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# Calibration of partial discharge measuring systems by a reference impulse charge generator

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***Abstract***-The calibration of a partial discharge measuring system is carried out to determine its scale factor. This operation is performed in the complete test circuit by injecting across the terminals of the device under test a known charge generated by a traceable calibrator. The paper presents the calibration of four different partial discharge measuring systems, carried out by using a programmable reference impulse charge generator developed at the Istituto Nazionale di Ricerca Metrologica. The device is composed of an arbitrary waveform generator and a series capacitor. By this instrument, the performances of the four systems (linearity, response to opposite polarity pulses, response to pulse train and pulse resolution time) are deeply investigated and compared. The results obtained show that the tests prescribed by the standards do not fully characterize the partial discharge measuring system behaviour. Additional checks should be carried out to better evaluate their performances, with particular reference to measuring systems which include advanced analysis tools.

## I. Introduction

Partial discharges (PD) are localised electric discharges that partially bridge the insulation between the conductors of electrical apparatuses. PD phenomena occur in presence of insulation defects (e.g. gas or oil-filled cavities), when the electric field is locally beyond their breakdown strength. As PD can lead to the insulation degradation [1], their detection is a powerful tool to evaluate the state of the insulation, identify possible defects and prevent breakdown. Therefore, PD tests are nowadays prescribed as acceptance tests for a lot of high voltage devices (cables, bushings, transformers, machines, etc.).
Since actual PD, which appears inside the insulation defect, cannot be directly measured, another related electrical quantity, the apparent charge $q$, is used to quantify the PD phenomenon. The apparent charge of a PD pulse is the charge which, if injected within a very short time across the terminals of the Device Under Test (DUT) in a specified test circuit, would give the same reading on the measuring instrument as the PD current pulse itself. PD tests are performed by applying, through a supply circuit, the high voltage to the DUT and by measuring the apparent charge consequent to the PD event. The determination of the measuring system scale factor, that is the ratio of the input quantity to the instrument indication, is performed by means of a suitable calibrator in the complete test circuit, because the measuring system response depends on the test circuit configuration. The calibration procedure consists in injecting across the DUT a current pulse of known charge, generated by a PD calibrator, in absence of high voltage supply. The calibrator is essentially composed of a step voltage generator and a series capacitor. To a great extend, the accuracy of the PD calibrator used determines the accuracy of the PD measurement. The main characteristics of the calibrator (charge values, step voltage rise time) are prescribed by the related standard [2]. Commercial PD calibrators can generally produce stated discrete charge values, with fixed charge pulse shape and repetition frequency. To deeply characterise the measuring systems, the use of a more flexible PD calibrator is advisable [3, 4]. Moreover, with the development of PD measuring systems based on digital instruments, which can perform advanced analysis, additional checks should be considered.
A reference impulse charge generator has been developed and characterised at Istituto Nazionale di Ricerca Metrologica (INRIM) to investigate and characterise the PD measuring system behaviour under different conditions. In particular, the developed instrument enables the set of the charge magnitude in steps or continuously and permits the generation of opposite polarity pulses, with variable time interval between them. It also can simulate some discharge patterns, such as corona, in one voltage cycle synchronized with the supply voltage.

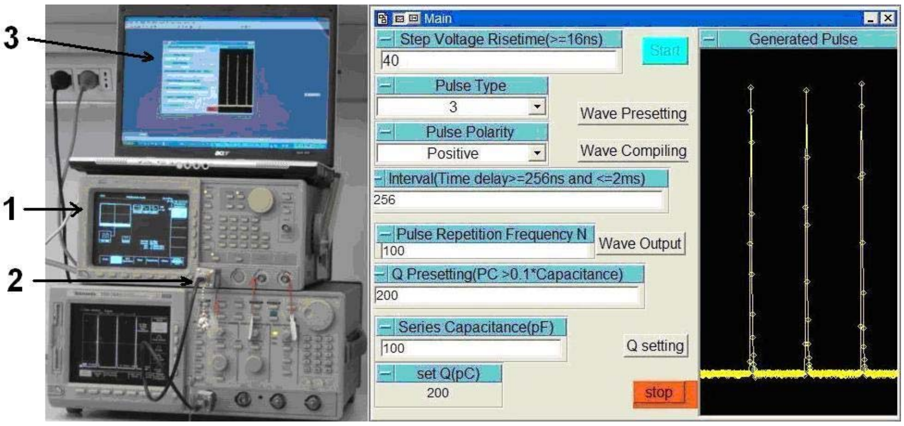


Figure 1. Reference impulse generator set up and example of generated pulse charge sequence

In the following, after a brief description of the main features of the INRIM impulse charge generator, the performances of four PD measuring systems, equipped with analog or digital measuring instruments, are investigated and compared.

## II. Reference impulse charge generator

The developed reference impulse charge generator, shown in Fig.1, consists of an arbitrary waveform generator AWG (1), which produces defined step voltages of amplitude $U_0$, and a series connected capacitor $C_0$ (2). The AWG is controlled by a VEE (Visual Engineering Environment) program (3), which can flexibly set the parameters of the step voltage waveform (e.g. rise and fall time) to meet the requirements of the specific application. By setting these parameters and choosing different run modes for AWG, the reference impulse charge generator can produce sequences of current pulses constituted by single positive or negative pulses, multi-pulses, long duration pulses, random pulses or combined pulses [5]. The combined pulses can be composed of positive and/or negative pulses, with variable charge magnitude and time interval between successive pulses. The AWG output can be externally triggered and synchronized with the supply voltage. By using this feature and setting the phase and magnitude of each pulse of a sequence, the reference impulse charge generator can simulate some real discharge pulse series, phase related to the supply, such as corona discharges, gas cavity discharges in solid insulation, and disturbances occurring during the PD measurement (Fig. 2). This facility enables the check of some advanced tools (e.g. use of time-windows, pulse averaging, frequency selection pattern analysis) implemented in the measuring systems, that are used both in the laboratory and on-site.
The AWG characteristics (12-bit vertical resolution, 250 MHz clock frequency, ±5 V output voltage, 256 kbytes memory) determine the performance of the reference impulse charge generator. The minimum rise time of the generated step voltage waveform is 16 ns; the step voltage repetition frequency can range from 1 Hz up to 5 kHz. By making use of three reference series capacitors (1 pF,

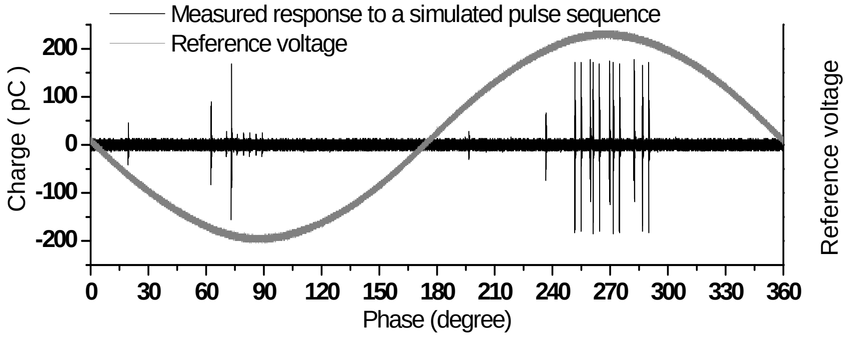


Figure 2. Response of a PD measuring system to a corona and partial discharge pattern, simulated by the reference generator

10 pF and 100 pF respectively) and by setting the magnitude of the step voltage, charges from 1 pC to 1000 pC can be generated. The value and the uncertainty of the charge released by the reference generator are obtained from the traceable measurement of the step voltage amplitude and the series capacitance value. The calibration of the generator has been also performed by comparison with a reference calibrator [6, 7]. The relative expanded uncertainty (coverage factor 95%) associated with the generated charge is 0.04 from 10 pC to 50 pC and 0.012 up to 1000 pC [5].

### III. PD measuring systems and calibration configuration

The calibration of the PD measuring system must always be carried out in the complete test circuit. By using the developed programmable reference charge generator, the performances of four PD measuring systems are investigated, with reference to the basic circuits shown in Fig. 3 [2]. In these schemes the capacitance $C_a$ represents the DUT, $C_k$ is the coupling capacitor, and CD, $Z_{mi}$ and MI are respectively the coupling device, the measuring impedance and the measuring instrument of the investigated system. For all the measurements reported below, a 1 nF low voltage capacitor is used as coupling capacitor $C_k$; when the reference impulse charge generator is connected across the DUT, the high voltage supply circuit is absent.

Two of the investigated systems (D1 and D2) adopt the straight detection circuit shown in Fig. 3a and make use of digital measuring instruments. The other ones (A1 and A2) use analog measuring instruments and are based on the bridge circuit of Fig. 3b, which combines two straight detection circuits to reduce the external disturbances. The characteristics of the four systems are summarised in Table I.

The performances of the four measuring systems are investigated by analysing their linearity, response to pulse with opposite polarity charge, pulse train response and pulse resolution time.

### IV. Comparison of the performances of the four PD measuring systems

The evaluation of the linearity is performed by injecting same polarity charges from 10 pC up to

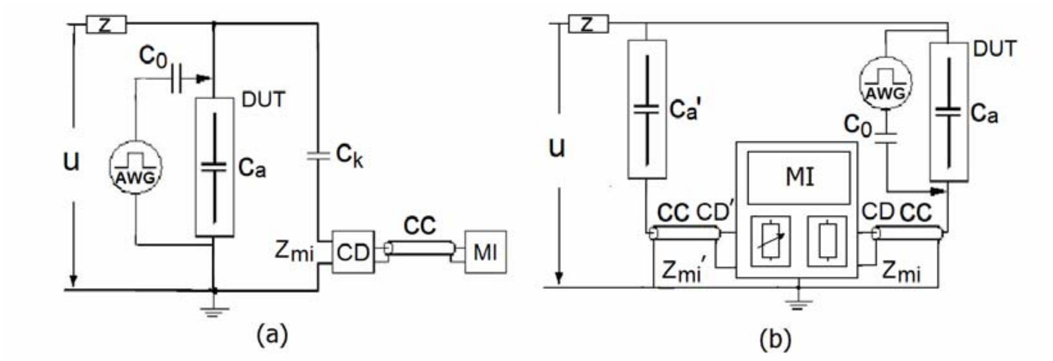


Figure 3. Test set up for the PD measurement systems based on
(a) straight detection circuit; (b) bridge or balanced circuit

Table I – Characteristics of the investigated PD measuring systems

| System | Detection circuit | Measuring instrument | Charge Range | Bandwidth |
|---|---|---|---|---|
| A1 | Bridge | Analog | Four fixed selectable ranges | 40 kHz to 200 kHz |
| A2 | Bridge | Analog | Six fixed selectable ranges | 16 kHz to 180 kHz |
| D1 | Straight | Digital | Continuous autoranging | 80 kHz to 400 kHz |
| D2 | Straight | Digital | Continuous autoranging | a) 150 kHz to 450 kHz<br>b) 295.5 kHz to 304.5 kHz |

1000 pC, with repetition frequency of 100 pulses per second; the rise time is 40 ns and fall time is set to be long enough to avoid the detection of opposite polarity pulses. As a first step, the range and gain of the measuring instruments are set by injecting a reference charge with magnitude of 100 pC for systems A1 and A2 and of 200 pC for systems D1 and D2.
The ratio $K$ between measured and injected charge is reported in Fig. 4 as a function of the injected reference charge. The results show that all the systems, except A2, comply with the standard requirements [2], being the variation of $K$ within ±5% for charges ranging from 50% to 200% of the calibration one. However, beyond the indicated range, three systems out of four, including digital system D1, rapidly overcome the limits, reaching deviations up to ±20%. This result can be related to

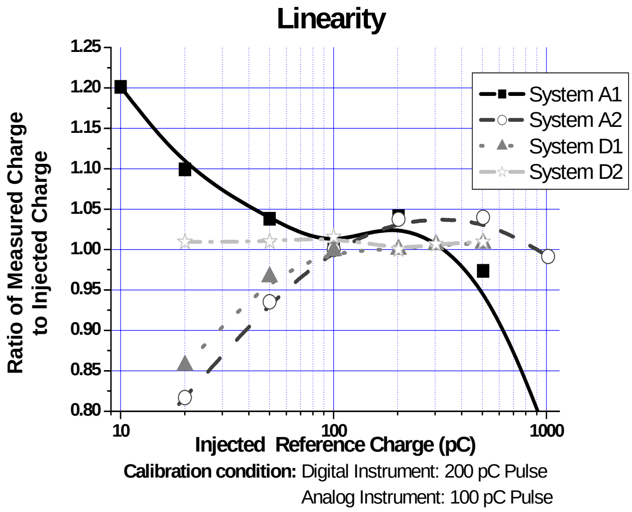


Figure 4. Linearity comparison of PD measuring systems.

the PD signal processing: in particular, for analog measuring instruments, the linearity of the output indication may be influenced by the performances of the different system components, such as the amplifier and the logarithmic converter used in some instruments.
The response of the measuring systems to opposite polarity pulses is then analysed under the same conditions of charge magnitude, pulse repetition frequency, rise time, fall time and calibration charge adopted in the linearity test. As it can be seen from Fig. 5, the performances of two systems, also including a digital one, show significant deviations. The ratio between the measured opposite polarity pulse charges at the same injected charge magnitude can reach values higher than 1.3. Further

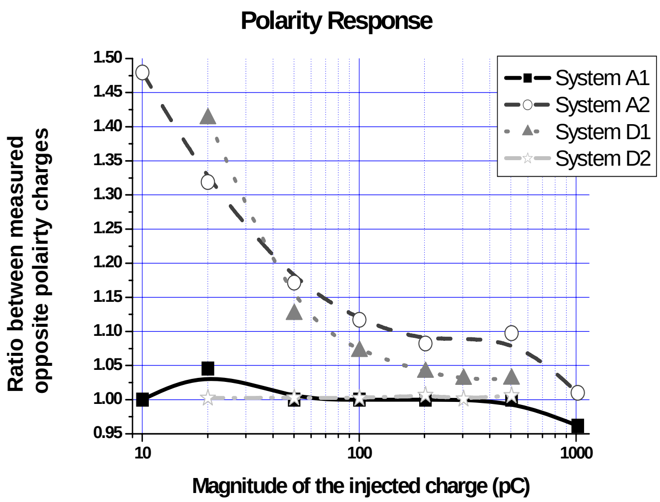


Figure 5. Polarity response comparison of PD measuring systems.

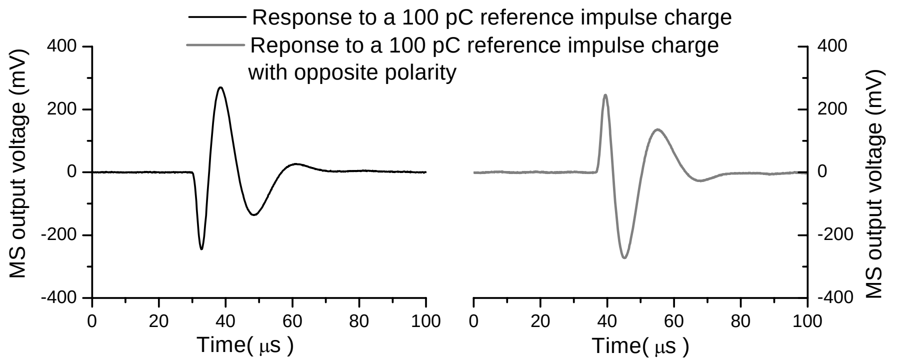


Figure 6. PD measuring system (MS) response to opposite polarity single PD pulses.

investigations indicate that the polarity response can depend on the measuring instrument configuration; moreover the quantity adopted to indicate the apparent charge value is not integrated directly from the PD impulse current, but it is obtained from the peak value of the response signal of the instrument [2]. As an example, Fig. 6 shows the amplifier output signals of system A2 when opposite polarity impulses of the same magnitude (100 pC) are injected. From the comparison with the related measuring system outputs, the indications of the PD apparent charge appear to be proportional to the negative peak voltage, regardless of the polarity. As a consequence, different measuring indications are obtained for injected impulses with same charge but opposite polarity.
The PD measuring system pulse train response is evaluated by injecting reference charge pulses and by decreasing the pulse repetition frequency $P$ (number of pulses per second) from 500 $s^{-1}$ to 1 $s^{-1}$. The test consists in verifying that the measuring system response is included between the maximum and minimum values indicated by the standard [2]. Calibration is performed at a repetition frequency $P_c$=100 $s^{-1}$ with 100 pC (A1 and A2) and with 200 pC (D1 and D2). The tests results of Fig. 7 are expressed as the charge read by the instrument normalised to the injected one. On the whole, the pulse train response of all the systems, but A2, is included within the standard limits, indicated in Fig. 7 by a solid line. For the analog instrument, the mechanical and electrical properties of the peak voltmeter can determine the pulse train response. In particular, the indicator equipment can give rise to swing and big variations under the low pulse repetition frequency condition.

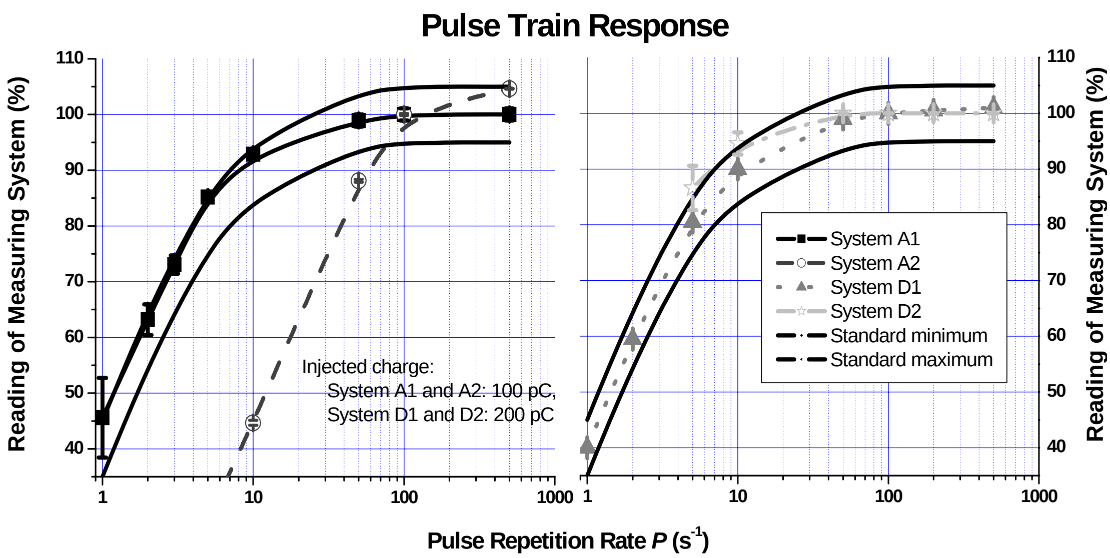


Figure 7. Comparison of pulse train response of the considered PD measuring systems

Table II – Estimated pulse resolution time

| Pulse resolution time τ (μs) | | | | |
|---|---|---|---|---|
| System A1 | System A2 | System D1 | System D2 (150 kHz to 450 kHz) | System D2 (295.5 kHz to 304.5 kHz ) |
| $28<\tau<32$ | $20<\tau<23$ | $\tau<0.256$ | $4.6<\tau<6.2$ | $75<\tau<100$ |

Pulse resolution time should depend on the bandwidth of the measuring system and its centre frequency. Tests are performed by decreasing the time intervals between two successive pulses from 200 μs to 256 ns. Table II shows the limit interval, or the value above which the relative deviation between measured and injected charge is found to be less than 10%. All the wide bandwidth systems are able to correctly measure the injected charge with pulse distances greater than 40 μs, while for the narrow bandwidth system the interval increases up to 100 μs.
The D1 system capability of correctly measuring very close pulses does not appear to be related to the declared bandwidth. This fact can be explained by considering that pulses are digitalised at high sampling frequency (> 10 MHz); the single pulses are then identified and software filtered according to the declared bandwidth.

## IV. Conclusions

The use of the flexible programmable impulse current generator here presented, has enabled us to deeply check the characteristics of PD measuring systems, including analog and more recently developed digital instruments. The obtained results show that the performances of some instruments, including digital ones that are more and more adopted for PD detection and analysis, should be improved with respect, in particular, to impulses of opposite polarity. The analysis of the same results also indicate that the performance tests prescribed by the standards cannot fully characterize the partial discharge measuring system behaviour, so that additional checks (e.g. response to opposite polarity impulses) should be carried out to better evaluate the measuring system performances. In addition, the reference impulse charge generator capability of reproducing discharge pattern and disturbances opens the way to the evaluation of the performances of recent production instrument equipped with diagnosis tool.

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