

ON-LINE PD MONITORING OF MEDIUM VOLTAGE ASSETS: AN INNOVATIVE APPROACH TO IMPROVE ASSET MANAGEMENT

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ABSTRACT

One of the main causes of fault in Medium Voltage (MV) distribution grids is the breakdown of the insulation system of the electrical assets constituting the network. Such grids are composed of a large number of electrical apparatuses and each one of them is a possible cause of fault. Asset managers aim at increasing the reliability of the networks and decreasing the maintenance/ replacement costs of their parts. Thus it is necessary to have a thorough understanding of the overall status of each component in order to efficiently manage the assets. The focus of the condition assessment is turning toward smart solutions, integrable in networks, able to evaluate autonomously the condition of electrical assets and, only in case of anomalies, to request for man-operated support.

On-line Partial Discharge (PD) monitoring has been identified as an effective diagnostic tool for electrical assets. It is not intrusive and it does not affect the working conditions of the grid apparatuses.

In this paper, a novel approach to manage the MV grid assets through on-line PD monitoring is described. The main requisites of this solution are related to the characteristics of the distribution grids: easy to install, non-invasive, low cost and reliable. The technological solution is comprehensively described, focusing mainly on the automatic acquisition, noise rejection and processing of PD data and the recognition of increasing PD trends as a tool to trigger warning signals. The effectiveness is shown by means of case studies about various MV pieces of equipment, particularly switchgears and Ring Main Units (RMU).

INTRODUCTION

The condition of the electrical asset can be effectively investigated by means of continuous on-line PD monitoring [1-3], a technique allowing to assess the status of the insulation system of the electrical assets without interfering with their normal operations. Due mainly to economic reasons, such technique is commonly used at generation and transmission levels only: failure costs are related to both the repair and unavailability of the power to the loads that are very high in the case of generation and transmission. The overall value of the assets and the outage costs, where outage can be associated to a fault or to unnecessary maintenance operations, can justify the cost of the monitoring equipment and of its operation. Instead, at the distribution level there are factors that hamper the spreading of the on-line PD monitoring.

In particular:

- the wider possibility for redundant connections;
- the use of automatic systems for reconfiguration;
- the availability of spare equipments;
- the complexity of the grids;
- the relatively low value of the assets.

On the other side, MV grids experience frequent electrical faults because of the large number of assets in service, their overall vintage and the harsh environmental conditions in which they are often required to operate. In addition, it has recently been noticed that the random fluctuations of the loads associated with renewable sources have worsened the electromechanical stresses on the cables and they have also been observed to have a negative impact on liquid-filled transformers.

In the following, on-line PD monitoring of MV grid components will be described using an approach designed to take care of the main factors that have limited its diffusion discussed above. The reasons for privileging such approach will be discussed together with a description of the measurement setup, the analytical and statistical elaboration performed to avoid that the large data stream coming from the grid prevents an effective screening of the information. Eventually, case studies on switchgears and Ring Main Units (RMUs) will be discussed.

ON-LINE PD MONITORING

Variations of PD phenomena on timely basis (daily, weekly or seasonal) due to load, temperature or humidity are quite common. On-line PD monitoring enables to track the time behaviour of such phenomena, in particular the intermittent ones or the most influenced by external conditions (e.g., humidity, transients due to power capacitor bank switching on/off, voltage fluctuations due to operation of renewable sources). Moreover, in MV equipments high but stable PD activities are sometimes not problematic for the asset (e.g., PD close to the screen of power cables). On the contrary, low PD activities but having an increasing trend could be harmful. On-line PD monitoring identifies an increasing trend in the PD activity as soon as it starts [4-6]. Thus it allows to discriminate between a harmful phenomenon and one not affecting the insulation or to understand if the time behaviour of the phenomenon could be considered harmful for the MV asset, requiring maintenance.

PD detector

The technological solution devised for the on-line PD monitoring of MV assets is directly derived from the PD detectors used in the High Voltage.

Innovative solutions have been added to fit the requirements of the distribution grids. The key feature is mainly the low target cost but the other characteristics are not less important:

- full digital sampling of the complete waveforms of the detected signals;
- on-board processing of the detected signal waveforms;
- correlation with the voltage applied to the equipment under test;
- automatic separation of multiple PD sources based on the time-frequency mapping of the signals;
- automatic matching of the clusters on consecutive acquisitions in order to establish a focused time behaviour per each single phenomenon;
- warnings related to the time behaviour of the single phenomena.

The listed features enable the operator to have a fully automatic and interconnected solution able to keep track of the status of the monitored asset and to provide early warnings in case of development of potentially harmful PD phenomena.

Table I summarizes the hardware capabilities of the PD detector.

Table I. Summary of the characteristics of the PD detector

PD channel	1
PD bandwidth	16 kHz ÷ 30 MHz
Input impedance	50 Ohm
Resolution	12 bit
Synchronization channel	1
Synchronization bandwidth	1 Hz ÷ 1 kHz
Synchronization resolution	12 bit
Signal elaboration	on board
Connectivity	Ethernet
Protocols	OPC UA/ IEC61850
Dry contacts	normally open/ close

The unit is designed to be integrated into Supervision and Control systems (SCADA) by means of standard communication protocols such as OPC-UA or IEC61850 or simply through dry contacts. Other than the alarms or warnings, the main elaborated outputs of the units are the trendings of PD-related quantities (e.g. the PD amplitude and repetition rate). In order to access to the information stored on the PD detector, it is also possible to connect to it through a standard web browser on a laptop connected to the same network.

PD sensor

Standard PD sensors are used in the measurement chain. Among all the sensor typologies available, the sensors listed in the following are the ones with most easiness of installation, low cost and having a bandwidth meeting the requirements of sensitivity in terms of frequency content of the PD signals and frequency range of the acquisition instrument. The Radio-Frequency Current Transformers

(RFCT), both clamp and compact versions, can be installed on the ground connection of the electrical assets under test and they can sense the high frequency signals flowing through it. The Transient Earth Voltage (TEV) sensor is sensitive to the high frequency potential differences occurring across small impedance mismatches between the metallic parts of the electrical equipment connected to ground. It can be magnetically installed on the surface of the asset, preferably between discontinuities of the surface.

Both sensor typologies can be installed internally to the electrical apparatus or outside it, in case the installation is required to be carried out on-line. Since the evaluation method of the PD phenomena is not based on the absolute PD magnitude, the differences in transfer impedance between the alternative detection schemes are not considered important as long as the signal to noise ratio is similar [7].

Measurement approach

Installed close to the equipment under test, the PD detector performs a set of signal acquisitions at each pre-defined interval of time. Together with amplitude and phase (related to the voltage applied to the equipment under test) used to build the Phase Resolved Partial Discharge (PRPD) pattern, the instrument automatically processes the acquired signals in order to extract the shape parameters, such as equivalent time length and equivalent frequency according to equations (1) to (4) [3].

$$\tilde{s}(t) = s(t) / \sqrt{\int_0^L s(\tau)^2 d\tau} \quad (1)$$

being $s(t)$ the normalized PD signal,

$$t_0 = \int_0^L t \tilde{s}(t)^2 dt \quad (2)$$

being t_0 the “gravity center” of the normalized signal,

$$T = \sqrt{\int_0^L (t - t_0)^2 \tilde{s}(t)^2 dt} \quad (3)$$

being T the equivalent time length, and

$$F = \sqrt{\int_0^\infty f^2 |\tilde{S}(f)|^2 df} \quad (4)$$

being F the equivalent frequency.

The decomposed PD signals are then plotted in an XY graph, the T-F map. Signals coming from the same source are characterized by similar shape parameters, allowing the sources to be grouped into clusters in the T-F map. These clusters are automatically separated by the PD detector in order to discriminate between the different sources [4]. Figure 1 shows an example of a separation of the detected signals of a PD acquisition into three clusters, each one belonging to a different signal source relevant to the color of the cluster. The resulting PRPD patterns are built according to the separation carried out in the T-F map.

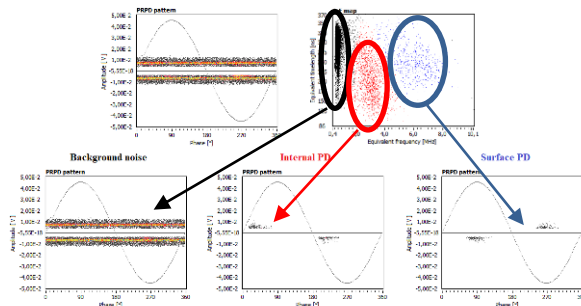


Fig. 1: Example of separation of signals by means of the T-F map clusters

The three clusters identified in the T-F map are relevant to completely different phenomena detected on a switchgear, being the black cluster related to background noise, the red cluster to internal discharges (in the cable terminations) and the blue cluster to surface discharges (again on the cable terminations).

PD acquisitions are performed at time intervals and T-F map separation is automatically carried out on each one of them. Then, in a set of consecutive acquisitions the resulting clusters are retrieved and matched in order to link the ones belonging to the same sources within different acquisitions. The cluster matching allows to elaborate the time behavior of each PD source individually so that the statistical results are the most effective. Tracking each PD source alone means that it is possible to understand if any of them have a stable, increasing or decreasing trend.

PD warnings are raised by the system after a learning period, typically shorter than a week, when the trending of one or more of the detected PD phenomena are increasing beyond a pre-defined rate. Depending on the slope of the increasing rate, the severity of the alarm can be adjusted with a traffic light logic.

The purpose of such alarm is to raise an early warning on the overall condition of the insulation system under investigation. Thus, the end user can focus on the most problematic assets in its distribution grid, having a better understanding of the grid conditions. The maintenance scheduling is more accurate and the asset managers can target the investments in a more precise way.

FIELD RESULTS

In the following, some examples of installation of the on line PD monitoring on MV switchgears and Ring Main Units (RMU) are reported together with the analysis of the data acquired and automatically elaborated in the field by the instruments itself, using the method discussed above to evaluate the time behavior of the single phenomenon alone and to raise warnings only in case there is a significant trend in the diagnostic parameters, particularly repetition rate and amplitude.

The first example is an installation performed on a 15kV RMU, air insulated. As depicted in figure 2, the PD detector is installed on the enclosure of the RMU by means of magnets.

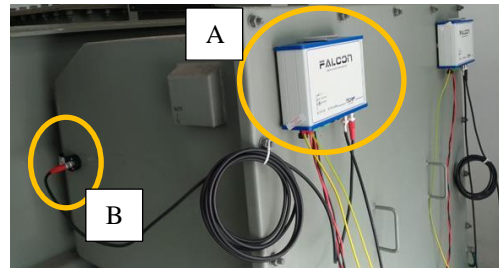


Fig. 2: installation of the PD detector (A) on the front panel of the RMU enclosure and the PD sensor (B)

The PD sensor, in this case a TEV, is installed in the same way on the enclosure on a discontinuity of the metallic panels.

It is noteworthy in figure 2 the possibility to install the PD detectors in cascade in order to establish a communication daisy chain for redundancy. In this way it is possible to set up a subnetwork of the instruments and more electrical equipments can be monitored at the same time inside a substation.

Data related to the PD acquisitions are stored in the PD detector and they are elaborated. In figure 3, the T-F map of the acquisition and the PRPD pattern relevant to the red cluster highlighted in the T-F map.

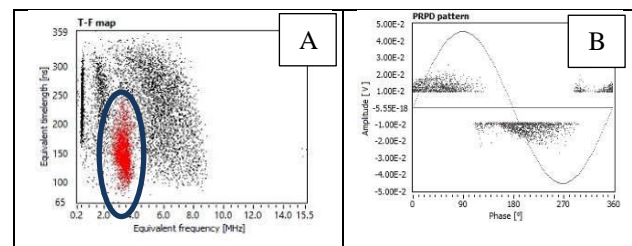


Fig. 3: T-F map (A) and PRPD pattern (B) of the red cluster separated in the map

The depicted phenomenon is related to some internal PD probably occurring inside one of the cable terminations connected to the RMU.

Figure 4 shows the time behavior of the PD amplitude and repetition rate of the red cluster of the previous picture of a time range of about ten days.

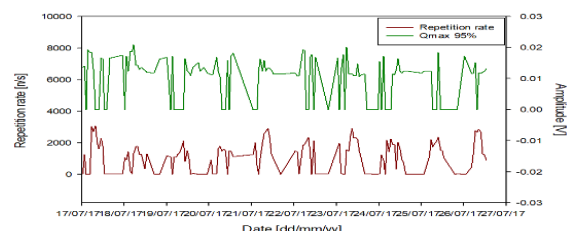


Fig. 4: PD amplitude and repetition rate time behavior of the red cluster

The trending in the figure 4 shows that even if the PD phenomenon is subjected to daily fluctuations, the overall behavior is steady.

The alarm algorithm recognizes the steady state of the PD phenomenon and it does not raise any warning despite the variations that are probably due to daily load cycles or to environmental parameters, like moisture or temperature, since some typologies of PD phenomena are influenced by such parameters.

The second example is relevant to an on-line PD monitoring session performed on a 15kV air insulated switchgear. Figure 5 shows the installation of the PD detector, again on the metallic enclosure by means of magnets and of the sensor, a RFCT clamp wrapped around the ground lead of a panel of the switchgear.



Fig. 5: installation of the PD detector (A) and the PD sensor (B) on a 15kV air insulated switchgear

This installation requires an outage for accessing safely live parts, but it also allows the placement of a Rogowski coil that provides the unit with a synchronization signal used as a reference for the phase calculation. Figure 6 shows the T-F map relevant to an acquisition belonging to a two-month period and the PRPD pattern related to the red cluster (highlighted by the ellipsis in the T-F map), automatically separated by the PD detector. Such cluster is relevant to surface discharges.

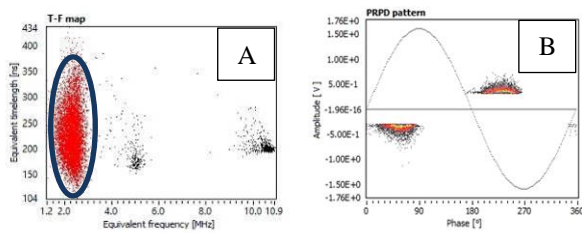


Fig. 6: T-F map (A) and PRPD pattern (B) of the red cluster separated in the map

The time behavior of such phenomenon, plotted in terms of amplitude and repetition rate in figure 7 after removing signals due to other sources, shows an erratic behavior with decreasing trend or no trend at all.

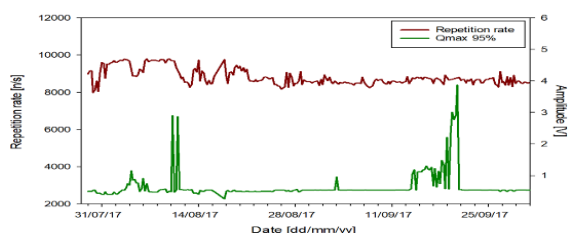


Fig. 7: PD amplitude and repetition rate time behavior of the red cluster

Such behavior is generally associated with air humidity fluctuations and therefore, not considered harmful. The software did not raise any warning message.

The third example is an installation on a MV cubicle with measurement transformers for a railway application. As shown in figure 8, the PD detector is installed in the front panel of the enclosure, while the PD sensor is an RFCT wrapped around the ground lead at the bottom of the cubicle.

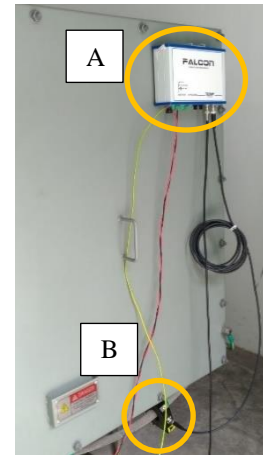


Fig. 8: installation of the PD detector (A) and the sensor (B) on a 15kV air insulated switchgear

In the following figure 9 the overall trend of PD amplitude in a five-month period is reported. It is noteworthy that the overall trend is steady.

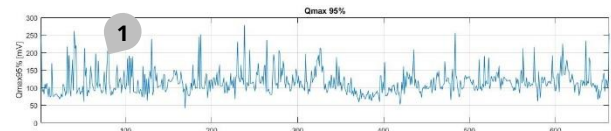


Fig. 9: PD amplitude and repetition rate time behavior of the overall signals acquired

When the elaboration of the T-F map is performed, two phenomena are identified as shown in figure 10. The first one (A) in red is related to surface discharges, the second one (B) in black is corona.

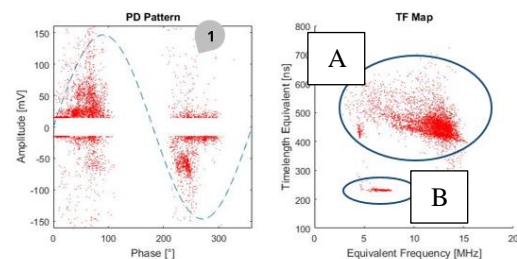


Fig. 10: entire PRPD pattern and T-F map highlighting two clusters (A) surface and (B) corona

The elaborated trending of the two phenomena is then built separately and analyzed as depicted in figure 11.

It is noteworthy an increasing trend of the surface phenomenon (A), estimated at about 10% per week. Such increase of a possibly harmful phenomenon was concealed by the corona phenomenon.

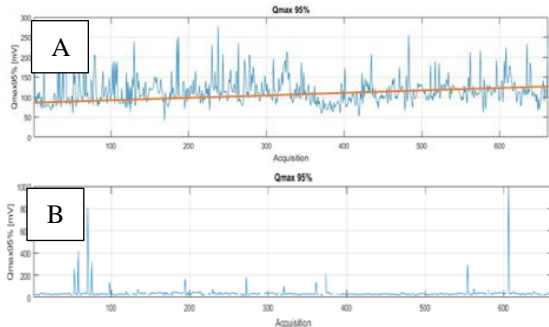


Fig. 11: PD amplitude and repetition rate time behavior of the two identified clusters

In this case the PD detector raised a warning, allowing the operator to focus the investigation on the cubicle under test. Once opened the cubicle, the fault was identified in a surface tracking of a measurement transformer that was afterward replaced. Figure 12 shows the surface tracking activity that was growing on the transformer, leading to a fault.



Fig. 12: measurement transformer identified as the source of the PD activity

CONCLUSIONS

This paper presented a novel approach for the on-line PD monitoring of MV equipments, directly derived from the technology applied to High Voltage assets, though fulfilling the requisites of distribution grids.

The measurement approach was described and field results obtained monitoring from MV assets in the field where presented.

The results show that the PD detector, thanks to the ability to track individual phenomena is not affected by the false positive warnings typical of current technologies available for on-line PD monitoring of distribution grids.

Thus the system enables a more accurate maintenance activity on the assets belonging to a MV distribution grid, allowing a better planning of the activities and providing the asset management with a tool to plan ahead of time replacement and maintenance activities and, as a consequence, the costs.

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