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Review

Review on Detection and Analysis of Partial Discharge along Power Cables

Xiaohua Zhang [1], Bo Pang [1], Yaxin Liu [2], Shaoyu Liu [3], Peng Xu [1], Yan Li [4,*], Yifan Liu [4], Leijie Qi [4] and Qing Xie [4]

[1] State Grid Jibei Electric Power Company Limited, Beijing 100054, China; zhang.xiaohua@jibei.sgcc.com.cn (X.Z.); pang.b@jibei.sgcc.com.cn (B.P.); academicpaperjibei@163.com (P.X.)
[2] State Grid Jibei Electric Power Company Limited Smart Distribution Network Center, Qinghuangdao 066199, China; liu.yaxin@jibei.sgcc.com.cn
[3] State Grid Qinhuangdao Electric Power Supply Company, Qinghuangdao 066099, China; liu.shaoyu@jibei.sgcc.com.cn
[4] School of Electrical and Electronic Engineering, North China Electric Power University, Baoding 071003, China; 220192213307@ncepu.edu.cn (Y.L.); 220192213283@ncepu.edu.cn (L.Q.); xieqing@ncepu.edu.cn (Q.X.)
* Correspondence: yan.li@ncepu.edu.cn

Abstract: Partial discharge (PD) detection and analysis plays a crucial role for acceptance testing and condition monitoring of power cables. Various aspects are related to PD in power cables from theory to practice. This paper first summarizes the PD mechanism and models used for PD analysis in power cables. Afterwards, PD detection is addressed in the aspects of off-line test, on-line test, and sensors. PD analysis is discussed in detail. Specifically, related quantities and algorithms for PD analysis are outlined. PD characteristics with affecting factors, e.g., dielectric type, load, and applied voltage are discussed. Experience on PD development trend with measurements in field is analyzed. Based on the comprehensive review, challenges of PD detection and analysis along a power cable are proposed.

Keywords: modeling; monitoring; parameter estimation; partial discharges; power cable insulation; transmission lines

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1. Introduction

Partial discharge (PD) is a breakdown that occurs in part of the insulating material caused by overhigh electric field. It is widely used in power equipment testing and diagnostics since it is a widely accepted indicator for defects.

The research on measurement and location of partial discharge phenomena started from the early 1940s [1]. A large amount of work has been undertaken regarding PD from modeling to measurement since then. The International Electrotechnical Commission (IEC) adopted the nomenclature "partial discharges" in 1967, which helps to formulate the relevant research [2].

PD can happen wherever there is an insulation defect, from gas insulated to oil insulated to solid insulated equipment. Different equipment with various structures and insulation materials may show different PD characteristics. Reviews of PD for different power equipment exist, e.g., for transformers [3,4] and gas insulated switchgear [5].

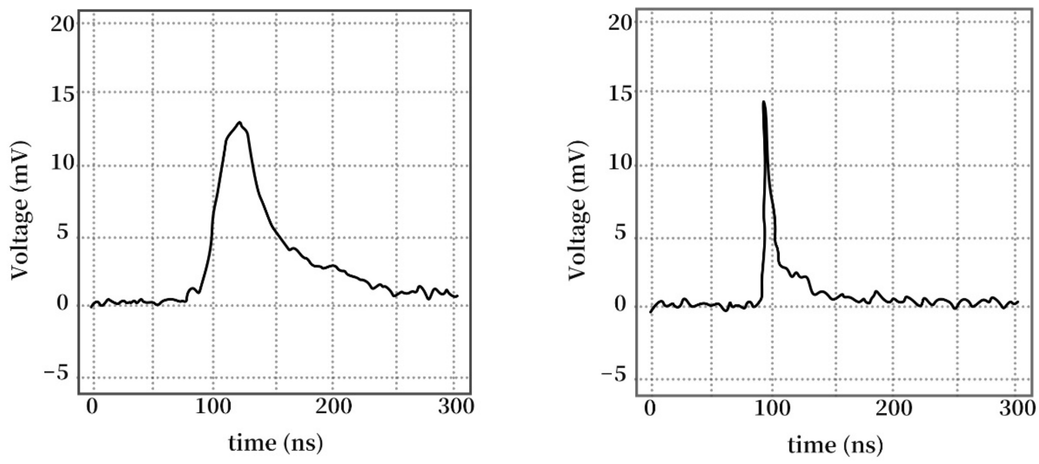
Power cables refer to medium voltage and high voltage power cables with the related accessories. They are essential components in power systems. PD detection and analysis plays a vital role for power cable diagnostics. Though reviews about PD are available in the literature, this paper focuses on PD detection and analysis in power cables, which has not been reported in depth previously [6,7]. A large amount theoretical and practical work has been performed for PDs in power cables. From the theoretical point of view, different models with various emphases are proposed to reveal the PD phenomenon. Artificial defects can be created in a laboratory to generate PDs for model validation [8]. In practice, off-line tests for PDs are commonly employed and on-line monitoring is developing fast due to its in-time characteristics. However, interpreting the practical measurement results on defects of cables in service is much more complicated. With development of new application scenarios, e.g., DC cables, more research on cable PD detection and analysis is needed. This paper tries to cover both theoretical and practical aspects of PDs along cables by giving a comprehensive review on the present literature. The paper is organized as follows: partial discharge phenomenon, models, typical location, and propagation along power cables are reviewed in Section 2. Detection is discussed in Section 3. Afterwards, the PD analysis is summarized in Section 4. Section 5 proposes the challenges and Section 6 is the conclusion.

2. Partial Discharge Model

There is no clear distinction between PD models for power cables and other power equipment. Still, details need to be noted and clarified for PD in power cables, e.g., typical PD location. A different feature of PD in cables compared with other equipment is that the cable's coaxial structure forms a natural propagation channel for electromagnetic waves and since PD is typically a narrow pulse containing high frequency components, it can be regarded as an electromagnetic wave. Thus, PDs originating in the cable can travel within the transmission line. Given the determined cable system as a travelling path, it allows to quantify the PD magnitude in terms of pC and therefore comparing PD magnitudes obtained from different cable systems is possible. This section briefly reviews aspects of the partial discharge phenomenon and model.

2.1. Partial Discharge Phenomenon

Two conditions must be fulfilled for partial discharge occurrence. (1) An initial electron must exist for ionization avalanche. (2) The electric field in the specific spot must be higher than the inception field [9]. The emission of initiatory electrons from the cathode is a stochastic process [10,11]. Thus, after the ignition voltage has been reached, an avalanche will start after a time delay τs. In practice, τs can be expected to be in the order of milliseconds, several orders of magnitude larger than the formation time of an electron avalanche [11–13]. In the literature, different discharge mechanisms were described with different nomenclature [11], from "Townsend-like" [14], "streamer-like" [14] to "glow" [15] "pseudo-glow" [15] and "swarming micro partial discharge" [16]. Reference [17] gives an overview of different definitions, in which the author claimed that explanations of all different PD phenomena should be studied in terms of Townsend and/or streamer discharge. Townsend discharge has the large pulse width and short height while streamer discharge has a fast rise time and short tail. Figure 1 shows a typical comparison between these two kinds of discharge. A criterion to distinguish such phenomena is proposed by different researchers, e.g., Penning claimed a streamer when the number of electrons per avalanche is between 10^8 and 10^9 [18]. Raether regarded pulse risetime less than 3 ns as an indicator for streamer [19].



(**a**) (**b**)

Figure 1. (**a**) Townsend type partial discharge. Reprinted from Ref [20]. (**b**) streamer type partial discharge. Reprinted from Ref [20].

2.2. Partial Discharge Model

Partial discharge can be subdivided into corona discharge, surface discharge, and internal discharge [21]. Corona discharge is a discharge caused by the air ionization near the high voltage electrode [22]. It is argued that corona discharges are not directly related with cables but may originate from the cable terminal connections such as switchgear [23]. Surface discharge occurs along the surface of a dielectric material and quite often at the interface between two materials. Power cables, especially cable joints are made of several layers of solid dielectric materials. Thus, surface discharge is one of the main reasons for cable failure [24]. Internal discharge happens within dielectrics with low strength. Crack, contamination, air void, and trees, etc., can cause internal partial discharge.

Various models have been developed for PDs with different study intentions. More literature focuses on the internal PD compared with surface or corona discharge [25], especially discharge in void. For internal PD, a widely used model is the three-capacitance model or abc-model proposed by Whitehead in 1951 [26]. Since then, capacitor model is commonly used to represent the partial discharge process [27–29]. Development on the capacitor model was continued by later researchers. For example, integral equations and Monte Carlo simulation are integrated into the abc-model to represent the PD statistical distribution [30,31]. However, there are arguments about the model [32–34], which claims that the capacitive network model is not capable of representing the partial discharge physics. One solid reason is that the potential along the cavity surface is not equal when a PD happens [34,35]. Instead, induced charge theory is used to model the partial discharge phenomenon [36–39]. The induced charge is defined as the difference between the charge on the electrode with and without a discharge event [32]. Rather than circuit based as the capacitor model, this model is field based and analytical solutions can be derived with defined defect geometries in the cable [25]. The main equation is shown in (1), where ρ is volume charge density and σ is surface charge density. λ is a function satisfying the Laplace equation.

$$Q = -\iiint \lambda\rho dV - \iint \lambda\rho ds \tag{1}$$

However, it is unrealistic for the model to consider a uniform surface charge distribution on the cavity surface. The particle in cell (PIC) method is also used for internal PD simulation [40]. This method was initially accepted as a simulation tool for plasma in the late 1950s. The method follows the trajectories of charged particles and computes the electromagnetic or electrostatic field in a mesh [41]. Macro-quantities such as current density are derived from the velocity and position of these particles [42,43]. Fluid model is another modeling approach for internal PD. This model utilizes drift-diffusion equations to simulate the generation, movement, and dissipation of the charged species (electron, positive and negative ions). Furthermore, Poisson's equation is needed to determine the distribution of the electric field in the void [44]. Moreover, finite element analysis (FEA) can be used for PD simulation. The advantage of using the FEA method is that field distribution can be obtained, from which an insight of pre-discharge condition can be observed. FEA models can be categorized into electric current model and electrostatic model. In the electric current model, the gas dielectric breakdown within the cavity is simulated by increasing the gas conductivity [25]. In the electrostatic FEA model, a PD event is simulated by increasing the charge density along the void surface until the field across the void becomes lower than the extinction field [45]. Multiphysics can also be added to the model, e.g., the electric field distribution and the temperature. However, long time consumption is the disadvantage of the FEA method [46]. As for surface and corona discharge, similar approaches exist. RC network is used for modeling corona and surface discharge from the equivalent electric circuit point of view, corresponding to the abc-model for internal discharge [47,48]. Particle in cell (PIC) model, fluid model, and FEA based models are also used for corona and surface discharges. The advantages and disadvantages for each model are summarized in Table 1.

The chosen modeling approach mainly depends on the researcher's objective. For instance, efficient simulation for macroscopic parameters, e.g., repetition rate, without representing the PD physical process can be achieved by the abc-model. While, research on microscopic processes incorporating charged particles can refer to the fluid model. It should be noted that there is no perfect model yet and great potential exists to improve the modeling approach and this is discussed further in Section 5.

Table 1. PD models summary with advantages and disadvantages.

Model	PD Type	Advantages and Disadvantages
abc-model	Internal PD	+ Easy to understand and implement. − Cannot represent the physics behind the discharge.
Induced charge	Internal PD	+ Analytical solutions can be derived. − The model is developed with the following restrictions: uniform electric field inside the void. The electric field in the bulk of the solid dielectric remains the same during a PD event [49].
RC network	Corona [47] and surface PD [48]	+ Simple implementation. − Circuit model cannot completely reveal the physical process.
Particle in cell (PIC)	Surface PD [50], corona PD [51], and internal PD [40]	+ Clear physical interpretation and easy implementation. − The method requires a large amount of computation resources and converges slowly [43].
Fluid model	Surface PD [52], corona PD [43], and internal PD [53]	+ Microscopic physical processes of a PD can be obtained. − The stochastic characters are not taken into account [54]. Large computation consumption. Impractical in ageing and multiple PD analysis where simulations for a large number of power frequency AC cycles are required [25].
Finite element analysis	Corona PD [55], surface PD [56], and internal PD	+ Electric field in geometry can be derived without restrictions on the geometry or uniformity of electric field distribution. Non-linear or anisotropic media could be considered [25]. − Time consuming and there is lack of reliable knowledge on input parameters.

2.3. *Partial Discharge Location and Propagation*

PD often occurs in accessories of power cables, e.g., joints and termination [24]. Due to more complex structure and material design, the electrical field can be considerably higher to trigger PD to occur. A stress-relief cone with a specially designed shape and dielectric material is designed to reduce the electric stress in the accessories. A typical cable joint design is shown in Figure 2. Moreover, improper handling during installation can create defects leading to PD also. It has been reported that for the high voltage corrugated aluminum sheath cables, discharge is observed between the sheath and water blocking layer, whose mechanism is still under investigation [57,58]. Figure 3 shows these typical phenomena.

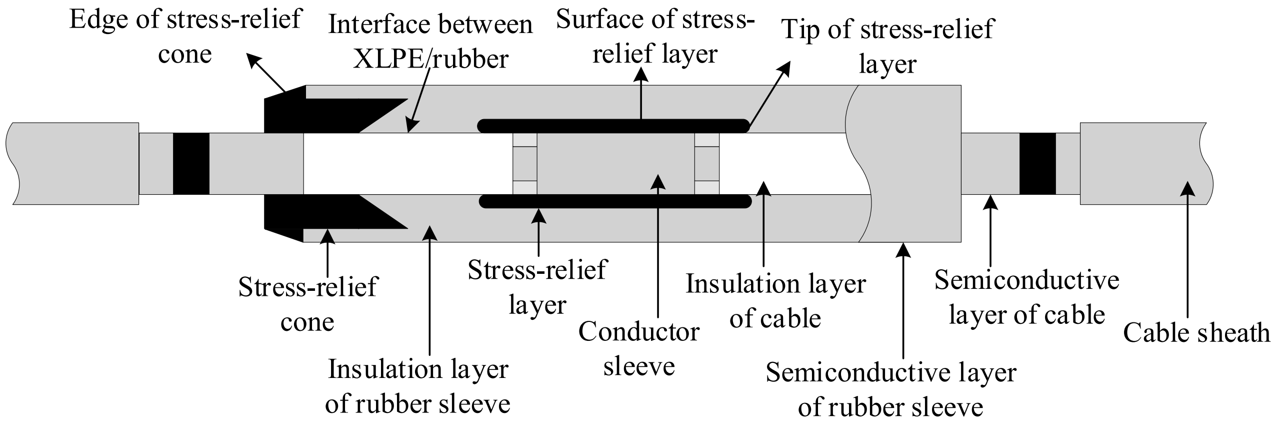


Figure 2. Illustration of cable joint design for electric stress control.

Figure 3. (**a**) Discharge at the distribution cable joint. Reprinted from Ref [59]. (**b**) discharge at the buffer layer under corrugated aluminum sheath.

As long as PD occurs in power cables, it will propagate along the cable, which shall be considered as a transmission line. Lumped parameters model [60], Bergeron model [61], and frequency dependent model [62] are the three mainly used models to describe the cable's transmission line behavior. The lumped parameter model can only be used when the cable length is short enough that the propagation time of PD along the cable can be ignored. When the cable is sufficiently long, the distributed parameter model shall be used. The Bergeron model can reveal the time delay along the cable caused by PD propagation. However, it considers the line losses by lumped resistance at cable ends. The frequency dependent model is the most accurate one to model a transmission line in which the distributed parameters vary with frequency. For a single-core cable, there is one propagation path for the PD between the conductor and the earth shield. For multi-core cables, the propagation modes become complex and mathematical treatment can be utilized to decouple these channels. For instance, phase to phase and the shield to phase channel can be accessed for the three-core cables [63]. For PDs in the power cable, the propagation effect is vital since it affects the senor location, detection accuracy, etc.

3. Partial Discharge Detection

A power cable normally has to experience several tests from manufacturing to service, such as type test for the qualification, sample test and routine test in the production period, and after lay test. There are different standards existing to regulate these tests from

IEC standards, European standards to IEEE standards. The most applied international standards can be categorized according to nominal voltage:

- 1 and 3 kV, IEC 60502-1,
- 6–30 kV, IEC 60502-2/4 and VDE 278,
- 30–150 kV, IEC 60840,
- 150–500 kV, IEC 62067.

Although the contents differ from different standards, a partial discharge test exists in all standards above 3 kV and it plays a crucial role in the cable tests.

Partial discharge is such a complex phenomenon that it is extremely difficult to reproduce the PD detection measurement. A specimen tested in rapid succession often exhibits variation in the detected discharge amplitudes at the inception voltage. Additionally, the inception and extinction voltage for discharge slightly differ for every applied voltage excursion [64]. The reasons may be in part due to changes in the cavity configuration, e.g., wax formation within the voids in the oil-impregnated insulation cable, statistical variations in the discharge process, vapor pressure, and gas composition changes within the cavities. The nature of the cavity wall may change due to pitting and erosion as well as the deposition of compounds on the walls [64–66]. Despite the difficulties, PD is still employed as a parameter for condition measurement [67–69]. Compared with oil/paper insulated cables, polymeric cables are strongly susceptible to degradation induced by PD. Thus, the polymeric cables are required to be free of PD at operating voltage with a detection sensitivity of 5 pC [70].

Partial discharge in the solid insulation is a transient process and it can reach several hundred MHz [71], even up to 1 GHz [70,72]. The measured charge is so-called apparent charge [27]. Both inductive and capacitive sensors can be applied for PD detection, which will be discussed in detail below.

3.1. Off-Line Test

There are on-line PD tests and off-line PD tests for power cables. The partial discharge test circuit was reviewed in [15]. For the off-line test, several options are available with the difference of how to energize the cable. Since the power source can be the bottleneck for the off-line test and the off-load cable can be considered as a capacitor, it is crucial to decrease the demanded capacitive power from the source to energize the cable and hence to reduce the cost and weight of the test equipment. Three types of tests are generally adopted for the off-line test, namely the alternating current (AC) voltage test, very low frequency (VLF, for instance 0.1 Hz) test, and damped AC (DAC) test. The methods are listed in Table 2 [73]. To ensure well comparable test results, the PD measuring circuit is specified in Standard IEC 60270. The PD measuring circuit commonly used is shown in Figure 4, where U is the high-voltage supply, Zmi is the input impedance of measurement system, CC is the connecting cable, Ca is the test object, Ck is the coupling capacitor, CD is the coupling device, MI is the measurement instrument, and Z is the filter.

Table 2. Different off-line PD tests.

System	Source	Main Parameters
AC voltage test	Alternating current voltage with resonant test system	Test voltage and test frequency
VLF test	Very low frequencies down to 0.01 Hz	Test voltage and test duration
Damped AC test	Damped alternating current at frequencies between 20 and 500 Hz	Test voltage, frequency, and damping

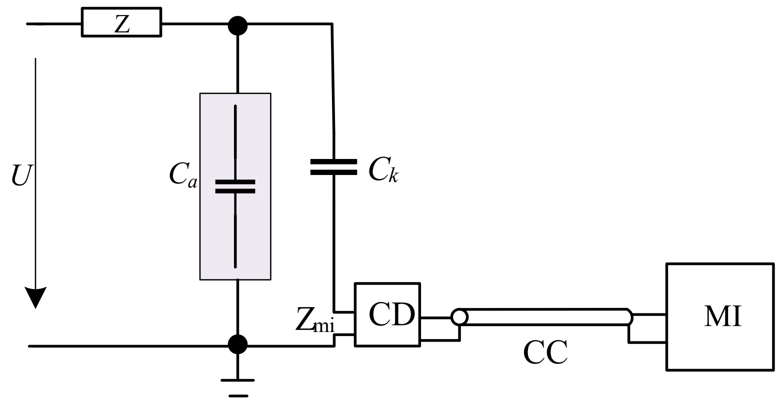


Figure 4. Schematic of the partial discharge test circuit.

The AC voltage test: the resonant test system normally connects an inductor in series with the tested cable to form a series resonant circuit [73–77]. The frequency can be adjusted to fulfill the resonant condition, as schematically shown in Figure 5 [78]. The system consists of a three-phase source, the frequency converter (normal topology is converter and inverter), exciting transformer, the series resonant reactor, the capacitive divider, and the cable under test. The frequency converter has three-phase input while one-phase output to reduce the demanded supply capacity. The exciter transformer can be excited with variable voltage and frequency. The exciter transformer energizes the series resonant reactor and the cable capacitance. With this method, frequency is normally between 20 and 300 Hz. Otherwise, the inductor value can be tuned to form a resonant circuit with the cable around 50 Hz. The frequency tuned method is preferred since it can bring the specific weight of the testing device down to 1 kg/kVA [79]. Care must be taken for PD measurement since power transistors switching may generate noise.

VLF: the schematic circuit for the VLF test is show in Figure 6 [80]. Since the power P demanded to energize the cable is proportional to the test frequency f as

$$P = 2\pi f C U^2 \tag{2}$$

where C is the cable capacitance, VLF can reduce the test power significantly. The voltage levels for installation and acceptance test are based on the most used worldwide practices from $2U_0$ to $3U_0$, where U_0 is the rated rms phase to ground voltage [81]. The VLF voltage can be sinusoidal, cosine-rectangle, or trapezoidal [82]. The test voltage and test duration are the main test parameters [83]. For DAC, the applied voltage has the oscillation frequency from several tens Hz to several hundred Hz [84].

Damped AC test: two commercially available systems are used for the oscillating voltage waveform procedure [83]: (1) oscillating waveform test system (OWTS) [85]; (2) complex discharge analysis (CDA) [86]. The principle of OWTS test is shown in Figure 7 [59]. The cable is charged with a DC power supply over several seconds to the rated voltage, after which a specially designed solid-state switch connects an air-core inductor to the cable in a closure time of <1 µs. The circuit will be resonant at the frequency dependent on the fixed air-core inductor and the tested cable capacitance. The inductor is designed to have a low loss factor and the resonant frequency is from 50 Hz to 1 kHz. The CDA system has quite a similar idea compared with OWTS. The charging time for the cable system is in the order of 10 s to keep a low power demand. The tail time should be chosen around 10 milli-seconds, which corresponds to half of a power frequency cycle. Consequently, the PD detection must be performed during the tail time of the transient voltage [86].

The question for these methods is whether they can represent the condition under power frequency energizing? Three parameters can be investigated: the PD inception voltage (PDIV), the PD magnitude, and the PD patterns [87]. However, existing investigations are often based on various defects without statistical validation, often leading to contradictory results [88]. Dutch experience [89] used the VLF from $1U_0$ to $2U_0$ depending on the circumstances. Reference [90] stated that VLF will fasten the increase of electric tree compared with 50 Hz AC while it is less stressful if there is no defect. References [59,91] showed that oscillating voltages lead to higher ignition voltages for the electrical trees and water trees (about 1.7–2.5 times higher of inception voltage than 50 Hz). While, for 0.1 Hz sinusoidal voltage, the tree ignition voltage is about 1.6–2 times higher than the value under 50 Hz. Reference [85] claimed that the OWTS method gives the PD magnitudes and inception voltage in the same range as 50 Hz AC energizing based on measurement of 6 kV plastic insulated cable accessories for different defects. However, higher PDIV of OWTS on cable samples is reported by [87]. The test on cavity in XLPE showed that the use of OWTS voltage seems to provide PD inception voltage values well above (up to 200%) those measured at 50 Hz [92]. The DAC method was compared with 50 Hz and similar PD behavior has been observed based on the XLPE cable test [93]. The CDA system manufacturer has proposed recommendations for its usage [94]. In [95], PD of cavities in cast polyester was performed and it was found that the PD inception voltage is not dependent on the applied voltage frequency-shape. However, in [96,97], the authors claimed that 25–30% difference exists when testing PDIV and PDEV (partial discharge extinction voltage) at different frequencies for PE material. In general, both PDIV and PDEV for internal and surface PDs have a non-monotone behavior from 0.01 to 1000 Hz. In [98], it was described that the PDIV at 50 Hz is about 80% of 0.1 Hz measurement based on XLPE cable test. A test on XLPE material showed that although differences are limited, PDIV seems to be lower when testing with a lower frequency rather than a higher one [88]. Field experiences (paper, EPR, and XLPE cable) [99] showed that neither 0.1 Hz nor DAC can always give close inception PD voltage compared with 50 Hz and the maximum difference is about 200%. The PD tests mentioned above are summarized in Table 3.

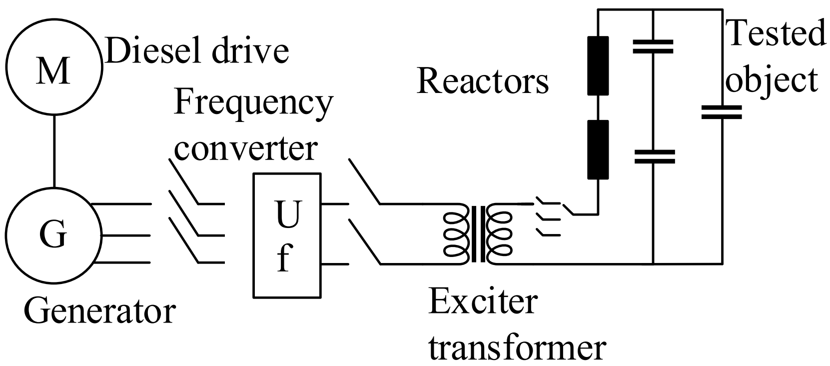


Figure 5. Resonant testing system schematic diagram.

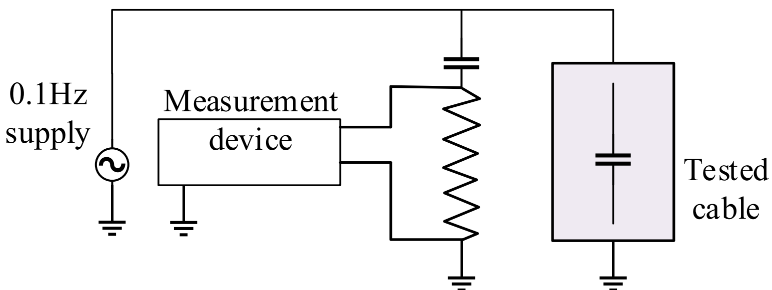


Figure 6. VLF testing system schematic diagram.

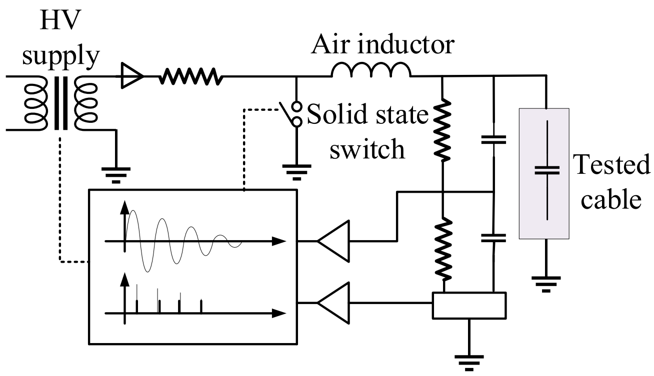


Figure 7. OWTS testing system schematic diagram.

Table 3. Off-line PD measurement results.

Test Object	Result
6 kV plastic insulated cable accessories with realistic internal defects: bad contact between semiconducting layer and the stress cone, bad adjustment of the stress cone and internal cavities [85]	50 Hz AC power frequency and oscillating wave voltages of 1066 Hz gave PDIV and PD magnitude in the same range without a consistent difference.
10 kV cable sample [87]	Higher PDIV for OWTS than 50 Hz.
Dielectric cavities embedded in an XLPE sandwich [88]	PDIV values with OWTS significantly exceeded those obtained with sinusoidal voltage waveforms. PDIV with 0.1 Hz was on average lower than those obtained for higher frequencies.
Electrical treeing on an XLPE cable sample [90]	A widespread electrical tree for 50 Hz while a straight channel with VLF. Tree growth rate for VLF was faster. Number of PD per second for VLF was much lower.
Needle and water tree damage [91]	Oscillating voltages lead to higher electrical tree inception voltage than 50 and 0.1 Hz while 0.1 Hz tests indicate higher tree ignition voltage than 50 Hz.
Three layers of polyethylene [92]	0.1 Hz VLF with sinusoidal waveform, 50 Hz AC and OWTS using frequencies of 200, 500, and 1000 Hz were performed. PDIV increased slightly with frequency and PDIV for OWTS was in general much higher than the ones derived with sinusoidal waveforms.
Full size test setup of 100 m 150 kV XLPE cable with defect created in cable joint [93]	Continuous 50 Hz AC voltage and Damped AC voltage (60 Hz, 400 Hz) were applied, and similar PD characteristics was observed.
A spherical air-filled cavity between two brass electrodes cast in polyester resin [95]	DAC, VLF, and 50 (60) Hz test were performed. PDIV is not dependent on the voltage frequency shape. The PD level measured at frequencies above 200 Hz was slightly lower than that with the 50 Hz AC energizing; both the PD magnitude and the PD pattern demonstrated that the PD process at VLF frequencies can be either very close to that at 50 Hz or quite different. The main reason is supposed to be that the deposited charge decay time can vary over several orders of magnitude depending on the condition of the cavity surface.
Spherical electrode on a 1 mm thick LDPE disc placed on a grounded plane electrode activating surface discharges on the LDPE disc. Three 1 mm thick PE foils, the layer in the middle had a punched hole [97]	25–30% differences can be observed when testing PDIV and PDEV at different frequencies. In general, both PDIV and PDEV had a non-monotone behavior from 0.01 to 1000 Hz for internal and surface PD activities.
Two XLPE cables consisting of 168 and 233 m were connected by a defective cable joint. Artificial defects were made to generate internal and surface PD [98]	PDIV at 50 Hz is about 80% of 0.1 Hz measurement.
Five cables made of paper, EPR, and XLPE with terminations having artificial defects in laboratory and 18 field cable circuits (paper and EPR) [99]	For the laboratory test, 0.1 Hz VLF gave higher PDIV result than 50 Hz AC, however, it is not always the case in the field. Neither 0.1 Hz nor DAC can always give close inception PD voltage compared with 50 Hz and the maximum difference is about 200%.

To summarize, there are three main off-line PD testing methods as in Table 2. The applied voltage shapes differ from each other. Yet, the PD measurement is similar by recording at the energizing side. PD location can be derived based on the time domain reflectometry.

Though they are accepted as an effective tool to diagnose cables with the measured PD result, it is still not completely clear how to correlate their measured result with each other or with the cable performance under 50 Hz AC.

3.2. On-Line Test

On-line PD measurement is usually more costly. Thus, it is mainly for assets with high importance such as high voltage cable accessories [67,100]. Reference [101] described an on-line system for medium voltage cable. It is not unusual that cable defects generate PDs over a long period without failure. On-line tests offer the opportunity to collect all PD measurement data. Such data must be analyzed in a statistical way. Data such as discharge number, intensity, density, and pattern need to be recorded per PD location [102]. Field tests also show that different off-line methods may give different PD locations. This fact reflects the nature of the insulating medium and highlights that a clear identification of defective points can be obtained if one considers not only the PD level associated with the defect but also other diagnostic indicators such as the repetition of the PD activity in the specific location [99]. With the continuous monitoring ability under the rated working condition, the on-line partial discharge condition assessment of high voltage and medium voltage cables is becoming more widespread in power electric systems [103]. It is worth noting that more benefits can be obtained if the PD location can be pinpointed by an on-line testing system for cables. Due to the higher attenuation and complicated cross-bonding paths for PD, PD location for medium voltage cables over length is more feasible and PD on-line monitoring for high voltage cables is mainly focusing on accessories. The general approach to locate PD online is to install the time-synchronized sensors at both ends of the cable section to be monitored and the location of PD can be determined by the arrival time difference at the two installed sensors [104].

3.3. Sensors

The discharge is accompanied by (1) a current caused by charge displacement; (2) radiation emitted by excited particles falling back to a lower energy state; (3) ultra-sonic sound; (4) heat generated by particle impact; (5) chemical reactions [11]. Thus, the detection can be divided as electrical discharge detection and nonelectrical discharge detection. The nonelectrical phenomena are chemical reaction, gas pressure, heat, sound, and light, from which the last two are of practical importance [105]. Photography and acoustic emission (AE) sensors can be used for detection. Dissolved gas analysis (DGA) is related to the chemical transformation. While for the electrical discharge detection, inductive and capacitive sensors are used. Refs. [106–108] summarized inductive coupling (a sensor that picks up the magnetic field of PD), galvanic coupling (PD signal is measured as the voltage drop across an impedance inserted into the current path), and capacitive coupling (a sensor that picks up the electric field of PD); directional coupler is also introduced as an integrated sensor in the cable joint with both capacitive and inductive coupling. When the sensor is considered by frequency range, then there are AE sensors covering the frequency in 20–500 kHz; high frequency current transformer (HFCT) with the frequency range of 30 kHz–300 MHz; very high frequency (VHF) methods which measure frequency range of 30–300 MHz; ultra-high frequency (UHF) method with window type sensor measuring frequency range from 300 to 3000 MHz [109]. Typical sensors used for PD detection along power cables are summarized in Table 4 with advantages and disadvantages. Their locations with respect to the cable system are indicated in Figure 8. The inductive sensors need a current path for PD while the coupling capacitor has issues for installation since, for example, it needs to interrupt the cable shield. AE and UHF sensors are non-contact sensors. However, the attenuation needs to be considered. An ultraviolet imager is easy to use but it can detect only corona discharge at cable termination. New progress has been made by researchers to develop novel sensors for convenient and accurate measurements in field, e.g., the spherical electromagnetic sensor [110], which is not included in Table 4.

Table 4. PD sensors with advantages and disadvantages.

Sensor Type	Advantages	Disadvantages
AE sensor	Immune to electromagnetic noise	High attenuation [111]
HFCT	Non-intruding installation, wide bandwidth [112]	Material saturation caused by large current at power frequency Current loop is needed
Rogowski coil	Light weight, low cost compared with HFCT [113]	Narrow frequency band [114] Current loop is needed
Coupling capacitor	High sensitivity, possible to be integrated in cable [115]	The size and cost of a coupling capacitor can become problematic for onsite measurement [116] Installing can be an issue, safety risk due to galvanic contact needs to be considered
UHF	Good anti-disturbance performance [111]	Strong attenuation, cannot be calibrated [117] Cable shielding effect
Ultraviolet imager	Easy to use	Can only detect corona discharge at cable termination

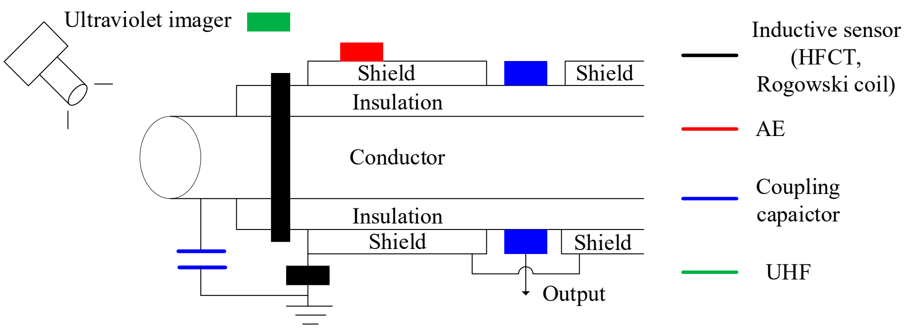


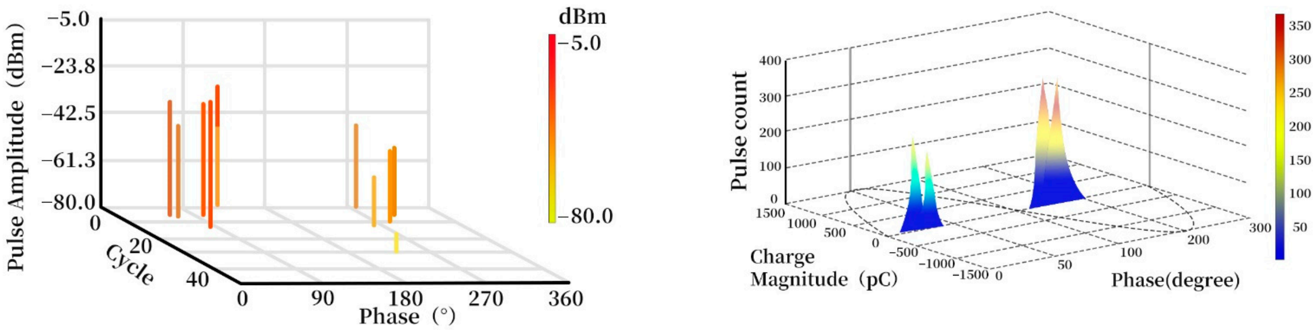
Figure 8. Illustration of sensor locations.

4. Partial Discharge Analysis

4.1. Quantities and Algorithms for Analysis

Standard quantities are used for PD analysis: inception voltage, extinction voltage; maximum and minimum PD amplitude in mV or pC. For AC test, the time and phase information of applied voltage are utilized, such as inception and extinction phase of the applied voltage (the phase interval defined as difference of the two), mean number of discharges per cycle of the applied voltage, mean integrated charge quantity, or mean integrated signal height per cycle of the test voltage [118]. Phase-resolved PD (PRPD) and phase resolved pulse sequence (PRPS) are two typical patterns to analyze PD as shown in Figure 9. The PRPD patterns show phase, pulse count, and charge magnitude information and PRPS includes PD intensity, time of occurrence, and PD phase. Another alternative approach is to consider the dynamic between consecutive PD pulses proposed by Hoof and Patsch with the name of "Pulse Sequence Analysis" (PSA) [119]. A PSA pattern is usually constructed with the instantaneous voltage differences/time difference between consecutive pulses, as shown in Figure 10. Compared to AC, the major issue for PD measurements under DC is the absence of phase information. If there is ripple in the applied DC voltage, it can be utilized to help PD analysis as a phase reference, similarly to AC [120]. For DC without noticeable ripple, one can observe only a series of impulses. Many algorithms and techniques are used for PD extraction and interpretation [121,122].

Denoising, pattern recognition, arrival time estimation, and PD location are the main areas where algorithms are crucial for analysis. Considering the noise reduction, there are mainly three types of noises in PD detection: white noise, sinusoidal noise, and pulse interference. Wavelet analysis, empirical mode decomposition (EMD), and mathematical morphology methods are generally used to treat white noise and the filtering technique is used to remove sinusoidal noise [123]. Denoising algorithms that are effective also for pulse interference are not trivial. Yet, researchers proposed methods that are valid in their test, such as k-means clustering and recursive continuous s-shaped algorithm [124,125]. Pattern recognition is usually to classify different PD types, e.g., PD from different defects in cable joints. Fuzzy logic [126], support vector machine, genetic algorithm, and neural network [127] are used for this purpose. New methods are being continuously proposed such as rough set theory [128], deep learning, and texture feature-based algorithms [129,130]. PD arrival time estimation is vital for its location along cables. The available methods include the trigger level based method, signal energy based method, Akaike information criterion (AIC) method, Gabor centroid method, phase-based method [131], and multiple signal classification algorithm [132]. Each method may have different performance under various noise conditions or PD shapes. The PD location algorithm is essentially used to determine the time difference between the detected PD and its reference. Thus, by application of arrival time estimation on the individual pulses, the location can be derived. Moreover, methods based on the relation between the studied pulses were researched to locate PD, such as the correlation algorithm [133] and phase difference method [134]. It can be foreseen that with the rapid development of information computer technology and its application in various industries, PD analysis can be improved dramatically in the future.



(**a**) (**b**)

Figure 9. (**a**) Typical example of PRPS. Reprinted from Ref [111]. (**b**) typical example of PRPD. Reprinted from Ref [135].

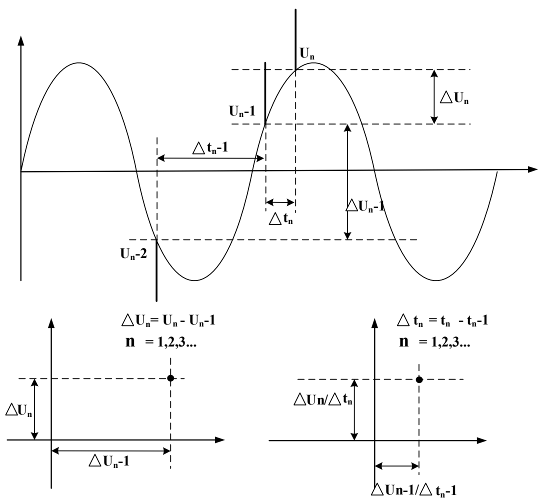


Figure 10. PSA construction for PD. Reprinted from Ref [119].

4.2. PD Characteristics for Different Cables

There are basically two kinds of cable structure: laminar dielectric structure (with multiple layers of paper impregnated with a dielectric fluid) and solid dielectric structure (a metallic conductor covered with a semiconducting screen over which a solid dielectric insulation is extruded) [136]. Reference [137] claimed that the PDs between paper layers are mainly the Townsend discharge; and when a metal becomes one of the electrodes, streamers can be developed from some of the Townsend discharges. If a deep cavity experiences high enough over-voltage between two ionizing events, the streamer releases more energy at one time and it is more harmful to the paper insulated cable. For solid dielectric material, a void is usually created to study the partial discharge [11,37,138–140]. Reference [141] stated that for the situation of a flat cavity, the aging process is generally agreed on as follows. (1) The dissociation products of air due to PD increases the conductivity of the cavity surface. (2) The surface roughness increases caused by charge carrier attack and deposition from by-products. (3) PD activities produce localized solid by-products, i.e., crystals. (4) Such solid by-products further increase the field to intensify the PD, initiating the tree growth. (5) Finally, a breakdown may happen due to the tree growth. If fillers are present in the dielectric, the insulation between filler particles is normally most severely degraded. For flat cavities in polyethylene, the author in [11] discovered a featured pulse shape relating to each aging step. At the beginning, streamer-like narrow pulses with high magnitude show in the cavity. Afterwards, a conductive surface appears across the cavity, and the PD develops into Townsend-like, which is wide with low amplitude. When crystal by-products appear, the PD evolves to pulse with small amplitude and intermediate width.

4.3. PD with Temperature and Load

For some insulation defects, the operating condition of the cable will influence the PD testing [142]. The test result in [142] showed for voids in paper insulated cable, the PD decreased obviously if the cable load increased. Additionally, the PD magnitude and the number of PD sites vary as the cable load changes. While for cavities and electrical treeing in XLPE cable, PD was found not to be significantly influenced by the cable loading conditions. However, it is not the case for interfacial defects. Both the PD magnitude and the number of PD sites are a function of the cable temperature. PD tends to increase as the cable load increases. A recent test shows that with the temperature increase, PDIV may decrease slightly for XLPE and EPR [143].

4.4. PD under AC and DC

With the increasing application of HVDC projects and emergence of distributed DC systems, PD behavior under DC is starting to draw people's attention. Electric field distribution under AC depends on the material's permittivity while the electric field in DC cables is dependent on conductivity, which in turn relates to the electric field and temperature. The complicated charge injection conduction mechanisms can be modeled by a bipolar charge transport model at the interface between electrode and dielectric [144]. PD in AC cables has been extensively studied while much less is available for DC cables. Experiments show that the PD repetition rate under DC is much lower than that under AC. An analytical model for this explanation can be found in [145,146] based on the abc-model while a qualitative description is available in [143]. Research also confirmed that the PDIV in DC can be much higher than in AC for the same defect at room temperature. However, the PDIV in DC can become lower than that in AC for higher temperature, at least for the typical XLPE materials used from cables [143,147]. The reason is that temperature rise can increase the dielectric conductivity significantly [143]. Regarding the PD magnitude, its value under AC is higher than under DC. The reason is considered to be the statistical time delay for the firing electron [143,145]. Taking the PD in cavity as an example, the PD will occur after a statistical time delay when the electric field exceeds the PDIV. Under AC voltage, the delay may wait for a further increased voltage, leading to a larger PD. While under DC voltage, a constant residual field can be assumed after PD. Thus, it is plausible to get a smaller mean PD magnitude at DC energization. Voltage polarity inversion can lead to PD and cause premature insulation breakdown. It can be dangerous for cable life when operation transient occurs a few times per day. Faster DC voltage rise rate leads to higher PD cumulative damage [148].

4.5. Experience on PD Development

Study [143] shows that actual failed cables have experienced a drop in PD intensity before complete failure. The reason behind this could be that the internal arcing had carbonized the dielectric to such a degree that the resistive component is low enough to prevent a voltage build-up across the void. This low resistive component would also increase current flow, leading to additional heating and resultant insulation damage. Yet, this phenomenon has not been verified completely by cable partial discharge observation. To observe the trend of partial discharge is of vital importance for condition monitoring [149]. Reference [150] showed a 2-year experience on MV paper insulated cable with an off-line VLF PD test method, in which it was claimed that the high and concentrated discharges are often located to places at or adjacent to joints. Different phases often show similar PD behavior. Repeated measurement sometimes showed confusing results: PD magnitude and location may change. Ninety percent of PDs are with the magnitude of 5000 pC which is regarded as a "normal" level, however, cable may fail even with PD between 1000 and 4000 pC. Some cable may even fail without PD behavior. Though some literature is published [140,151,152], it is important to further study the cable aging mechanisms with PD. Reference [153] shared an experience with on-line PD monitoring for paper insulated cable: 12 cable sections out of 17 showed clear rising levels of PD activity within 5–150 days before failure. Although the activity rate appeared to fluctuate periodically through the day, there is no direct relation with the load profile (this non-direct relationship is also mentioned in [154]). Occasionally, the activity rate first climbed up and then decreased prior to the failure with or without PD magnitude increase. When part of the circuit is switched off and the other parts re-energized, a significant step down change in discharge activity can be observed. Furthermore, when the circuit is re-energized after repairs, a rise in discharge activity for a few days can be often observed due to the reason that the internal pressures in the cable recover. This indicates that the off-line and off-load PD test performed when the circuit has been de-energized for some time may not be comparable with its on-line conditions. Reference [155] compared on-line PD measurement with HFCT and offline test with OWTS; results showed 75% agreement. Reference [156] stated that online PD measurement could be used as a pre-selecting method for off-line diagnostics. Reference [157] reviewed six cases with on-line PD monitoring systems and it stated that the number of discharges per second, and PD density change significantly depending on the type of developing fault. Some defects deteriorate slowly, with a high PD frequency and intensity. Yet there are also weak spots that result suddenly into failure. Most weak spots discharge at a low level first and then high frequency, high intensity discharges develop. In general conclusion, it takes years (on average) for a weak spot in PILC to develop into a fault while for XLPE cable, this can be a couple of days to months (on average) [104].

5. Challenge and Discussion

PD modeling still needs improvement. On one hand, a balanced model between efficiency and physical accuracy needs to be developed. On the other hand, PD nature is not completely revealed by the available models. Plasma dynamics and plasma chemistry started to draw researcher's attention to better understand PD's mechanism [44,158] since these models focus more on PD internal physical process rather than the macroparameter from the outside. Only full PD mechanism interpretation can help explain phenomenon. However, the mechanism interpretation calls for new measurement methods, especially on the microscale. It is desired to obtain the relevant quantities relating to the PD process, such as electric field and gas pressure variation at the PD spot.

Correlation between PD tests on samples in the laboratory and PD measurements in the field should be strengthened. Denoising needs to be improved from both sensor and algorithm aspects. Precise diagnostics based on PD are still challenging since the correlation between PD and aging till failure is not clear.

PDs in new scenarios need to be studied further. Compared with AC, PD under DC awaits to be further explored. PD for different cable insulation materials under extreme conditions need to be studied further accompanying its application, e.g., superconducting cable, PD of cable in extreme cold environments, PD of cable in vacuum pressure [159,160].

Facing so many aspects, it is vital to be clear about the objective in practice. For instance, cable circuit connections and long-distance propagation may make characteristics of different types of PDs no longer detectable. Thus, to find and locate PDs for power cables would be of more significance than to distinguish their type.

6. Conclusions

The paper reviewed the mechanism and test aspects of PDs along power cables. PD phenomena can be categorized into Townsend or streamer. Various PD models were introduced from a capacitor model to analytical model to FEA based ones with their pros and cons. Specific model can be chosen to use according to the study purpose. Off-line and on-line PD measurement systems were summarized. For off-line tests, alternating current voltage with resonant test system, damped alternating current, and very low frequencies down to 0.01 Hz method are widely used. On-line systems are getting more popular now. Sensors (mainly capacitive and inductive for electrical character of PD measurement) used for PD measurement were also discussed. For PD interpretation, evaluation parameters, affecting factors for PD behavior, and the trend of observation were discussed. Although PD is a topic with a long history, there are still many challenges to be solved.

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