Implementation and Analysis of a Reference Partial Discharge Measurement System

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ABSTRACT

Partial discharge (PD) detection is based on the measurement of apparent charge originated from PD in test sample. Since the measurement system configuration affects the PD measuring system response, a PD reference calibrator is the most important part of measuring system for the determination of scale factor in measurement system. In this paper, the design and implementation of reference partial discharge measurement system for the calibration of reference calibrator is presented. The reference pulses to be checked in the implemented measuring system are generated by the reference partial discharge generator or calibrator (PDCAL) that is constructed for the characterization of the reference measuring system according to the requirement of IEC 60270. Proper correction for known errors and estimation of uncertainty contributions proved that traceable measurement of partial discharge can be made with an uncertainty of less than 1% in the range of between 2 pC and 1000 pC.

Keywords: Partial discharge, partial discharge measurement, charge measurement, calibration, reference partial discharge calibrator

Introduction

The rapid growth of electrical energy consumption over the years has led to the development of many high voltage transmission and distribution systems. High voltage equipment and apparatus used in power system networks such as insulators, rotating machines, cables, switchgear, transformers, capacitors, and bushings must have good insulation conditions to prevent the possible breakdown and failures for safe and reliable operation. The most important indication of insulation problems is electrical partial discharges, which occurs on the surface of conductors, between conductors and dielectrics and in gaps of the inside of dielectrics. Therefore, one of the most critical tests conducted to high voltage apparatus is the partial discharge (PD) measurement, and it aims to ensure to determine the quality and service life of insulation. PD tests are required as an acceptance test according to the product's standards after manufacturing or repairing of high voltage equipment. PD measurements are also used to monitor and diagnose PD activities for the reliability of devices used in the power system in service life [1-4].

There are different measuring circuits for partial discharge measurements related to the testing object to ensure reproducibility of PD measurements. PD measurement system called as PD detector is based on the principle of converting the PD pulse current to a voltage signal for the determination of apparent charge. The acceptance limit of discharges on any insulating system is generally in the range varying from 5 pC to 500 pC. The rise time level of the PD current pulses has been varying the range between ns and µs [5-8].

Reliability of a PD measurement system depends on the interaction between the PD coupling circuit and the test object. Due to this specific situation, the test circuit should be calibrated by using a reference PD calibrator. The PD calibrator is thus a crucial component in the quality assurance of PD testing such as PD measuring instrument. The accuracy of a PD testing is directly related to the accuracy of reference PD calibrator and PD measuring instrument, and measuring circuit. Though the commercial type of PD calibrators gives the user an advantage due to being portable, they have limited flexibility with fixed charge pulse and repetition frequency [9-12].

Reference PD Calibrator Construction

The PD calibrator is one of an important part of a measurement system for partial discharge detection. Before PD test on high voltage, calibration of all test circuit is performed by using a reference calibrator and then desired detection can be done under high voltage. The purpose is to see how accurately this electric charge is measured by the PD measuring instrument when a certain magnitude of electric charge is applied to the test object in the test circuit. The reference PD calibrator has to be checked and calibrated periodically by a reference measuring system such as described in this paper. According to IEC 60270, PD pulse parameters and their uncertainties applied from PD calibrator should be as indicated in Table 1 [7, 11, 13-15].

Table 1. Uncertainty values for the PD calibrator given in IEC 60270

PD Calibrator Uncertainty (IEC 60270)	Parameters	Uncertainty (k=2)
	Calibrator charge (q_0)	± %5 or ≤ 1 pC
	Pulse rising time (t_r)	± %10 (≤ 60 ns)
	Pulse repetition rate (N)	± %1

For the characterization of PD measuring system, the programmable partial discharge generator (PDCAL) is developed in TUBITAK National Metrology Institute (UME) of Turkey. This system has the features of wide-band charge measuring capability and remote control. PDCAL consists of a programmable arbitrary waveform generator, series capacitors, and specially developed software. The charge generated from calibrator is controlled and characterized by the reference measuring system. Table 2 shows the characteristic uncertainty values of PDCAL [8, 16].

A programmable arbitrary waveform generator used in PDCAL can generate various types of current pulses needed for the calibration procedure. The capacitors with nominal values of 1 pF, 10 pF, and 100 pF in the calibrator are used to generate the reference charges from 1 pC to 500 pC. The capacitors consist of series and parallel multilayer ceramic capacitors with low uncertainty values and the voltage level is up to 200 V. The reference charge applied on the terminals of the test object in the calibration circuit can be expressed as in (1) [17-19].

$$q_0 = C_0 \times U_0 \quad (1)$$

where q_0 is the electric charge (Coulomb) obtained from the PD calibrator, C_0 is capacitance (Farad) of the precision capacitors in the calibrator, and U_0 is the voltage (Volt) applied from the digital pulse generator to C_0 capacitors.

Table 2. Uncertainties of implemented PDCAL

	Parameters	Uncertainty (k=2)
PDCAL Uncertainty 1-1000 (pC)	Calibrator charge (q_0)	± % 1 or ≤ 0.2 pC
	Pulse rising time (t_r)	± % 0.1 (≤ 4 ns)
	Upper-frequency limit	-

The characteristics of a programmable digital pulse generator determine the performance and uncertainty of the reference calibrator. In PDCAL setup, Agilent 33220A is used as pulse generator having the characteristics of 14-bit resolution, the sampling rate of 50 MS/s, frequency range up to 20 MHz, ±10 V output voltage and 256 kB memory. The rise time of generated current pulses is 4 ns, and the range of the pulse repetition frequency is between 1 Hz and 5 kHz. The system software that controls the digital pulse generator was developed using Keysight ® VEE Pro 9.3.

Reference PD Measuring System Design

The general diagram and hardware configuration of reference PD measuring instrument is shown in Figure 1. According to the general diagram given in Figure 1, the reference partial discharge measurement system consists of two different parts. The first one is the partial discharge generator called as PDCAL, and the other is partial discharge detector that measures the apparent charges in the test circuit. Reference partial discharge generator having low uncertainty parameters has been developed for the characterization of the reference measuring system. The definition of reference PD calibrator was given in the previous section.

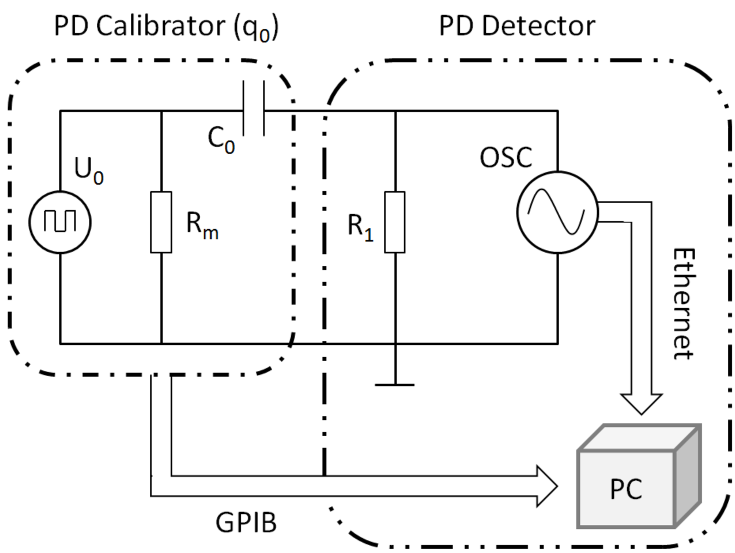


Figure 1. General diagram of PD measuring system

In Figure 1, U_0 is the step voltage generated from the arbitrary waveform generator, C_0 is the capacitors described in PDCAL, R_m is the matching resistor (50 Ω), and R_1 (50 Ω) and R_2 (200 Ω) are the measurement resistors described in IEC 60270 [16]. OSC and PC represent the digital oscilloscope and personal computer, respectively. Computer connection for controlling and analyzing has been made via GPIB connection. Figure 2 shows the general view of the measuring system. General characteristics of the new PD measuring system are given in Table 3.

Figure 2. Implemented Reference PD measuring system

Table 3. Characteristics of the new PD Measuring System

Software	Resistors	Digital Oscilloscope
Keysight VEE PDM.vee	50 Ω (R_1) 200 Ω (R_2)	600 MHz Avg. 12-bit Sample rate: 2GS/s Max. Volt.: 80 V

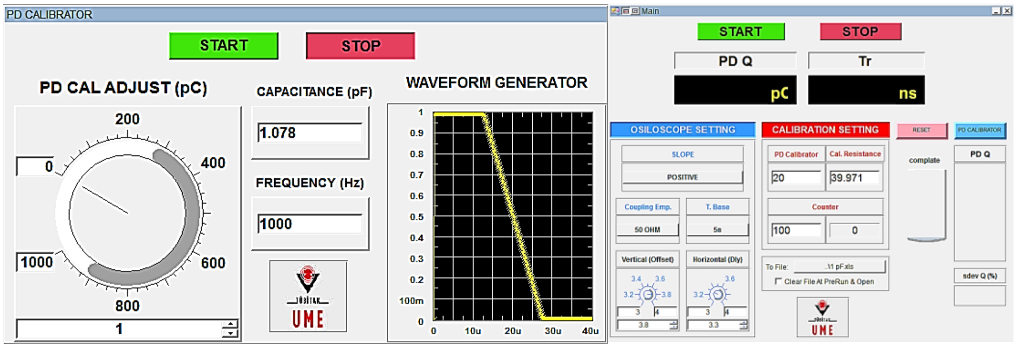
The current pulse shape, an electric charge value, rising time of current waveform, and pulse repetition frequency to be applied to the measuring instrument is controlled with the specially developed software tool based on Keysight® VEE 9.3. The PD signals generated from PD calibrator are applied to the oscilloscope through the measurement resistor (R_1) and analyzed by the software. The software also detects the PD charges automatically and calculates the average of the apparent charges and rise time [8, 16].

Figure 3 shows the software interfaces for the controlling of the partial discharge generator and detector. PD software interface shown in Figure 3a includes of measuring parameters and settings of the detector, and Figure 3b shows the interface of partial discharge generator/calibrator for controlling [1, 19].

Analysis of New PD Measurement System

The general view of the reference measurement system as block schema is given in Figure 4 and includes the programmable waveform generator, capacitors, measuring resistors and input impedances of a digital oscilloscope. In the circuit, V_s and V are the source and output voltages of the generator, respectively. R_1 is the resistance on the output terminals of the generator, R_2 is the load resistance or impedance, R_3 represents the input impedance of the digital oscilloscope and C_0 is the charging capacitor and [8, 10].

Metrological traceability of components in PD measurement system are provided by TÜBİTAK UME. The metrological traceability of the waveform generator and the digital oscilloscope is provided by using reference DC voltage standards in voltage laboratory. And additionally, the capacitor and resistor modules have been traceable by using reference capacitance and resistance bridges in the impedance laboratory.



(a) (b)

Figure 3. PC interfaces of the reference PD measuring system for a) partial discharge generator/calibrator and b) the measuring instrument/detector

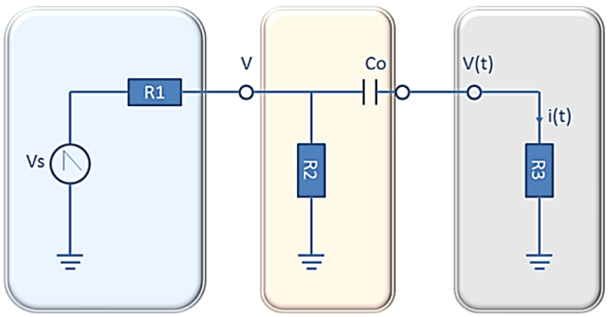


Figure 4. The equivalent circuit of the PD measuring system

The apparent electric charge to be measured from the measuring circuit is calculated by integrating the current flowing through resistance R_3 or by integrating the voltage across resistance R_3 as (2),

$$q = \int i(t).dt = \frac{1}{R_3} \int v(t)\,.dt \tag{2}$$

where, *v(t)* is the voltage of terminals of the input resistor, R_3 of the digital oscilloscope, *i*(*t*) is pulse current applied to the circuit, and *q* is the apparent charge. This equation can be written in another way, the apparent charge is calculated as in (3):

$$q = \sum_{n=1}^{N} \frac{Vn}{R3} \Delta T \tag{3}$$

where, ΔT is the interval time between two consecutive pulses and v_n is the voltage value for *n.* pulse, and N is applied pulse number [17, 19].

Table 4. The uncertainty components of PD measurements for 10 pC

Symbol	Description	Uncertainty Contribution
ΔQ	The error of PD charge	-
V_s	The output voltage of the pulse generator	5.0E-04 V
$\delta V_s'$	The drift the pulse generator	2.5E-02 V
C_0	Capacitor	1.5E-15 F
$\delta C_0'$	The drift of the capacitor	5.4E-16 F
$\delta C_0''$	The temperature effect of the capacitor	5.4E-16 F
V_n	Measured voltage value of digital oscilloscope	1.0E-04 V
$\delta V_n'$	The drift amplitude measurements of digital oscilloscope	2.0E-05 V
Δt	Time measurements of digital oscilloscope	1.0E-12 s
R	RThe resistance of load impedance	1.2E-01 Ω
$\delta R'$	The drift of load impedance	2.0E-02 Ω
$\delta R''$	The temperature effect of load impedance	2.0E-02 Ω
δQ_r	Resolution of digital oscilloscope	1.0E-14 C
-	Repeatability	1.9E-14 C

Uncertainty Calculation

The model function of uncertainty is described as in (4) by considering the apparent charge formula presented in (1). The uncertainty contribution of the pulse generator is determined by calibration of the amplitude and time base of digital oscilloscope.

$$\Delta Q = (V_s + \delta V_s') \cdot (C_0 + \delta C_0' + \delta C_0'') - \left(\frac{(V_n + \delta V_n') \cdot \Delta t}{R + \delta R' + \delta R''}\right) + \delta Q_r \qquad (4)$$

For the determination of the uncertainty of the PD calibrator, the sensitivity coefficients and the standard uncertainty of each element in the model circuit have been calculated. Because the model function is complicated including the measuring assignments with a large number of input quantities, special calculation software such as GUM Workbench, can be used. This software package is based on the GUM Guide and analyzes the complicated uncertainty calculations, easily [20-22]. Table 4 gives the uncertainty components of model function for 10 pC as an example. Uncertainties of the 1 pF, 10 pF and 100 pF capacitors used in measuring system are 130 µF/F, 35 µF/F and 15 µF/F, respectively.

Results and Discussion

The performance tests of reference calibrator have been performed with different capacitors to determine the characteristic of the new PD measurement system. The test results and uncertainties are given in Tables 5. The most sensitive and reliable measurement regions of charge values have been identified for different capacitors. The reference apparent charges between 1 pC and 10 pC are determined with low uncertainty by using 1 pF capacitors. The charges in the range of 10 pC-50 pC and 50 pC-1000 pC are calculated with the best uncertainty by using 10 pF and 100 pF capacitors, respectively. The reason of this type of capacitor selection is related to the measurement range of DC input voltage of the reference generator. The generator is fed up to 10 V and the measurement uncertainty of input voltage between 10 mV and 10 V is less than other ranges. The measurement of partial discharge can be made with an uncertainty of less than 1% in the range of between 2 pF and1000 pC. This measurement system also allows the measurement of partial discharge below 2 pC with an uncertainty of 0.01 pC. Results of the measurement of the PD measuring system are shown in Table 5.

Table 5. Results of the measurement of the PD measuring system

Applied Electric Charge From Reference Generator	Measured Electric Charge From Reference Measuring System	Error		Uncertainty (k=2)		Output Voltage of Signal Generator	Capacitors
pC	pC	pC	%	pC	%	V	pF
0.11	0.10	0.01	7.0	0.01	11.9	0.09	1
0.19	0.20	-0.01	-5.9	0.01	7.15	0.19	1
0.39	0.40	-0.01	-2.2	0.01	3.83	0.37	1
0.49	0.50	-0.01	-1.4	0.01	2.37	0.46	1
0.59	0.60	-0.01	-1.90	0.02	2.57	0.56	1
0.78	0.80	-0.02	-2.6	0.01	1.57	0.74	1
1.00	1.00	0.00	-0.5	0.01	1.40	0.93	1
1.98	2.00	-0.02	-1.0	0.02	1.00	1.86	1
4.97	5.00	-0.03	-0.6	0.05	0.96	4.64	1
9.95	10.00	-0.05	-0.5	0.09	0.91	9.28	1
19.87	20.00	-0.13	-0.7	0.17	0.87	1.96	10
50.10	50.00	0.10	0.2	0.39	0.77	4.91	10
99.7	100.0	-0.34	-0.3	0.84	0.84	1.01	100
503.2	500.0	3.15	0.6	4.20	0.83	5.03	100
1006	1000	6.32	0.6	8.39	0.83	10.06	100

Conclusions

A reference partial discharge measurement system designed and constructed in TÜBİTAK UME is intended to be used for the traceability of partial discharge measurements. This system gives the novelty for the measurement of partial discharge below 2 pC with 1 % uncertainty and less. The uncertainties of partial discharge measurements of National Metrology Institutes having entries to Bureau International des Poids et Mesures (BIPM) key comparison database are between in 6 % and 20 %. This is the best uncertainty declared in the BIPM key comparison database. For the characterization of PD measurement system, reference partial discharge generator (PDCAL) has also been designed and constructed up to 1000 pC within 1 % relative uncertainty. The earlier works have been implemented changing input voltage of system for the generation of partial discharges up to 1000 pC. In this system, the input voltage is limited up to 10 V and output capacitors are adjusted 1 pF, 10 pF and 100 pF for the generation of partial discharges up to 1000 pC. This limited voltage decreases the uncertainty of the measurement system.

In the future, it will have been possible to participate in the interlaboratory comparison with this constructed system about the partial discharge measurements and this measurement capability in TÜBİTAK UME will be the entries for Bureau International des Poids et Mesures (BIPM) key comparison database.

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