ISA Transactions 58 (2015) 389–397

Contents lists available at ScienceDirect

ISA Transactions

journal homepage: www.elsevier.com/locate/isatrans

Separation of sources in radiofrequency measurements of partial discharges using time–power ratio maps

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ARTICLE INFO

Article history:
Received 28 November 2014
Received in revised form
23 February 2015
Accepted 24 April 2015
Available online 18 May 2015
This paper was recommended for publication by Dr. He Peter.

Keywords:
Partial discharges
Dielectric materials
Condition monitoring
RF measurements
VHF and UHF measurements
Vivaldi antennas
Spectral power

ABSTRACT

Partial discharges measurement is one of the most useful tools for condition monitoring of high-voltage (HV) equipment. These phenomena can be measured on-line in radiofrequency (RF) with sensors such as the Vivaldi antenna, used in this paper, which improves the signal-to-noise ratio by rejecting FM and low-frequency TV bands. Additionally, the power ratios (PR), a signal-processing technique based on the power distribution of the incoming signals in frequency bands, are used to characterize different sources of PD and electromagnetic noise (EMN). The calculation of the time length of the pulses is introduced to separate signals where the PR alone do not give a conclusive solution. Thus, if several EM sources could be previously calibrated, it is possible to detect pulses corresponding to PD activity.

1. Introduction

The insulation systems of electrical assets are subjected to mechanical, thermal and electrical stresses that degrade their behaviour and can lead to unexpected equipment outages and failures, such as in rotating machines [1]. Knowing the condition of the insulation is key for the reliability of power systems [2]. Partial discharges (PD) are low-energy ionizations in sites where highly divergent fields are present [3], so they represent a measurable manifestation of electrical stress and a symptom of other problems in the electrical asset. They are classified into three groups: corona, surface and internal [4]. Corona PD often occur in sharp metallic structures under high-voltage stress. Surface PD may also occur in inhomogeneous locations on dielectrics when there exist a tangential component of the electric field parallel to the dielectric surface. And, finally, the most harmful PD for electrical insulation are internal, occurring in gas filled cavities inside the dielectric, due to imperfections in the manufacturing process, installation or external damages. In addition, its continued activity gradually degrades the insulation system in which they occur leading to a total discharge and the breakdown of the electrical equipment. Therefore, the detection of PD activity is an important test for determining the quality of the insulation system [5]. Moreover, the analysis of partial discharges helps us to perform a correct condition-based maintenance (CBM) of power system assets such as air-insulated substations (AIS) and gas-insulated substations (GIS), transformers, power cables, motors and generators.

One immediate consequence of the PD activity is an electromagnetic (EM) emission in the very-high-frequency (VHF) and ultra-high-frequency (UHF) bands, 30–300 MHz and 300–3000 MHz, respectively, that can be measurable in RF with disc couplers and antennas [6,7]. The use of EM sensors can be applied to any type of insulating material with the advantage of not needing a galvanic connection to the equipment when compared with capacitive and inductive sensors. Moreover, the nature of an insulating dielectric can be related to the frequency band emitted by the PD, being their energy higher at high frequencies for stronger dielectrics than for weaker insulations [8].

On the other hand, the advantage of galvanic insulation turns into a disadvantage when the phase of the sinusoidal voltage is needed to find out what type of PD is active. This is usually done with phase resolved partial discharge (PRPD) patterns where the amplitude of the pulse versus the phase referred to the applied voltage are plotted, and the type of PD is identified through the pattern it draws [4]. Additionally, there is not a clear relationship

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http://dx.doi.org/10.1016/j.isatra.2015.04.006
0019-0578/

between the power emitted by the PD and the power received by the antenna. This loss of information makes it difficult to separate the signals of interest from other interferences (considered, henceforth, as noise). The electromagnetic noise (EMN) can be classified into several categories:

- Continuous sinusoidal noise from communication systems such as FM radio, digital TV, Digital Audio Broadcasting (DAB), Global System for Mobile communications (GSM) and Wi-Fi, which can hide the sources of PD and even can be superimposed to PD pulses. All sources together emit energy in a broadband so their filtering can be laborious as well as the subsequent separation from PD.
- Stochastic noise, random both in time and amplitude such as corona in air, that can emit energy up to 500 MHz, though in most cases they only reach 250 MHz [9] sparking and lamp ignition.
- Periodic-pulsing noise from thyristor operation, i.e. inverters in electrical motors and voltage or current regulated sources.

For these reasons, the characterization of PD in RF is an open and current research topic whose challenge is the possibility of separating different EM sources. All current methods are based on the frequency characteristics of the emitted signals and what changes is the way they represent the differences. In some cases, these representations are based on triangles in which every side is a frequency band at low, medium and high frequencies. In [10], the curves represented in these ternary plots are not absolute values for the magnitude of every source but relative values to each of the sources. In [11], the representation is again in a ternary plot, this time with the energy of the signals. In [12], the representation is based on a time–frequency map already used in measurements with high-frequency transformers in conventional methods with PRPD. Finally, in [13], support vector machines are used to classify signals but a previous training of the SVM is needed.

The proposed algorithm represents the differences in frequency in only two dimensions so one of its main characteristics is its simplicity and the facility to extract conclusions from the representation map. Moreover, when the spectra are very similar and cannot separate the sources, it is complemented with the time duration of the signals. In this sense, the aim is that the separation technique integrates calculations with low computational load to open the possibility to be implemented in Field-Programmable Gate Arrays (FPGA) or in low-cost microprocessors.

In this paper, the use of a specific sensor together with an ad-hoc signal-processing technique is proposed to separate several PD sources and electromagnetic noise (EMN). First, Vivaldi antennas, due to their constructive nature, allow us to mitigate FM radio and low-frequency TV broadcasting bands. Second, the spectral Power Ratios (PR) [14] were selected as a low computational load tool to isolate the measured sources. With this aim, measurements of corona and surface PD have been carried out when two EM sources of disturbances are present. Their power spectral content in two bands of frequency (low-frequency and high-frequency) is plotted in a two-dimension map to separate the signals. It may occur that some EM sources have power in the same frequency bands so they cannot be easily separated. The observation of the signals shows that certain powerful interferences such as sparking due to relays and lamps ignition always have long duration pulses while their frequency content remains in the same band as PD. Hence, this paper proposes the use of the time duration of the pulses as a third variable when two dimensions are not successful in the separation of the sources. Moreover, if several EM sources are previously characterized, it is possible to identify pulses from other sources that very likely could come from PD activity.

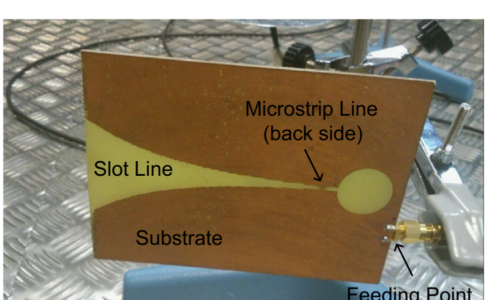

Fig. 1. Vivaldi antenna layout.

2. Vivaldi antenna

Vivaldi antennas are aperture-planar antennas that use two pieces of copper, each one aside of a dielectric substrate [15]. This sensor is a waveguide, or slot line, of small size integrated into a dielectric substrate and an appropriate transition from a feeding transmission line installed in the antenna as depicted in Fig. 1. These antennas are not resonant in nature and broad bandwidth can be achieved with low return losses by optimizing the profile of the slot and the feeding network. Moreover, this antenna has a directive pattern with linear polarization that allows us to be more selective in pulse acquisitions if the sensor is set pointing to the EM emitter.

In this case, a Vivaldi antenna with a total size of 9 cm $\times$ 12 cm was originally designed and optimized to operate centred around 2 GHz. The dimensions of this sensor are chosen according to the restrictions summarized in [16] and to operate in compliance with the requirements of the measurement of PD in UHF. The antenna was manufactured by photolithography in a FR4 dielectric substrate with a thickness of 1.5 mm. Not only is this sensor an inexpensive alternative to log-periodic antennas, but also its behaviour is better than log-periodic and monopole antennas [17]. The reason is that this Vivaldi antenna, adapted for high frequencies, can also measure EM pulses with low-frequency content where corona and surface PD emit power. Thus, these types of antennas mitigate the background interference of FM radio and the low frequencies band of TV broadcasting and, furthermore, they are able to measure PD in a broader band of frequencies than monopole antennas because of their non-resonant nature.

The emitter–channel–receiver system in which the antenna works can be represented by a quadrupole by using the scattering parameters [18]. In this equivalent circuit, the return losses of the antenna are obtained from the measurement of the reflection parameter, S_{11}. When $S_{11}=0$ dB all the power is reflected and for values more negatives than -10 dB the sensor is considered to be matched. To measure the return losses for the manufactured prototype, an Agilent Technologies E8364B Network Analyser is used and its reflection parameter is shown in Fig. 2. As it can be seen, the antenna is matched in the range between 1.3 GHz and 3 GHz. Besides, the antenna has S_{11} values close to -10 dB in the 0.7–1.2 GHz range and between -5 dB and -8 dB in the 0.6–0.7 GHz range which permits us to acquire pulses with power at those frequencies, however mitigated. For frequencies lower than 0.4 GHz, the reflection parameter is greater than -2 dB, so the Vivaldi antenna works as a high-pass filter. Thus, frequency components from FM radio (the EM noise source with higher amplitude) are attenuated in more than 15 dB compared to other high-frequency components.