Frame-by-frame measurement and recording of DC partial discharge under different ramp excitations

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Abstract **– This study presents a comparatively low-cost measurement system for recording, extracting, and processing partial discharge in a dielectric insulation material sample. The purpose of the measurement is to combine developed measurement tools and equipment through a method of synchronisation to capture partial discharge pulses, under direct current or unipolar excitation, in real-time with accurate timing information. A coupling capacitor-based detection method is used for measurement. Each partial discharge event was captured on a single oscilloscope frame and exported in a synchronised order. Results showed that sufficient resolution can be captured for all partial discharge events, where the trigger threshold is selectable.**

Key-words: Partial discharge; Ramp voltage; High-frequency current transformer.

I. INTRODUCTION

Partial discharge (PD) detection in AC or DC systems has been largely explored. Professional PD measurement systems [1] - [3] using commercial-grade sensors are available and can be configured to analyse a broad spectrum of insulating materials in various industrial systems energised with high voltage (HV). However, the PD measurement is demanding from a signal processing viewpoint, and hence sophisticated and expensive equipment is required. Very high data acquisition rates are needed due to the nature of the nanosecond-range discharge phenomena (i.e., translating into high-frequency bandwidth). Laboratory PD experimental research is usually conducted in a very well-controlled environment using professional (but not necessarily industrial-grade) equipment, including high-power sources and fast-rate data acquisition hardware and software [4] - [6].

The PD testing is well-established and widely used for identifying incipient faults in industrial systems, and appropriate requirements for such industrial PD testing are well documented and specified in several international standards [7], [8] and implemented in the equipment that follows these standards [9], [10]. However, even though these methods are well-known and widely used, there is continuing international research that aims at improving the quality of the diagnostics of dielectric materials that can be achieved with PD testing.

To achieve a reproducible measurement, studies often employ a similar measurement approach [4] and [11] in which the response of a custom PD test sample is measured by a suitable sensor, and the sensor output is sampled for further analysis using computer software. Nowadays, signal processing appears to be mostly digital, as this opens new possibilities in very sophisticated diagnostics methods such as per-phase identification of PD faults [9]. In all cases (AC or DC), accurate PD event timing is crucial because it forms part of the PD pattern detection algorithm for quantification and analysis. Under AC, the task is somewhat less daunting because the events can be relatively easily synchronised with the mains frequency. PD cloud pattern recognition is widely used as a diagnostics method, for quick and simple as well as much more complex analytics, involving the separation and classification of sub-parts of the total PD cloud pattern [1]. However, with DC, the analysis is far more difficult as there is no additional phase synchronisation, concerning the applied HV. This is where the study relies on very fast data acquisition using high-end digitisers capable of megasamples per second (MS/s) rates. The focus on AC-only or DC-only is understandably driven primarily by the industrial applications of HV. However, ramped HV is also used for more ordinary insulation diagnostics of HV insulation [12], [13] as well as arguably enables an interesting angle of attack of expanded diagnostics [6], [14].

This paper presents the development of a laboratory-based measurement system for recording experimental data from a custom-made sample that generates reproducible PD events. The proposed measurement setup involves commercially available laboratory equipment and is utilised according to the requirements of the PD recording system. The connection follows the IEC 60270 guidelines [7] with a coupling capacitor and indirect PD sensing path, and allows combining multiple sensor arrangements with synchronised sampling, for example, combining current and ultrasonic sensing.

II. MEASUREMENT SYSTEM DESIGN

As mentioned above, ramped DC voltage may offer additional diagnostics capability because, depending on the ramp rate, this excitation method has similar characteristics to either constant voltage (DC) or AC excitation testing. As is well-known [1], [5], the PD inception voltage is the breakdown voltage of the cavity imperfection inside the dielectric structure under voltage stress. For example, when the electric field is high enough to ionize the gas-filled cavity, the process initiates an avalanche mechanism, which eventually triggers a local (partial) discharge. Under AC excitation, the process can re-trigger on every cycle (or sooner) as the applied voltage crosses the inception threshold, and with the local cavity being recharged by the electric field due to significant internal capacitive currents. Synchronisation to the supply phase gives a solid basis for the interpretation of PD activity.

With constant DC voltage, this mechanism is different as the inception voltage is re-crossed, and global capacitive currents are mostly absent. A ramp voltage test would have similarity to AC testing, as the cavity recharging after a discharge would experience an increasing electric field as a function of the ramp level. This process, however, would not be strictly repeatable, because local discharge will reduce the instantaneous voltage to zero, but the global electric field will be at a different level due to the ramp. There is no "phase” to which the event can be synchronised, so that a PD cloud pattern can be analysed. The capture of these events is in the time domain only. But under certain conditions, calculations can be attempted both in the time domain and the frequency domain. In this study, the main aim of experiments with such a ramped voltage system is to be able to measure the peak amplitude of the current converted to voltage by the sensor and the exact time this event occurs relative to the overall test duration.

There are critical requirements regarding measuring PD, with the critical being the bandwidth of the sensing element, which can be wideband, but also a narrowband implementation is possible [1]. In this case, a 40 MHz bandwidth was used. But a similar importance is given to a sufficient sampling rate to ensure narrow PD pulses can be discretised successfully. For example, a 20 ns pulse yields a high frequency component of at least 50 MHz. According to the Nyquist sampling theorem, the frequency component must be sampled with at least a 100 MS/s rate. In this study, this is achieved by using a 100 MS/s oscilloscope.

Another significant requirement is sufficient digital resolution of the event counter for capturing very closely spaced consecutive discharge events. A sufficiently fast system clock (as well as the associated analogue trigger electronics) is important to report the real-time information of these events. Ripple on the applied voltage is arguably unwanted because it can contribute to the PD events, thus obscuring the desired events caused just by the ramped voltage. Studies used the ripple as a “phase” information so that synchronisation can be attempted with the regular ripples [6], [14]. In this system, the ripple was consciously and purposely kept to an absolute minimum, as discussed in Section III. Some trade-offs, such as parasitic inductance in the test lead connections and test sample joints, were minimized where possible. The negative effects were greatly reduced by keeping lead connections as short as possible, as shown in Fig. 2. Furthermore, HV insulating “putty” was applied to all exposed sharp corners and any other exposed conductive elements (to suppress any surface PD).

III. Measurement Setup

The measurement setup, as shown in Fig. 1, includes a low-ripple variable high-voltage (HVDC) source, which can generate ramped or DC voltages. The no-load ripple is at the level of 30 parts per million (ppm). The ripple may change depending on the load but typically increases only with a purely resistive load. The load is mostly slightly capacitive, and therefore, the ripple would be reduced as compared to the no-load condition. With even larger load capacitance, the effective output ripple of this device can be reduced below 10 ppm. This measurement setup can accommodate various combinations of sensors and PD test samples that can be used for the measurement of different types of PD events.

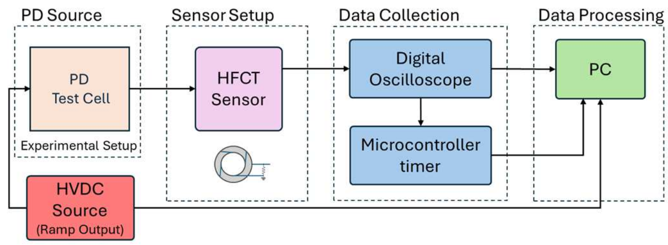

Fig. 1. Overview of the PD measurement system.

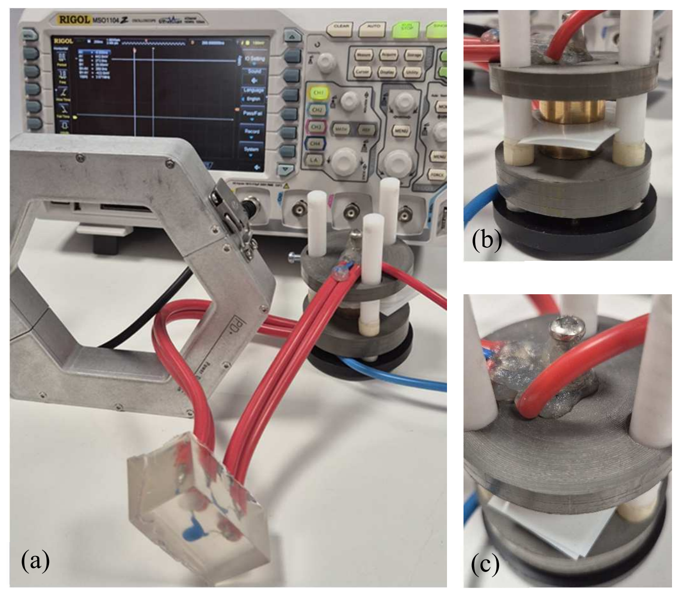

Fig. 2. Physical setup of the PD measurement system – (a) example of test setup, HFCT, coupling capacitor, and oscilloscope, (b) test cell with cylindrical electrodes and dielectric layers, and (c) semi-translucent HV “putty” application to exposed conductive connections.

Each PD event was triggered by the extremely fast, adjustable-amplitude internal trigger mechanism of the oscilloscope so that each full PD event was recorded in its entirety as a full trace, or a frame of data (e.g. 600 ns long) in the digital oscilloscope (Fig. 3), which can be later downloaded and post-processed off-line, after the experiment was finished.

The oscilloscope was equipped with a built-in physical output of the trigger signal. This digital edge was connected to a microprocessor-controlled counter/timer input, which recorded each event with a time stamp. The recorded frames for individual PD events were exported using a custom virtual instrument built in LabVIEW, and the data were aligned with the timing during further post-processing. This additional counter/timer approach was required because the digital oscilloscope recorded each of the frames but did not provide a suitable time-stamping mechanism linked to the real elapsed time.

A. System architecture design

The measurement system illustrated in Fig. 1 has four major functional blocks: a PD test cell connected to a 10 kV DC ramp generator; a high frequency current transformer sensor (HFCT); data collection hardware and processing virtual instrument on a computer. Other PD studies [15,16] also use an oscilloscope as a capturing device. For example, [15] focuses on AC PD testing and employs a high-performance oscilloscope capable of time-stamping individual pulses, along with a dedicated hardware block for synchronization. However, this architecture differs in that the oscilloscope is less specialized, and event timing is captured separately, which is necessary for DC PD testing. As a result, three major parameters are available for post-processing: high-resolution pulse shape, ramp voltage profile, and accurate timing for alignment. The HVDC source in Fig. 1 has an internal low-pass filter on the output. This ensures a smooth ramp transition and serves as a blocking impedance. The HV source instrument interfaces with a virtual instrument where the ramp voltage is reported as measured internally. All low-voltage connections are shielded.

B. Components and equipment

Table 1 presents a comprehensive list of the specific hardware components employed in the experimental setup. The HV generator instrument was chosen for its exceptionally low ripple characteristics and programmability. The industrial current sensor was selected due to its specialised application and justifiably high bandwidth rating.

TABLE I EQUIPMENT AND SPECIFICATIONS

Device	Model	Specification
Megger HV DC insulation tester	S1 – 1568 [13]	Up to 15 kV, < 30 ppm ripple
Vishay, coupling capacitor	HVCC203Y6P101MEA	Ceramic Disc, 100 pF, 20 kV, ± 20%
Megger PDIX	CT100 HFCT [17]	1.2 - 40 MHz bandwidth, 1:10
Counter/timer	DAQ NI USB-6008	200 ns re-trigger counter, 32-bit
Digital oscilloscope	Rigol MSO1104	1 GS/s, 100 MHz BW, 8-bit vertical resolution
PD sample	Custom-made, different for various experiments	
Test leads and connections	PD-free solid insulation, HV putty added where necessary	

The external counter/timer resolution is capable of counting events with 200 ns proximity to each other. However, because the devices were driven in the Windows operating system, the real-time resolution was limited to around 1 ms. This was deemed acceptable for experiments with relatively slow ramped HV, because the number of PD events in a typical experiment is relatively low, and the temporal distance between the events is typically much larger than 1 ms. Nevertheless, if several PD events had occurred within 1 ms, then the hardware counter would count them up correctly (i.e., how many times they occurred), but the elapsed time would be assigned as being under 1 ms. This was deemed to be statistically sufficient, as justified by the behaviour of the real data [18].

C. System calibration and environmental conditions

In the system, each device was individually calibrated as per its normal maintenance procedure. Each test required temporal alignment of the start of the test between the HV source instrument and the data acquisition (DAQ) virtual instrument (VI). This was necessitated by the DAQ's real-time clock, which was employed to record the total test duration, as well as the time of each PD event. Environmental parameters were also monitored throughout the experiments, which were conducted in an air-conditioned controlled environment with a stable ambient temperature of 23 °C and relative humidity of approximately 44%.

III. DATA COLLECTION

The PD measurement system acquires data with the oscilloscope preset in its "record" mode setting. The HFCT sensor is terminated with 50 Ω, and its output signal connects to Channel 1 of the oscilloscope. The DAQ hardware monitors the oscilloscope trigger output for a rising edge, indicating a PD event has been detected. The HV source instrument starts the test synchronised with the DAQ. It also streams internally measured output voltage level and corresponding test time, once per second. This ensures actual test time and PD event time can be aligned. The HV source automatically stores streamed data output in a file. The DAQ VI is running in parallel to count the PD event triggers in sync with the oscilloscope, which stores the PD pulse shape information in on-board memory, as shown in Fig. 1.

Fig. 3. Example of an extracted frame no. 14 (out of the total 34) of the recorded PD test data.

After the test has been completed, another VI tool is employed for a combined extraction of the oscilloscope frame data, Fig. 3, the stored test time and test voltage, and the stored PD event time. All the extracted information is saved in a single file for plotting and post-processing analysis.

IV. RESULTS AND DISCUSSION

Figure 4 shows an example of the combined data, recorded on the proposed system. The information of five tests at an identical ramp setting is aligned with the corresponding test voltage on a single time axis. The test time depends on the DC test ramp setting. An identifiable inception voltage region as well as the predefined trigger threshold level are evident in such data. Each PD event is extracted together with its high-resolution pulse shape information, which can then be processed for the estimation of PD charge.

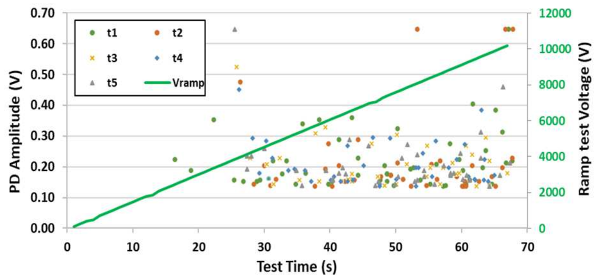

Fig. 4. Example of PD test data for five identical tests (t1-t5) at a ramp setting of 9 kV/min to 10 kV/min.

Measurements showed a level of repeatability as shown in Fig. 5. The standard deviation is comparable to the average value in Figs. 5 (a) and (b), even though the average value changes greatly between the three different test ramps. The results showed that PD recording is not only possible but also sufficiently repeatable and reproducible by using an oscilloscope as a trigger source and a recording device for PD pulse shape in the frame-by-frame method. Results show that good synchronization is attainable as the microprocessor board provides high-resolution time capture.

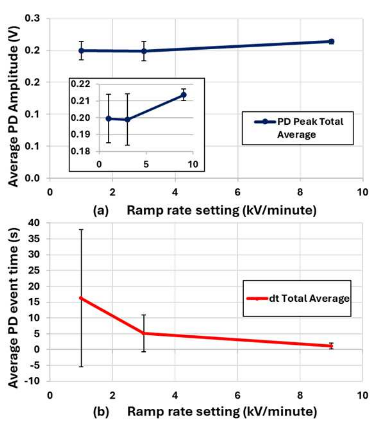

Fig. 5. Standard deviation for five averaged tests of exported PD data at different ramp speed settings to 10 kV, (a) PD amplitude with inset showing the same data on a different scale, and (b) PD event time.

IV. Conclusions

This paper proposes a laboratory-based measurement system for recording experimental data of custom-made samples of partial discharge events. The study demonstrated that partial discharge could be measured and recorded in a more controlled environment, albeit with low-cost equipment. The developed measurement system was achieved with a sampling rate of 100 MS/s and a 32-bit partial discharge event counter. The timing resolution was derived from a 24 MHz time base clock. Frame-by-frame partial discharge pulse data was recorded, and information was exported through a custom virtual environment. The well-tested and established methods using film insulation layers to replicate voids in dielectric material have proven to work repeatably, but there are also many other factors to be considered, and these will be investigated in the future. This method of recording DC partial discharge can allow for more accessible research on the subject and potentially can have applications when used for industrial-level research and development. The versatility of the system lies in the ability to use different sensors or partial discharge cell samples with different materials for multiple sources of partial discharge. It can be used for constant voltage as well as ramped DC. This potential provides an opportunity to expand the knowledge base in the field of DC partial discharge testing.

As ongoing research, more test samples and detailed results, including the measurement analysis, will be provided.

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