WHITE PAPER

High-speed acquisition solution enabling electrical grid monitoring through UHF partial discharge detection

Partial Discharge White Paper
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INTRODUCTION

Throughout the 20th century, electricity has become ubiquitous and a requisite for day to day life. Unsurprisingly, the power grid constructed to support our need for electricity today is vastly complex, dealing with issues such as maintaining or replacing old systems, interfacing older installations with new green power generation solution, supporting and reacting to the fluctuating demand for energy, transporting energy over long distances or crowded areas and standards and overall ensure customer satisfaction. Interruption of service has thus been a strong focus over the past decades and has driven research in monitoring, predicting, and preventing complications within the installation. One physical phenomenon, partial discharge (PD), has been used to detect such issues. This paper introduces briefly the concept and benefit of partial discharge, the different technologies used to capture them, focuses on Ultra-High Frequency (UHF) system and more specifically on its data acquisition system before introducing data conversion solution suitable to build such systems

PARTIAL DISCHARGE AND WHY THEY SHOULD BE MONITORED

Partial discharges are electrical discharges occurring in the insulation layer of electrical equipment (cables, switchgears, circuit breakers, etc). They are called partial, as they do not completely bridge the space between the two conducting terminals.

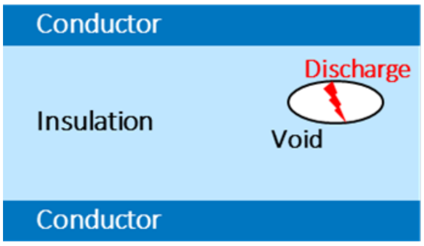

Figure 1: Partial discharge

Partial discharge can occur in many parts of an electrical grid, where high-voltage circulate and is surrounded by some type of insulation (solid, liquid, air). Due to their localized and repetitive characteristics, they build over time and result in insulation breakdown in transformers, power cables, and cable accessories. Being a good indicator of future breakdown leading to material replacement, it is a useful effect to monitor in order to enable early detection and plan preventive replacement through localized interruption of the grid with minimal impact to users.

Today, the manufacturing process for modern cables is well known and established and thus few faulty pieces of equipment are produced and they are generally detected and discarded before reaching the installation stage. Thus, the most critical issue induced by partial discharge happens in joints and accessories.
Monitoring partial discharge in any type of grid brings benefits in maintenance planning as previously mentioned. In addition, having the capability to localize the position of the partial discharge allows to quickly find and resolve the issue. This is particularly compelling for underground sections as digging has significant cost and generate further impact such as road closure.

HOW A PARTIAL DISCHARGE IS DETECTED AND LOCALIZED

Multiple technologies exist to detect partial discharge each with its own benefit, challenge, and use case. This paper focuses on Ultra-High Frequency (UHF) that requires a high-speed detection system to correctly detect the short pulses captured. Nevertheless, a short, non-exhaustive summary of the different technologies to detect partial discharge is presented in Table 1. Note that not all technologies mentioned below are suitable for all types of equipment. For example, UHF and optical technologies are more suitable for Gas-Insulated (GIS) EHV (Extra-High Voltage) transformers. In addition, multiple techniques can be used to improve the performance of the overall monitoring system. More detail on the different use cases, benefits and, challenges of the different technologies can be found in references [A], [B] and [C].

Technology	Advantage	Disadvantage
Acoustic / Ultrasonic	PD location possible	Low sensitivity Susceptible to environment noise
VHF (Very-High Frequency) UHF (Ultra-High Frequency)	High sensitivity PD location possible Low noise / noise mitigation possible	Susceptible to electromagnetic interference
Chemical	High sensitivity	Not suitable for continuous monitoring Uncertain correlation between result and severity of PD
Optical	High sensitivity PD location possible Immune to electromagnetic and acoustic noise	Not suitable for opaque insulation (e.g most liquid and solid insulation)

Table 1: Main partial discharge detection technologies overview

In principle, a UHF partial discharge detector is monitoring the short discharge pulse generated (typically a few nanoseconds in duration). Due to the short pulse time, the discharge signal spans a frequency range from DC to multiple GHz. Using the UHF portion of the signal provides multiple benefits. This frequency band is subject to less or more easily mitigated interference. In addition, with the latest UHF sensors and data conversion technologies providing high-sensitivity; the UHF detection system enables better location precision and default pattern recognition. For power grid monitoring, this translates into a better understanding of where the effect is occurring and how threatening it is.

Partial discharge localization can be done through multiple techniques. Each of them requires multiple sensing channels and determine the location by comparing different parameters of the pulse captured by each channel. Most solutions require a minimum of four sensing channels and the partial discharge location can be determined with an accuracy of 1 meter or less. The most prominent technique is trilateration. The propagation of the pulse from the partial discharge to the sensing channel location (Time-of-Flight) is related to the distance between the two. By comparing the relative time of arrival of the pulse between the different sensing channels, the location of the partial discharge can be inferred, generally within a precision of about 1 meter or less (see reference [D]).

Another solution is based on considering the signal strength captured by different sensing channels. The signal strength correlates to the distance between the partial discharge and the sensing channel. Thus comparing the signal strength captured between the different sensing channels enables pinpointing the partial discharge event. Multiple research papers have been published in the past few years covering this technique (see reference [E], [F] and [G])

THE UHF ACQUISITION SYSTEM IS KEY TO DETECTION PERFORMANCE

The acquisition system objective is to accurately capture the analog output of the partial discharge sensor that represents the partial discharge information. After a step of signal conditioning, the analog signal is converted into the digital domain and is then processed to identify whether partial discharge occurred, their location and any other parameters of interest.

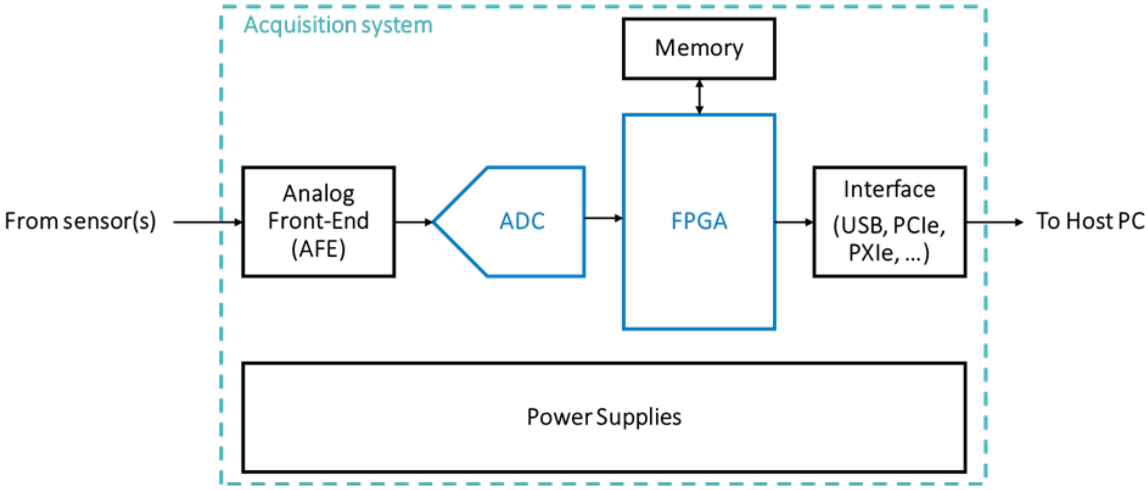

Figure 2: High-level diagram of the acquisition system

One of the most critical components in the acquisition system is the ADC (Analog-to-Digital Converter) converting the sensor output into a digital stream of data that can be processed by the host PC. Due to the impulse nature of partial discharge, their UHF component can reach transient times below 1ns. For accurate capture of the pulse multiple parameters of the ADC need to be considered:

- -3dB analog input bandwidth: the ADC bandwidth needs to be sufficiently high to accurately capture the pulse frequencies. If the pulse frequency is higher than the ADC bandwidth, part of the pulse information will be filtered out by the system. A rule of thumb is to have an ADC bandwidth 5 or 10 times larger than the highest frequency component of the pulse to capture it with adequate accuracy. In order to translate the pulse transient time into frequency, the following equation can be used:

$$Bp = \frac{0.35}{Tr}$$

With Bp the bandwidth of the pulse and Tr the 10-90% rise/fall time of the pulse. This equation is based on an RC low-pass filter response and is a simple way to estimate the necessary bandwidth to capture a pulse. For example, with a 10-90% rise time of 1 ns, the bandwidth of the pulse is 350 MHz and the -3 dB analog input bandwidth of the ADC to recover it accurately should be between 1.75 to 3.5 GHz.

Note that different systems have different requirements translating into different needs for higher ADC bandwidth. Generally speaking, the more information we want to get out of the equipment, the more precise the pulse capture should be and thus the higher the bandwidth requirement. Inversely if the equipment's aim is only to identify whether partial discharge occurs, lower bandwidth of 2 to 3 times the pulse frequency is sufficient.

- Resolution: this can also be understood as vertical (voltage) resolution. It indicates how accurate the value of each sample can be. Higher resolution results in improved accuracy of the conversion. For example, an ADC with a resolution of 10 bits, corresponds to 1024 (2^{10}) possible values covering the full-scale. Assuming a full-scale of 1 V, each step corresponds to 977 µV and with an ideal ADC, the input signal will be sampled and converted with a vertical error within +/-488 µV. From this reasoning, it should also be understood that increasing the resolution by 2 bits quadruples the precision (2^{12} = 4096). While increasing the full-scale to enable larger pulse capture results in lower voltage resolution, it should be noted that the vertical resolution identifies a theoretical performance. In practice, different types of noise impact the performance of the ADC. Thus, it is better to consider the ENOB (Effective Number Of Bits) when looking at the vertical resolution as it includes noise effect. Again, the system target will drive the requirement of ENOB. Generally speaking, the higher the ENOB, the more complex processing, and more detailed information can be extracted from the partial discharge pulses.

- Sampling speed: this can also be understood as horizontal (time) resolution. This indicates how many samples the ADC captures per second. A higher sampling rate corresponds to a shorter time duration between consecutive samples and results in higher timing accuracy on the pulse. Theoretically, the minimum sampling speed needed to recover a given pulse is 2*Bp according to the Shannon-Nyquist theorem. With our previous example of a pulse bandwidth of 350 MHz, a 700 MSps ADC would then be sufficient. Once more the equipment objective will drive these requirements. If more complex information needs to be extracted from the pulse such as partial discharge location, partial discharge energy, or energy pattern, faster sampling may be necessary.

- Channel count: this is simply the number of acquisition channels available. The main benefit of multiple channels for a partial discharge system is the capability to locate the position through trilateration when 4 channels are available. Additionally, having more channels enables concurrent measurement and could be of interest for large-scale systems for example to gather all partial discharge results in a power substation control building and/or transfer the information for remote supervision.

Another key to the acquisition system is the front processing unit that interfaces with the ADC. In most cases, that role is filled by an FPGA (Field-Programmable Gate Array). The FPGA performs the interfacing with the ADC, a first stage of processing and then forward the processed data to the host PC where the data can be subjected to additional post-processing, stored, and translated to decide whether actions need to be taken if and when partial discharge is detected. They are particularly suited for this role due to their parallel processing capabilities and advanced interface options. In addition, they are able to cope with the huge amount of data that high-speed ADCs generate. For example a quad-channel, 10-bit ADC operating at 2GSps generates 80Gbps or 10GBps of raw data. The FPGA is able to interface with the ADC, recover all the data, apply a first level of processing in real-time (e.g. digital filter, non-linear noise suppression, digital baseline stabilization, etc), followed by a selection of the useful data based on complex triggering. In some cases a second level of processing (e.g. pulse analysis) is additionally performed in the FPGA in order to further reduce the amount of data that needs to be transferred to the host PC. Alternatively, this second level of processing can be performed in the host PC.

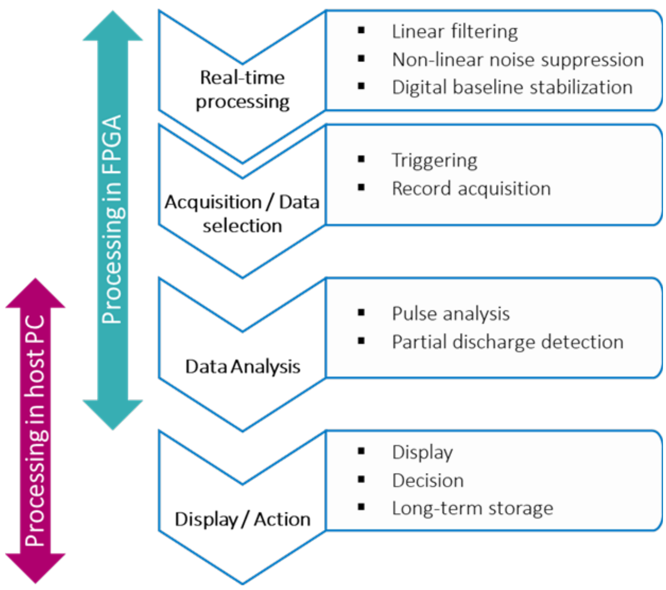

Figure 3: Processing steps overview

These two key components of the acquisition system are then surrounded by an eco-system comprising a front-end to condition the analog signal, on-board memory to support larger data storage, specific interface to host PC, and all power supplies necessary to support the solution as shown in Figure 2.

Teledyne provides two types of solutions suitable for partial discharge equipment manufacturers:

- Teledyne SP Devices develops high-performance data acquisition boards (digitizers) that integrate an ADC and FPGA into a full hardware solution supporting signal capture and processing. These digitizers can directly interface sensors with the host PC and come with powerful firmware capabilities and software solutions. As such, they bring additional benefit to partial discharge equipment by accelerating the product design leading to faster time to market and lower risk at the project level;
- Teledyne e2v develops high-speed Analog-to-Digital Converters. These ADCs bring interesting benefits to partial discharge equipment and are generally considered for equipment focusing on cost and size optimization without degrading the performance.

More details on these two options are shared in the following two sections.

TELEDYNE SP DEVICES – DIGITIZER/ACQUISITION BOARD

Teledyne SP devices, based in Sweden, has been developing high-speed digitizers for the past 15 years focusing on high-speed solutions coupled with flexibility that enables customers to optimize the digitizer to their specific use case. Three digitizers in particular offer good solutions for UHF partial discharge detectors as summarized in Table 2.

Part number	Sampling speed	Channel number	Resolution	Rise/Fall Time (10/90%)	Input range	Form Factor	On-board memory
ADQ8-4X	2 / 4 GSps	4 / 2	10	~350ps	0.25, 0.5, 1, 2, 5 Vpp	PXIe	1 GB
ADQ14	0.5 / 1 / 2 GSps	1 - 4	14	~300ps	0.25, 0.5, 1, 2, 5 Vpp	USB, PCIe, PXIe, 10GbE, MTCA.4	2 GB
ADQ7DC	5 / 10 GSps	2 / 1	14	~120ps	1 Vpp	USB, PCIe, PXIe, 10GbE, MTCA.4	4 GB

Table 2: Teledyne SP Devices' digitizers fit for UHF partial discharge system

As seen in the table above, the ADQ8-4X offers an interesting cost-optimized solution with a compact size and high channel count. It also supports synchronization between multiple boards and chassis with a precision of 200 ps facilitating a more complex detection system over a larger area. An 8 channels version with 1GSps sampling rate is also available (ADQ8-8C).

The ADQ14 offers a higher resolution than ADQ8, and therefore enables more precise pulse measurement. It is available in single-, dual- and quad-channel configuration where the latter is suitable for systems that want to localize or quantify the partial discharge effect.

Lastly, for extreme performance, the ADQ7DC offers fewer channels but with significantly higher sampling speed up to 10GSps enabling high-performance, high-bandwidth equipment.

All three digitizers come with different firmware options that range from general acquisition and triggering function up to firmware development kit option where the user can implement their custom algorithm within the on-board FPGA. On the software side, the user-friendly Digitizer Studio GUI enables easy configuration, acquisition, display, analysis, and storage of the data. While API and example designs enable optimizing the software for the requirement of more complex and/or dedicated systems.

In addition, ADQ14 and ADQ7DC are both available in a 10GbE form factor. This can be an advantage in harsh environments such as sub-stations as it provides complete electrical isolation between the digitizer and the host PC. The optical fiber also means that the distance between the PC and the digitizer can be long, which is adequate in large facilities where multiple measurement points are spread out over a large area.

TELEDYNE E2V – ANALOG-TO-DIGITAL CONVERTER

Teledyne e2v, based in France, has been developing high-speed data converters for the past 25 years and has been leading the market in high-speed quad-channel ADCs technology. Two main ADCs offer an interesting set of specifications for UHF partial discharge detectors as summarized in Table 3.

Part number	Sampling speed	Channel number	Resolution	Rise/Fall Time (10/90%)	Data output	Power consumption	Temperature range	Package
EV12AQ60x	1.6 / 3.2 / 6.4 GSps	4 / 2 / 1	12	~60ps	ESIstream 8 HSSL	6.6 W	0°C to +90°C -40°C to +110°C	CBGA323 (HITCE) 16x16 mm
EV10AQ190	1.25 / 2.5 / 5 GSps	4 / 2 / 1	10	~120ps	LVDS DMUX 1:4	5.6 W	0°C to +90°C -40°C to +110°C	EBGA380 31x31 mm

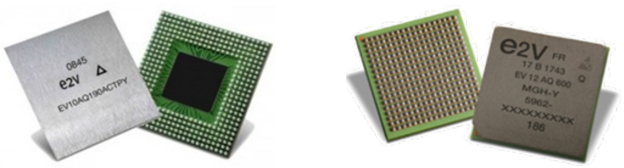

Table 3: Teledyne e2v's ADC fit for UHF partial discharge system

Both EV10AQ190 and EV12AQ60x offer quad-channel capabilities up to 1.25GSps and 1.6GSps respectively. Equipment that aims at localizing the partial discharge can thus achieve it with a single ADC component. In addition, 4 channels in a single component lead to less channel-to-channel variation compared to 4 channels on two devices, translating into a better correlation between the captured partial discharge and thus more precise trilateration.

The EV12AQ60x is an evolution of the EV10AQ190 and as such brings additional benefit:

- Increased resolution from 10b to 12b leading to better measurement precision;
- Serial interface facilitating the interface with the FPGA in particular in terms of layout;
- Better synchronization capabilities between multiple components that may be of interest for complex systems covering full sub-station.

Additionally, due to the choice of Bipolar and BiCMOS technology, these ADCs offer very fast rise, fall, and settling time resulting in more precise pulse capture. Figure 4 shows measurement results on the EV12AQ60x. The value in the table indicates the actual performance of the ADC as the impact from the input signal's performance has been de-embedded and only the ADC performance is considered. With such performance, the EV12AQ60x can support measuring signals with rise and fall times down to about 250 ps with accurate precision. Note that this measurement setup was not optimized, and in particular AC-coupling capacitors are present on the test hardware which results in degraded rise and fall time. Thus better performance than the result shown below is expected when the hardware is optimized for the capture of fast pulses.

The capability for four channels per device is also interesting in order to extend the dynamic range through the use of parallel data capture paths with staggered attenuation settings. This allows to improve the dynamic performance of the signal measured while having the four channels on a single device reduces unwanted effect such as mismatch between channels (offset, gain, and phase) and impedance mismatch leading to reflections. This architecture can also be extended over multiple ADC to further improve dynamic performance if required as mentioned in reference [H].

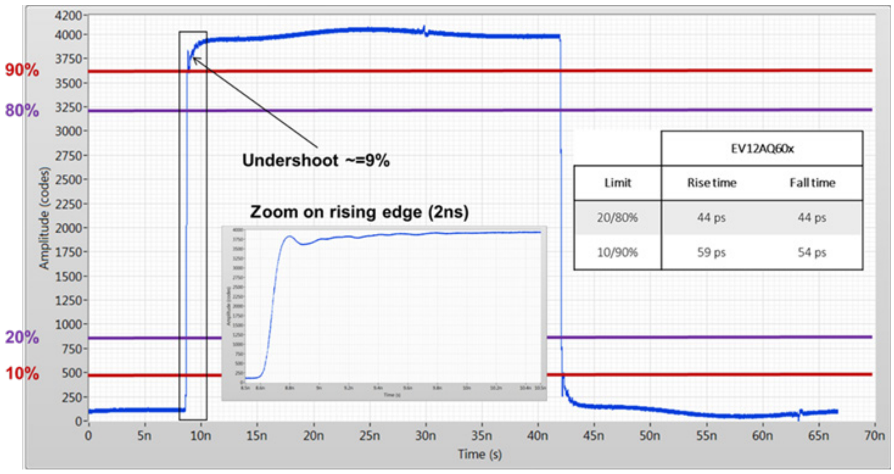

Figure 4: EV12AQ600, pulse measurement

CONCLUSION

In order to cope with our ever-increasing energy consumption, the power grid keep updating both their electricity generation, storage and transport capabilities. Monitoring these complex installation is paramount to improve the reliability of the grid and avoid damaging interruptions. As discussed in this paper, UHF partial discharge detection is a viable solution and integrated alongside complementing technologies enable detection and prevention of partial discharge related issues. Additionally, Teledyne SP Devices and Teledyne e2v offer COTS products matching the requirement of the high-speed acquisition system at either the hardware or the component level enabling our customer to design mid and high-performance UHF partial discharge detection equipment.

FIND OUT MORE

ADQ8-4X product page: https://www.spdevices.com/products/hardware/10-bit-digitizers/adq8-4x
ADQ14 product page: https://www.spdevices.com/products/hardware/14-bit-digitizers/adq14
ADQ7DC product page: https://www.spdevices.com/products/hardware/14-bit-digitizers/adq7dc
EV12AQ60x product page: https://www.teledyne-e2v.com/products/semiconductors/adc/ev12aq600/
EV10AQ190 product page: https://www.teledyne-e2v.com/products/semiconductors/adc/ev10aq190a/

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[F]: A Novel Partial Discharge Localization Method in Substation Based on a Wireless UHF Sensor Array, Zhen Li, Lingen Luo, Nan Zhou, Gehao Sheng, and Xiuchen Jiang, published in Sensors 2017 August

[G]: Partial Discharge Localization through a UHF Signal Amplitude Strength Attenuation Approach, Tingbo Jia, Nan Zheng, Anqing Sun, Peng Li, Qichen Yu and Lingen Luo, 2019 IOP Conference Series: Materials Science and Engineering 486 012123

[H]: RFEL stretches the Dynamic Range of ADCs to provide 'Best in Class' Product Performance, Press release published in Design & Reuse in October 2012

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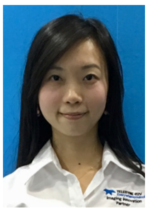

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