Electric Power Systems Research 137 (2016) 124–132

Contents lists available at ScienceDirect

Electric Power Systems Research

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

Modeling dispersion of partial discharges due to propagation velocity variation in power cables

J. Granado [a,*], A. Torralba [a], C. Álvarez-Arroyo [b]

[a] Department of Electronic Engineering, Universidad de Sevilla, Descubrimientos s/n, 41092 Sevilla, Spain
[b] Department of Electrical Engineering, Universidad de Sevilla, Descubrimientos s/n, 41092 Sevilla, Spain

ARTICLE INFO

Article history:
Received 3 July 2015
Received in revised form 16 March 2016
Accepted 3 April 2016
Available online 23 April 2016

Keywords:
Partial discharges
Propagation model
Distribution MV cables

ABSTRACT

Existing models for partial discharge (PD) propagation based on a single attenuation constant are unable to explain how each frequency component travels with a different propagation velocity. This paper proposes a new model based on a complex propagation term whose real component does not depend on the frequency (f), and whose imaginary part is modeled with a second order polynomial in f. The proposed model explains how the PD is attenuated, delayed, and dispersed due to the fact that each frequency component is differently delayed.

A closed-form expression is proposed for the PD peak value and width, and a method to derive the model parameters from a reference model existing in the bibliography. Simulation results show that the peak value and width of the propagated PD pulse are similar to those obtained with the proposed model. Additionally, the proposed model provides the velocity of each PD frequency component, which is crucial to get an accurate estimation of the PD source location.

The parameters of the proposed model have been estimated using a vector network analyzer for a XLPE cable. These results have been compared to the measurement obtained in a medium voltage test bench where intentionally induced PDs have been captured and processed, confirming the results of attenuation, delay and dispersion predicted by the proposed model.

1. Introduction

The observation of the phenomenon known as partial discharge (PD) in cables allows engineers to predict imminent failures in medium voltage (MV) distribution networks. Locating PD sources allows to identify the cable degraded areas and, preventively, replace it to avoid a power outage that could affect hundreds of subscribers.

To get an accurate location of the area where partial discharges are being generated, it is necessary to know how these PDs propagate along the cable. Published propagation models are based on classical transmission line (TL) approaches [1–5]. But these models have the following disadvantages:

- It is difficult to estimate their parameters, mainly due to the cable complex structure, as well as the lack of knowledge about the high frequency behavior of its materials [2].
- Existing propagation models for partial discharges, including those based on transmission lines, usually yield to a nearly constant propagation velocity [2,6]. However, experimental results shown in [1] or [2] demonstrate that this velocity depends on the PD frequency components. This dependence leads to dispersion, i.e. the pulse spreads because each frequency component travels at a different propagation velocity [7]. It is well-known that dispersion has a significant effect on the pulse shape [8], as well as negative implications for PD location using techniques such as Time Domain Reflectometry (TDR) [3]. Dispersion has also negative effect on PD pattern classification and recognition [9].
- Understanding how the propagation velocity varies with frequency, or even with cable aging, is crucial for an accurate location of the PD source [5].

Dispersion is mainly due to the high frequency behavior of the semiconducting layer [8]. In addition, small variations of the characteristic impedance along the cable, especially due to aging, also leads to dispersion [5].

Dispersion is modeled in the bibliography by means of a TL model where the propagation term is a real value that linearly depends on the frequency [10]. Thus, dispersion appears because

* Corresponding author. Tel.: +34 954481303; fax: +34 954487373.
E-mail addresses: j.granado@us.es (J. Granado), torralba@us.es (A. Torralba), cesaralvar@gmail.com (C. Álvarez-Arroyo).

http://dx.doi.org/10.1016/j.epsr.2016.04.005
0378-7796/

the high frequency components are highly attenuated. Consequently, the signal bandwidth is reduced, and the original PD shape is spread in the time domain. Since the propagation term is real, this model is unable to explain how each spectral component travels at a different speed.

Present techniques for fault location use those less attenuated spectral components to estimate the fault location. As the frequency components could change, even from experiment to experiment, due to changes in external conditions, or due to cable aging, assuming the same propagation velocity for every frequency component can yield a non-negligible error in the fault location.

This paper proposes a new propagation model for medium voltage cables. This model can be used to study the propagation of PDs, or even other transient phenomenon (lighting impulses, switching transients or breakdowns). It is based on the contributions of Marcuse in the field of light pulse propagation in single-mode optical fibers [11]. The proposed model approaches the attenuation term as frequency invariant, since the useful parts of the spectrum of the signals measured at the cable ends exhibit a low dependence with frequency. The phase term is approximated by a second order polynomial in frequency. This approximation allows to explain how the propagation velocity varies with frequency leading to dispersion.

A simple method valid for both, symmetric and asymmetric pulses, is proposed in this paper to estimate the model parameters from the reference model in [10]. The results obtained with the proposed model are compared by simulation to those obtained with the model of that reference.

The main advantage of the proposed model is that the model parameters can be estimated from experimental measurements, and two methods are proposed here. The first one uses a vector network analyzer (VNA) to measure the frequency response of a cable sample. In the second technique, partial discharges are captured in a degraded cable and digitally processed to measure the pulse dispersion due to cable propagation. Experimental results obtained with a XLPE MV cable are shown to illustrate these methods.

This paper is organized in 5 additional sections. Section 2 describes the proposed propagation model for both, symmetric and asymmetric pulses. Section 3 describes how to extract the model parameters from the reference model described in [10]. Section 4 illustrates how the proposed model agrees with the experimental measurements. In Section 5 we discuss some key aspects related to location of partial discharges that can be addressed with the proposed model. Finally, some conclusions are drawn in Section 6.

2. Proposed propagation model

A transfer function $H(\omega, L)$, shown in (1), is proposed to model the propagation of PDs in MV cables. In (1), $\gamma(\omega)$ is the complex propagation term, and L is the propagated distance.

$$H(\omega, L) = \exp(-\gamma(\omega)L) \quad \text{where}: \ \gamma(\omega) = \alpha_0 + j\beta(\omega). \tag{1}$$

The real part of the propagation term, α_0, is responsible for PD power reduction in $8.68\alpha_0$ dB/m. A typical value for α_0 is 0.03 dB/m.

Concerning the imaginary part of the propagation term, or phase term $\beta(\omega)$, it models the phase variation due to propagation. Term $\beta(\omega)$ determines the propagation velocity, the propagation delay, and is responsible for pulse dispersion. Unlike most of the models proposed in the literature, which assume $\beta(\omega)$ to have a linear dependence with ω, the model proposed here assumes a quadratic dependence with ω as shown in (2).

$$\beta(\omega) = \beta_0 + \beta_1\omega + (1/2)\beta_2\omega^2,$$
$$\text{where}: \ \beta_1 = \partial\beta/\partial\omega|_{w=0} \text{ and } \beta_2 = \partial^2\beta/\partial\omega^2|_{w=0}. \tag{2}$$

Delay constant β_1 is responsible for the delay (also called group delay) of the initial pulse after travelling a distance L. The propagation time $t_p = \beta_1 L$ can be considered to be the mean value of the propagation delay of every spectral components in the propagated pulse. Constant β_2, or dispersion constant, is responsible for the spreading of the initial pulse shape due to the fact that each spectral component propagates at a different speed.

2.1. Gaussian pulses

Expression (3) models an initial Gaussian pulse with amplitude and deviation A_0 and σ_0, respectively. Fig. 4(a) shows this signal. Using the proposed propagation model, the resulting propagated pulse at a distance L is shown in (4), where it can be observed that: (a) the resulting pulse is gaussian too; (b) it has been be attenuated (A_L is the resulting peak value and even if we consider a non dissipative ($\alpha_0 = 0$) medium, the peak value would be reduced due to dispersion if $\beta_2 \neq 0$); (c) it has been phase delayed in an amount of θ_L radians; (d) it has been time delayed t_p seconds; and (e) it has been dispersed along the cable: the original deviation σ_0 has grown up to σ_L due to dispersion.

$$v(t, 0) = A_0 \exp(-t^2/2\sigma_0^2). \tag{3}$$

$$v(t, L) = A_L \exp(-j\theta_L)\exp(-(t - t_p)^2/2\sigma_L^2), \tag{4}$$

where

$$\sigma_L = (\sigma_0^2 + \beta_2^2 L^2/\sigma_0^2)^{1/2},$$
$$A_L = A_0\sigma_0(\sigma_0^4 + \beta_2^2 L^2)^{-1/4}\exp(-\alpha_0 L),$$
$$\theta_L = \beta_0 L + \arctan(\beta_2 L/2\sigma_0^2) - \ldots$$
$$\beta_2 L/2(\sigma_0^4 + \beta_2^2 L^2), \text{ and}$$
$$t_p = \beta_1 L.$$

2.2. Asymmetric pulses

The skewed nature of the PD pulse is modeled in [10] by means of a sum of delayed gaussian functions. Using N_G components, the resulting pulse waveform is given in (5), where $A_{0,k}$, $\sigma_{0,k}$, and $\tau_{0,k}$ are the peak, typical deviation, and delay values of the gaussian component k, respectively. Fig. 6(a) shows the asymmetric pulse generated using this model.

$$v(t, 0) = A_p \sum_{k=1}^{N_G} A_{0,k} \exp(-(t - \tau_{0,k})/(2\sigma_{0,k}^2)), \tag{5}$$

where

$$A_{0,k} = 0.2245\exp(-k/10),$$
$$\tau_{0,k} = 10^{-9}(k + 5000), \text{ and}$$
$$\sigma_{0,k} = 10^{-9}\exp(k^{0.25})/\sqrt{2}.$$

Assuming that the propagation medium is linear, the expression in (6) describes the L meter propagated asymmetric pulse, where α_0, β_1, and β_2 are the attenuation, delay, and dispersion constants of the proposed method. The resulting $v(t, L)$ signal is composed of N_G Gaussian components, where $A_{L,k}$, $\sigma_{L,k}$, and $\tau_{L,k}$ are the amplitude, deviation, and delay of the k-th component, respectively.

$$v(t, L) = A_p \sum_{k=1}^{N_G} A_{L,k} \exp(-(t - \tau_{L,k})/(2\sigma_{L,k}^2)), \tag{6}$$