.

First we note that expression "PD source" (or its equivalent) is not found in the IEC 60270:2000 text at all. There are expressions "artificial discharge source", "sources of disturbances", "voltage source" "sources of error", "interference sources", but not "PD source". It is fundamentally because we are interested here in PD as the demonstration of the HV device (potential) defects but not PD as an electrophysical phenomenon. This question is formulated more wide in the [2]. There is: "The characteristics of the PD parameters depend on the type and location of defects, i.e., PD sources, in the insulation system".

The set of concepts offered by IEC Standard and other publications does not allow formulating and solving a number of problems related to the multiplicity and diversity of the PD.

General principles of the PD study are based now in the "apparent charge" conception proposed about 80 years ago. The model of the apparent charge creates the illusion of technical simplicity and correctness. It implicitly relies on the assumption of the electric field homogeneity, the uniqueness of the potential defect and information of its location. It can say that the techniques of diagnosing based on the "apparent charge" of the PD in the simplest cases are effective enough.

But in [1]-[3] it was shown the PD model on the basis of the concept of "apparent charge" for more complex cases is useless. Without discussing details we make several important remarks. First, the construction of an equivalent circuit for multiply PD sources and multiply calibrations requires the specification of the numerical values of the element parameters. Unfortunately, such objective data are usually not available and this task is almost impossible. Second, when applying the matrix description, it finds out that in the calibration process and in the PD registration process are activated different impedance matrixes. These matrixes are independent and it is not clear to make a decision about appointment rules of the "apparent" charges and what is its relation to the true charges. It concludes the development of the PD model on the basis of the concept of "apparent charge" for multiply defects is useless.

The interest in multiply PD research is increasing in recent years. There are some approaches to solve a problem of the multiple partial discharge sources. There are using time frequency sparsity roughness mapping, clustering techniques, self-adaptive partial discharge signal de-noising based on ensemble empirical mode decomposition and automatic morphological thresholding, using the wavelet and mathematical morphology, time-frequency sparsity map on automatic partial discharge sources separation, time-frequency representation of PD-induced ultra-high frequency signal and PD current pulse and other [4]-[16]. This article reflects the approaches of the authors in this field [17]-[19].

II. PD Sources and PD Set

The real HV device under operation voltage generates a set of partial discharges (PD). The integration pattern of

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the PD set is very complex 3-dimension (3D) diagram (Fig. 1).

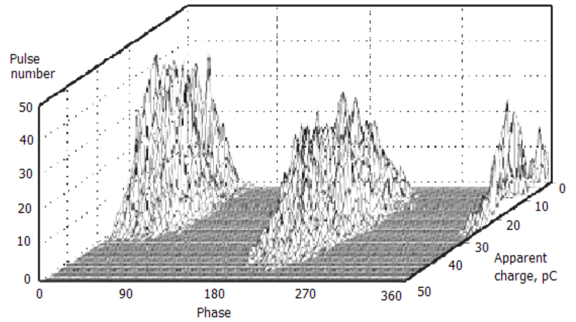

Fig. 1. Examples of the PD set representation in the real HV device

The traditional integral pattern of the PD apparent charge represented to further meaningful analysis, as a rule is the 3D function of the set of PD pulses in the coordinates time - apparent charge - pulse number. There are a sufficient number of methodologies, recommendations and normative documents (for example, manuals for using various technical means of measurement and control) to interpret this pattern in order to obtain some meaningful assumptions about the sources of the PD or numerical assessments of the dangers of these phenomena.

However, highly qualified specialists are aware of the fact that in this area there is still no sufficient clarity. This problem here can be briefly formulated by the following pair of question. How many PD pulses are there? And how many PD sources does this pattern reflect?

For concreteness, let us consider a simplified problem. Suppose the series of M approximately equal PD pulses is recorded during the operation voltage period. The question is which one of the three hypotheses is correct: either a sole (potential) defect generates the PD series of the all M pulses, or N different defects each with single PD are there in the active insulation space, or this is an intermediate option and there are $N<M$ PD sources with shorter PD series? It is clear the fault danger assessments in these three cases are very different.

The solution this problem requires to construct a new generalized concept of analysis of multiple PD. It is necessary to develop principles by which it is possible to isolate subsets of pulses corresponding to a certain defect from the total PD set.

III. An Approach to PD Sources Recognition

We consider the PD set as the technical process in the HV device which demonstrates the (potential) defects (or inclusion) but not PD as an only electro-physical phenomenon. To PD sources recognition as defects and its classification it is necessary to enumerate main properties of defects. There are: size of defect, its shape, geometrical coordinates in the device active space, electric field strength in its nearest neighborhood, PD breakdown voltage, PD extinction voltage. These factors all together and each separately can be as classification properties. However they must be associated with the PD measured parameters and the association must be mathematically formalized. In our opinion the foundation of the solving question under consideration can be conception PD process as a quasi-deterministic process [17], [18].

It considers the space in the active volume of the equipment element, which is filled with an insulating dielectric material. Sinusoidal operating voltage creates an operating alternating electric field in the insulation

$$\mathbf{E}(x,y,z,t):=\mathbf{E}_m(x,y,z)\,\sin(\omega t)$$

The most important parameter of each kth (k=1, 2, ⋯, N) inclusion is the magnitude of the forced electric field at its location E_{mk}. And if d be typical defect size we can introduce forced inclusion voltage:

$$v_{fk}(\omega t) = d\ E_{mk}\sin(\omega t) \ = V_{fmk}\sin(\omega t). \qquad (1)$$

Each real inclusion voltage as a time function $v(t)$ represents a relaxation charging insulating process and discharging it through the inclusion. PD in the inclusion arises if the inclusion voltage $v(t)$ reaches breakdown (ignition) voltage V_b. It is determined on the basis of reference data and depends on defect electro physical properties. The PD current is a short exponential impulse and as a result the PD voltage it falls to extinction voltage V_e. It is possible to think the PD extinction voltage to be depended on the inclusion burning voltage-current relation and the polarization component of the insulation dissipation factor δ.

Thus, each inclusion uniquely associates with set of energy parameters $\mathbf{V}_k=\{V_{mk},V_{bk},V_{ek}\}$. In this trio together related parameters indirectly include geometric coordinates, the pattern of the operation electric field at a given point of the active area of the transformer, the typical inclusion size and its shape, the dielectric properties of the basic insulation and inclusion, the polarization parameters of insulation, as well as the properties of the PD current-voltage characteristics.

IV. Quasideterministic PD Process

Each real kth inclusion voltage as a time function $v_k(t)$ represents a relaxation charging insulating process and discharging it through the inclusion. The process $v_k(t)$ is non-sinusoidal and there is no guarantee that the actual voltage $v_k(t)$ is a periodic, but we can consider it as a quasi-periodic.

PD processes are transient, so that in this context it is impossible to ignore the fundamental requirements of the initial conditions. Here it should be noted that the values of the initial conditions are random. Voltage $v(t)$ is dependent on the parameters of (kth) inclusion $\mathbf{V}_k=\{V_{mk},V_{bk},V_{ek}\}$ and as well as on the initial conditions V_0:

$$v_k(t)=f\left(V_{mk},\ V_{bk},\ V_{ek},V_{0k},t\right).$$

Calculation begins from time t = 0; the voltage continues to change according to the law

$$v_k(t)=v_{fk}(t)\ +V_{0k}$$

up to the moment t_{1bk} when it achieves ignition PD voltage V_{bk} and breakdown occurs. PD current very rapidly attenuates according to the exponential law and the voltage $v_k(t)$ falls down to extinction voltage V_{ek}.

Follow [17], [18] we can write the general recurrent formulae for inclusion voltage where index j used to indicate the next discharge pulse number:

$$\begin{aligned} v_k(t) &= v_{fk}(t) - v_{fk}\left(t_{k(j-1)}\right) + \\ &\quad \text{sign}[\cos(\omega t_{k(j-1)})]V_{ek}, \quad t_{j-1} < t < t_j \\ v_k\left(t_{kj}^-\right) &= \text{sign}[\cos(\omega t_{kj})]V_{bk} \\ v_k\left(t_{kj}^+\right) &= \text{sign}[\cos(\omega t_{kj})]V_{ek} \end{aligned} \quad (2)$$

The instant t_{kj} is determined from the relation:

$$\begin{aligned} t_{kj} := \min_t \Big\{ &\text{abs}\left[v_{fk}(t_{kj}) - v_{fk}(t_{k(j-1)}) + \right. \\ &\left. \text{sign}\left[\cos(\omega t_{kj})\right] V_e \right] = V_b \Big\}, \ t_{kj} > t_{k(j-1)} \end{aligned} \quad (3)$$

The function of burning current of the jth PD is written as:

$$\begin{aligned} i_{kj}(t) &= I_k \exp\left((t_{kj} - t)/t\right)[\mathbf{1}(t - t_k) - \\ &\quad \mathbf{1}\left(t - t_{kj} - t_b\right)] \ \text{sign}\left[\cos(\omega t)\right] \end{aligned} \quad (4)$$

where I_k is the initial (maximal) value of the PD current ignition, $\mathbf{1}(t)$ is the unit step function, τ is the PD burning time constant, and τ_b is the PD burning time.

A series of the PD current pulses in the kth inclusion is specified as a sequence:

$$\begin{aligned} \mathbf{I}_k(t) &= \left\{ I_k, \ \{t_{kj}\} \right\}, \\ &\text{for } k = 1, \ 2, \ \cdots, N, \ \ j = 1, \ 2, \ \cdots, k \end{aligned} \quad (5)$$

For example, the function of the inclusion voltage $v_k(\omega t)$ and PD current $i_k(\omega t)$ are shown in Fig. 2. Number of the PD pulses per period depends on the energy parameters are:

$$n_{k1} = n_{k1}(V_{mk}, V_{bk}, V_{ek}) = (V_{mk} - V_{bk})/(V_{bk} - V_{ek}). \quad (6)$$

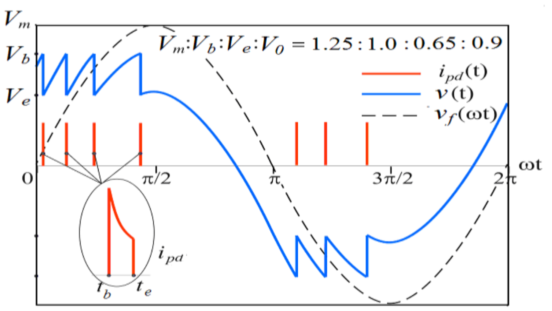

Fig. 2. Example of the PD main functions representation.

The voltage $v_k(t)$ and $i_{pdk}(t)$ as a time function with 4 parameters of the PD process $(V_m, \ V_b, \ V_e, \ V_{0k})$ are illustrated on the Fig. 2. It is clear, the increase of the force voltage V_m increases the number of series impulses, the decrease of the extinction voltage V_e reduces the number of series impulses, and variation of the initial condition V_0 moves the PD set.

As a conclusion of the PD quasi-deterministic model consideration we can say if would be assigned the energy coordinates and the electro physical properties of defects then the problem of analytical or numerical calculation process of all the PD sequence could be resolved unambiguously. In this sense, the PD process will be called quasi deterministic.

V. The Set of PD Sources and the Pattern of the PD Pulses

The general view of the PD pulses pattern is the sum all of the registered current pulses (7) initiated by PD sources:

$$\mathbf{I}_{\text{pat}} = \sum_{k=1}^{N} h_k \mathbf{I}_k = \sum_{k=1}^{N} h_k \left\{ I_k, \ \{t_{kj}\} \right\}, \ (j = 1, 2, \cdots, n_k) \quad (7)$$

where h_k is the attenuation constants.

Visually this picture can be represented in the form of Fig. 1 or if for simplicity we confine ourselves to one period, then we obtain the pattern in the form like Fig. 3.

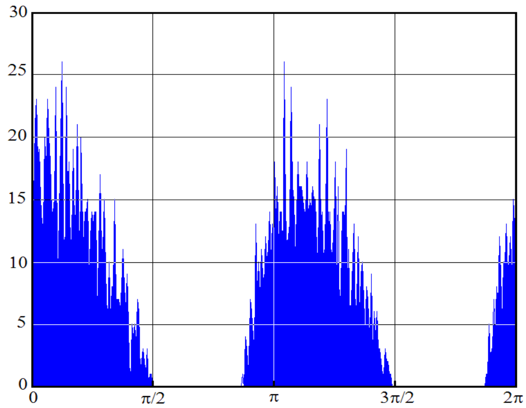

Fig. 3. Example of the 2-d PD current pulses pattern.

The diagnostic problem is to divide this complex pattern to parts which are corresponded to separate PD sources. The question is if the considerable observed pulse sequence has approximately equal amplitude of the PD pulses. Here the question arises: how many PD sources does this pattern reflect? We should take attention that all of attenuation constants h_k are unknown and pulse amplitudes are non-informative.

The set (sequence) of the PD current pulse time moments are here the main informative factor.

VI. The PD Series Decomposition

Let us return to equation (8) in which we see the set $\{t_{kj}\}$ for k=1, 2, ⋯, N, j=1, 2, ⋯, N_k, and $t_{kj} \in T_0$ (T_0 is an observation time) corresponds to kth potential defect.

Following [19], let us call the set $\mathbf{T}_k = \{t_{kj}\}$ as a right PD pulse sequence (right sequence) if it corresponds any PD current pulses. It is easy to show that not every time moment sequence is a right sequence.

Turning to the previous section and remembering that set of the voltage parameters $(V_m, \ V_b, \ V_e, \ V_{0k})$ generates the set **T**, we can introduce to consideration conception of a PD transformation, calling it **PDT**. It is shown with the expression (with the relative values, V_{bk}^{*}=1):

$$\begin{aligned}\mathbf{T}_k &= \mathbf{PDT}(V_{mk},\ V_{bk},\ V_{ek},\ V_{0k}) \\ &= \mathbf{PDT}(V_{mk}^{*},\ V_{bk}^{*},\ V_{ek}^{*}, V_{0k}^{*}) \\ &= \mathbf{PDT}(V_{mk}^{*},\ 1,\ V_{ek}^{*}, V_{0k}^{*})\end{aligned} \quad (8)$$

The operation when the set (trio) relative voltages (V_{mk}^{*}, 1, V_{ek}^{*}, V_{0k}^{*}) are found from set of pulse time moments $\mathbf{T}_k$ we will call an inverse PD transformation $\mathbf{PDT}^{-1}(\mathbf{T}_k)$ =(V_{mk}^{*}, 1, V_{ek}^{*}, V_{0k}^{*}).

But not for every sequence $\mathbf{T} \in T_0$ is possible the inverse transformation $\mathbf{PDT}^{-1}$ (or not every sequence **T** is Right sequence).

Now we can formulate the source diagnosis problem. We have registered current pulse sequence $\mathbf{T}_0$ ($|\mathbf{T}_0|=M$) and pulses have approximately equal amplitudes. And it is the question: how many PD sources does this pattern reflect? The answer to the question is theoretically given by [19]. We can make the exhaustive search of the subsets of the set $\mathbf{T}_0$. If any set $\mathbf{T}_s$ is subset of $\mathbf{T}_0$ we can apply inverse PD transformation $\mathbf{PDT}^{-1}(\mathbf{T}_s)$ and verify whether it is the set $\mathbf{T}_s$ corresponds to the Right sequence or not. At the end of this procedure we have presentation of the set $\mathbf{T}_0$ in the form:

$$\mathbf{T}_0 = \cup\, \mathbf{T}_k, \quad (k = 1, \ldots, N),$$

and we have search N independent sources, each of them generates the pulse sequence of the N_k pulses.

VII. Example

Let us give an example of the mathematical modeling results. As the basis of the decomposition the set of the 32 PDs with correspondence equations (1) to (4) is generated as:

$$\begin{aligned}\mathbf{T}_0\{t_j\} = \{&133,\ 344,\ 472,\ 541,\ 643,\ 834,\ 835,\ 969, \\ &1162,\ 1253,\ 1297,\ 1350,\ 1568,\ 1846, \\ &1895,\ 2019,\ 2500,\ 5267,\ 5521,?\,5541, \\ &5834,\ 5835,\ 5912,\ 6098,\ 6162,\ 6188, \\ &6350,\ 6568,\ 6639,\ 6660,\ 7039.\ 7500\} \\ &\text{for } (j = 1, 2, \cdots, 32);\end{aligned}$$

Here one period corresponds to 10^4 points and all t_j are the numbers of PD points (Fig. 4).

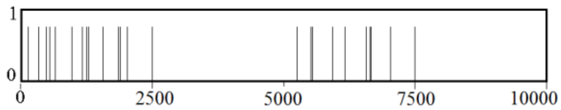

Fig. 4. The set of the 32 PDs.

For the decomposing this series, we create an auxiliary data base for V_m=1.1, 1.2, 1.3, 1.4, 1.5, V_b =1, V_e=0.75, V_0= 0.1, 0.2, ···, 0.9 (Table I).

Any PD sequence is declared as a right sequence if it corresponds any string in the data base.

TABLE I: DATA BASE FOR EXAMPLE

V_m	V_0	Right PD sequences (marked strings correspond to example answer)									
1.1	0.1		1526	6406	7500						
1.1	0.2	*	**1297**	**2019**	**6098**	**6660**					
1.1	0.3		1098	1660	6297	7019					
1.1	0.4		919	1406	2500	6007	6526				
1.1	**0.5**		751	1195	1817	6195	6817				
1.1	0.6		593	1007	1526	6406	7500				
1.1	0.7		440	834	1297	2019	6098	6660			
1.1	0.8		291	671	1098	1660	6297	7019			
1.1	0.9		145	516	919	1406	2500	6007	6526		
1.2	0.1		1350	2039	5834	6253	6846				
1.2	0.2		1162	1696	5992	6454	7500				
1.2	0.3		992	1454	2500	5758	6162	6696			
1.2	0.4		834	1253	1846	5912	6350	7039			
1.2	0.5		685	1075	1568	6075	6568				
1.2	0.6		541	912	1350	2039	5834	6253	6846		
1.2	0.7		403	758	1162	1696	5992	6454	7500		
1.2	0.8		267	612	992	1454	2500	5758	6162	6696	
1.2	**0.9**	*	**133**	**472**	**834**	**1253**	**1846**	**5912**	**6350**	**7039**	
1.3	0.1		1218	1728	5764	6135	6606				
1.3	0.2		1055	1497	2500	5563	5905	6305	6872		
1.3	0.3		905	1305	1872	5696	6055	6497	7500		
1.3	0.4		764	1135	1606	5834	6218	6728			
1.3	0.5		629	979	1397	2058	5629	5979	6397	7058	
1.3	0.6		498	834	1218	1728	5764	6135	6606		
1.3	0.7		371	696	1055	1497	2500	5563	5905	6305	6872
1.3	0.8		246	563	905	1305	1872	5696	6055	6497	7500
1.3	0.9		123	434	764	1135	1606	5834	6218	6728	
1.4	0.1		1112	1535	2500	5403	5705	6039	6439	7074	
1.4	0.2		969	1350	1895	5521	5834	6188	6639		
1.4	0.3		834	1188	1639	5643	5969	6350	6895		

1.4	0.4		705	1039	1439	2074	5462	5769	6112	6535	7500		
1.4	**0.5**		582	900	1267	1757	5582	5900	6267	6757			
1.4	0.6		462	769	1112	1535	2500	5403	5705	6039	6439	7074	
1.4	0.7	*	**344**	**643**	**969**	**1350**	**1895**	**5521**	**5834**	**6188**	**6639**		
1.4	0.8		229	521	834	1188	1639	5643	5969	6350	6895		
1.4	0.9		114	403	705	1039	1439	2074	5462	5769	6112	6535	7500
1.5	0.1		1025	1391	1916	5375	5655	5959	6311	6783			
1.5	0.2		896	1235	1669	5485	5773	6092	6476	7088			
1.5	0.3		773	1092	1476	2088	5321	5598	5896	6235	6669		
1.5	0.4		655	959	1311	1783	5430	5714	6025	6391	6916		
1.50	**0.5**	*	**541**	**834**	**1162**	**1568**	**2500**	**5267**	**5541**	**5834**	**6162**	**6568**	**7500**
1.5	0.6		430	714	1025	1391	1916	5375	5655	5959	6311	6783	
1.5	0.7		321	598	896	1235	1669	5485	5773	6092	6476	7088	
1.5	0.8		213	485	773	1092	1476	2088	5321	5598	5896	6235	6669
1.5	0.9		107	375	655	959	1311	1783	5430	5714	6025	6391	6916

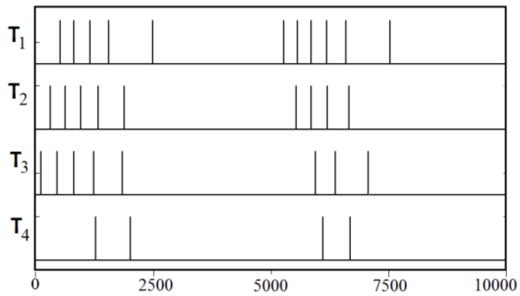

Fig. 5. The set of numbers of the 4 right PD sequences.

As a result of PD composition we divide all of 32 PDs to 4 series which associate with different defects (Fig. 5).

$$\mathbf{T}_1\left\{t_{1j}\right\} = \{541,\ 834,\ 1162,\ 1568,\ 2500,\ 5267,\ 5541,\ 5834,\ 6162,\ 6568,\ 7500\}$$
$$\left(V_m,\ V_0\right) = \left(1.5,\ 0.5\right);$$
$$\mathbf{T}_2\{t_{2j}\} = \{344,\ 643,\ 969,\ 1350,\ 1895,\ 5521,\ 5834,\ 6188,\ 6639\}$$
$$\left(V_m,\ V_0\right) = \left(1.4,\ 0.7\right);$$
$$\mathbf{T}_3\{t_{3j}\} = \{133,\ 472,\ 834,\ 1253,\ 1846,\ 5912,\ 6350,\ 7039\}$$
$$\left(V_m,\ V_0\right) = \left(1.2,\ 0.9\right);$$
$$\mathbf{T}_4\left\{t_{4j}\right\} = \left\{1297,\ 2019,\ 6098,\ 6660\right\}$$
$$\left(V_m,\ V_0\right) = \left(1.1,\ 0.2\right);$$
$$\mathbf{T}_0 = \cup\,\mathbf{T}_k,\ \ (k = 1, 2, 3, 4).$$

The first and second defects generate 11 and 9 PDs, respectively, and represent the greatest danger.

VIII. Conclusion

The International standard IEC 60270:2000 doesn't provide an idea of the PD sources and it is necessary to develop corrections. In the real case there may be many sources and consideration of this factor seems to be very important. Introduction of the concept of the PD process as quasi-deterministic process allows us to advance the PD theory. The idea of mathematical PD transformation is introduced for the purpose of extraction of individual sources.

Acknowledgment

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