Power Cable Modeling for PD Pulse Propagation and Sensitivity

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***Abstract*—In this paper a model is presented, which can determine the PD pulse propagation in power cable systems by considering the change of pulse shape and amplitude. The pulse shape changes due to frequency dependent attenuation and dispersion in the cable. All these parameters are dependent on e.g. the length of the system and material of the insulation. The model is able to handle arbitrary kinds of pulses, which are measured in the time domain.**

***Keywords*—Cable testing; PD measurement; PD diagnosis; HV power cable**

I. INTRODUCTION

To verify the correct installation and PD performance of the whole cable system, high voltage cables are tested by applying partial discharge (PD) measurements. This provides a verification of an accurate installation of new energy cable links or a condition assessment during maintenance tests. The occurrence of PD shows defects in the cable insulation or incorrect installed joints or terminations of the cable system. Because of the long dimensions of high voltage cable installations, the location of the PD source is an important information parameter [1], [2].

Nowadays time domain reflectometry (TDR) analysis is used as a common technique for the localization of the PD source. The excitation of a travelling wave by the partial discharge is used for localization [3]. With assistance of the pulse travelling time, the origin of the PD source can be determined. Not only the PD origin is an important information quantity for condition diagnosis, but also the PD magnitude is helpful information about the defect and its criticality [4], [5]. The determination of PD magnitude is based on the calculation of the actual charge, which has travelled from the partial discharge origin [6]. By the propagation of the pulses through the cable system, the detectable charge and amplitude of the pulse decreases due to attenuation and dispersion of the PD pulse [7].

Propagation of pulses in shielded power cable systems is an important issue for partial discharge measurements in such distributed insulation systems. Because of the length up to several kilometers and the influences by disturbances and noise during onsite measurements, the knowledge about pulse propagation is an important parameter for proper measurements. Limitations due to the dynamic range of the measurement devices, e.g. digitizer or oscilloscopes, the signal amplitude of the measured pulse should be high enough, otherwise it disappears in the background noise level. Also the sensitivity is an important value in partial discharge measurements. If the measurable pulses are too small or the background noise level of the measurement is at a high level, reliable information about the condition of the insulation cannot be obtained. The sensitivity of the measurement will also be influenced by the geometrical dimensions of the device under test. Large test objects like power cable systems have significant influence on PD pulses, due to attenuation and pulse deformation caused by dispersion [3]. Not only the magnitude of the pulse will decrease by travelling along the distance of the cable, also the shape may be modified. Therefore it is advantageous to have knowledge about incidents of PD pulses in such cables.

This paper focuses on the propagation characteristics of PD pulses in long cables and their influence on attenuation, dispersion and travelling time. Based on these properties a model is being developed for a better prediction of the pulse shape after travelling through the cable. This model can be used to get information about the sensitivity of measurements on long cables. In this context also the background noise level and the dynamic range of the measurement equipment play a significant role.

II. MODEL PARAMETERS AND PULSE CHARACTERISTICS

Different parameters are necessary to calculate the propagation of an arbitrary pulse given in time domain. These parameters differ for each cable type [7]. For the model which is shown in this paper, the input parameters are attenuation and wave propagation velocity. Both parameters are frequency dependent as illustrated in Fig. 1. The frequency dependency of the attenuation is caused by the skin effect and the dielectric losses in the insulation. Both effects increase with frequency and bring more attenuation at higher frequencies. The frequency dependent wave velocity, referred to dispersion, affects different spectral parts of the pulse.

The dispersion leads to pulse deforming, because most of the real impulses have different spectral densities over the distribution in their time duration.

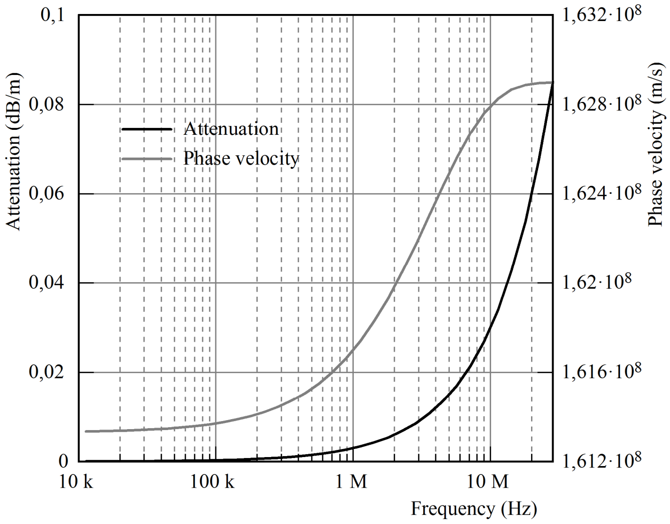

Fig. 1. Frequency dependent phase velocity and attenuation used as input parameters for the cable model calculation.

The third parameter which is necessary for the calculation is the travelling distance of the pulse. This parameter differs for each origin of the PD source and is an important factor for the calculation. For each distance, the model needs to recalculate the pulse shape and pulse amplitude.

In the following chapters, we will consider pulses whose time duration is much smaller than the travel time of the pulse within the total cable length. This assumption avoids the synthesis of distorted pulse shapes due to superposition of pulse reflections. This simplification is only valid for long cable lengths. For shorter cables, the effect of superposition has to be considered.

III. MEASUREMENT PROPERTIES AND INFLUENCES TO THE MODEL

Actual measurement data of the pulses within a cable were used in the model and resulted in some simplifications in the calculation. Actual PD pulses have a time duration of some microseconds, which makes it possible to reduce the data for the calculations. To obtain a proper time resolution a minimum sampling rate of about 100 MS/s is necessary, which results in a few hundred to thousand measurement points used for the calculation. Higher resolution bandwidth or more samples per record, increases the calculation time and possibly leads to insufficient memory.

Another simplification which can be applied for the calculation is the bandwidth limitation of the measured signal. Because the spectrum of the PD pulse has a margin to lower frequencies, the measurement setup with the coupling device in use leads to a lower cutoff frequency at about 10 kHz. The high frequencies will be damped by finite sampling frequencies and the low pass characteristic of the cable. Measurements have shown an upper cutoff frequency of about 30 MHz as a reasonable value. This leads to a band pass region from 10 kHz to 30 MHz where the model should operate. This limitation in bandwidth also reduces the time for calculation.

IV. FUNDAMENTAL FUNCTION OF THE MODEL

The basic function of the model is the calculation of a pulse response for an arbitrary input impulse with a user-defined travelling time in a cable. First the model parameters of cable length, phase velocity and attenuation have to be defined. Afterwards the model will calculate the response of the PD pulse after travelling a defined distance through the cable. With the adjusted parameters of the frequency dependent attenuation and the signal dispersion, the model determines step by step the requested output pulse for the specified cable length.

The model divides the input signal up into spectral components and scales, or shifts the components corresponding to their attenuation or dispersion. After each calculation step, the different signal components are super-positioned to obtain the result. If the total length is reached, the calculation is completed and the model exports the resulted data. The calculated pulse is dependent on the travelled length time shifted in relation to the original input impulse. Furthermore the pulse shape appears to be more flat and wider.

V. DETAILED FUNCTION OF THE MODEL

This chapter describes the essential procedure included in the calculation process. As a first step, the model reads the input signal. This signal is defined by amplitude values with equidistant time steps. A basic block scheme is shown in Fig. 2. For the next step, the model verifies the sampling rate and if necessary resamples the signal. Then the model splits the signal into several frequency groups with defined lower and upper cut off frequencies. As a result the signal is fragmented into a number of frequency components. For each frequency component the model has values for the attenuation and the dispersion from a lookup table. This table has to be defined by the user and contains the cable specific quantities.

The attenuation is given by a scalar which has a frequency dependent scale factor. For the dispersion coefficient the lookup table (plotted in Fig. 1) contains values for each frequency component as wave propagation velocity $v_{phase,n}$ with the dimension in m/s. Each separated frequency component of the input signal $Data_{in}(f_n)$ is scaled with the value from the lookup table, where f_n is the frequency component and SF_n the scale factor for each component, respectively. This process has to be repeated for every frequency component and the result is given by $Data_{out}(f_n)$.

$$Data_{out}(f_n) = Data_{in}(f_n) \cdot SF_n \qquad (1)$$

After scaling the signals, the dispersion factor is included. Hereby the signal gets a time shift, which would be calculated from the value obtained from the lookup table (plotted in Fig. 1).

$$\Delta T_{phase,n} = 1m \big/ v_{phase,n} \qquad (2)$$

As a next step, the signal components are combined together to construct the new output signal. The signals will be added with time delay of the frequency dependent phase shift

$\Delta T_{phase,n}$. If necessary the output data can be resampled to the rate of the original input signal.

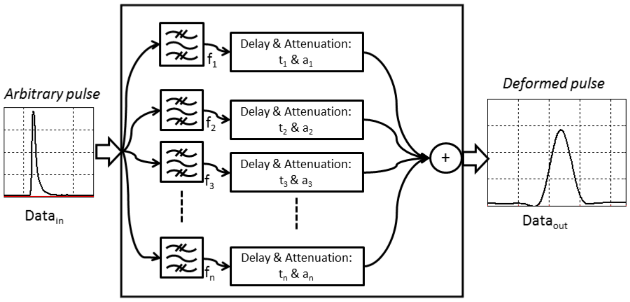

Fig. 2. Block scheme of the basic model function.

VI. VERIFICATION AND APPLICATION OF THE MODEL

A. *Verification*

The first example shows a comparison of a measurement with the result of the presented model. The test setup consists of a 500 m long EPR 120 kV DC cable, a PD pulse calibrator and an oscilloscope. The connection to the oscilloscope was done with a high input impedance probe (10 MOhm, 14 pF). The cable has an open end and the cable did not have any terminations or joints.

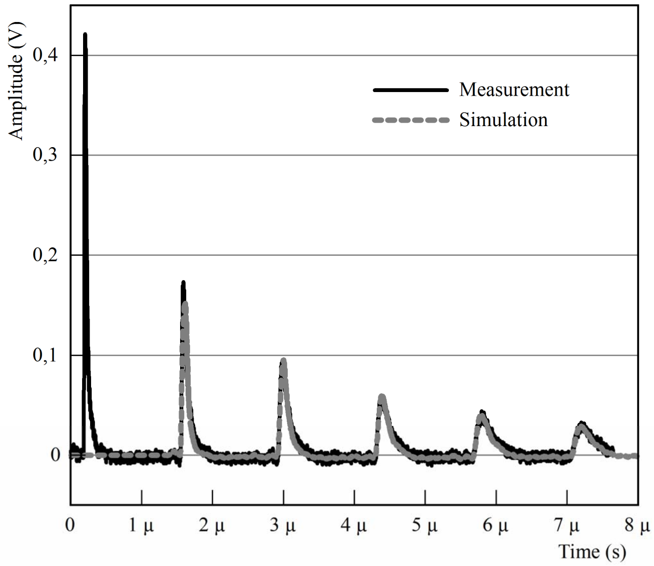

Fig. 3. Measured and simulated voltage amplitude as a function of time.

Fig. 3 shows the measured signal with the first five reflections and the calculated response by the model. The model parameter for the first reflection is the travelling length of two times the length of the cable, which is 1 km, forward and reverse way summed

To compare the PD magnitudes of measurement and simulation, each reflection is integrated with a time constant T_i. The formula for the PD value calculation consists of a summation of all absolute data values in the interval from t_0 to $t_0 + T_i$, see equation (3).

$$PD_{value} = \sum_{t_0}^{t_0+Ti} \left| Data(t) \right| \tag{3}$$

Data(t) is the measurement or simulated data whereas PD_{value} results from calculation and represents a dimensionless value to compare both measurement and simulation.

To compare the measurement results with the simulated PD value the first five reflections are evaluated and listed in Table I. It should be noticed that the first measured pulse and the first simulated value are normalized to 500 pC, respectively.

TABLE I
COMPARISON OF MEASURED AND SIMULATED PD VALUES

Reflection #	From Measurement Data (pC)	From Simulation Data (pC)
1	500	500
2	412	418
3	348	357
4	297	306
5	255	265

From the calculation of the PD values for the particular reflections, a similar trend of both measured and simulated data is observable. In Fig. 4 the values of the Table I were plotted in a diagram versus the travelling distance. Both curves have the same decay of amplitude.

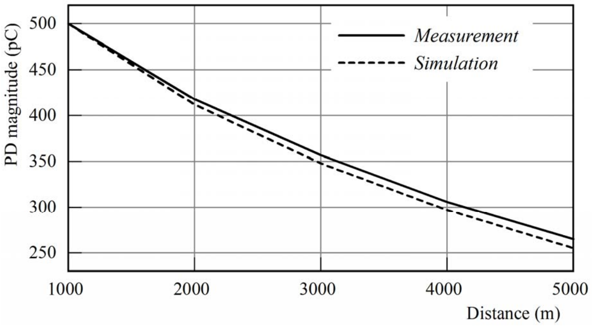

Fig. 4. Measured and Simulated PD magnitude as function of travelling distance. Both are normalized to 500 pC for the first value.

B. *Application for Sensitivity Check in a noisy environment*

The length of a power cable system is an important limitation of a reliably PD diagnosis. Due to attenuation and dispersion the measureable signal decreases with the travelling length in the cable. The attenuation decreases the amplitude with increasing travelling length. Also the dispersion leads to different results with longer travelling distance, regarding the impulse widening and the rise time reduction as compared to the integration time constant. Moreover, dependent on the actual noise levels and the finite dynamic range of the measurement equipment the overall sensitivity is affected.

Due to these factors, a minimum required PD level for each travelling distance can be derived, as the maximum length for PD detection of a certain magnitude is limited. To evaluate this issue a sensitivity check is proposed to provide a possibility to ensure reliable diagnosis.

The following example explains the above discussed points. The grey signal in Fig. 5 is a measurement with a certain noise level. The first peak of the signal shows a partial discharge injected by a PD calibrator with a level of 50 pC.

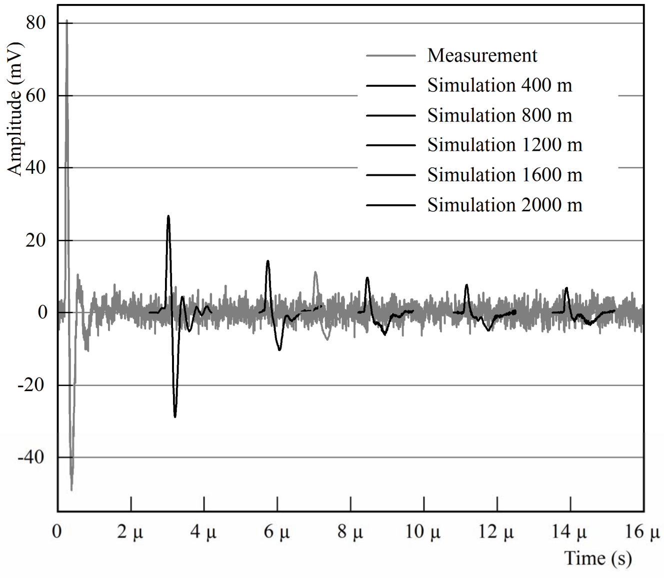

Fig. 5. Noisy measurement signal with partial discharge pulse and five calculated responses for different travelling lengths.

This injected pulse travelled the direct way from injection origin to the measurement device. After 7 µs the reflection over the far end in the measurement signal is detectable. The five black signal parts show calculated signal responses for different travelling length. The three left responses could be associated to the direct propagated signal, contrary to the last two signal fragments, which are within the actual noise level. The PD values for each pulse are shown in table II.

TABLE II
PD VALUES OF PULSES WITH DIFFERENT TRAVELLING LENGTH

Pulse #	Travelling distance (m)	PD magnitude (pC)
0	0	50
1	400	28.8
2	800	15.4
3	1200	11.8
4	1600	10.1
5	2000	9.4

Therefore it could be concluded, that a PD level of 11.8 pC could be detected in this cable system in a distance of 1200 m. Smaller partial discharges will disappear in the noise level of this example.

VII. CONCLUSION

In this paper a model is presented for the pulse propagation of PD pulses within a power cable. The model can calculate the pulse propagation in power cable and the resulting pulse in the time domain based on the cable parameters and PD pulse parameters.

The model was verified with a measurement and a test setup with multiple reflections to obtain different travelling length of PD pulses. For both, measured and simulated PD magnitude was compared.

By applying the sensitivity check an additional possibility is provided for PD magnitude estimation in relation to the travelling length determination. This could allow the model to be implemented in future PD measurement and analysis software. The limiting boundaries, e.g. the cable length and PD magnitude could be mapped to the measurement plot. Further investigation can be used to build up a database of the frequency dependent attenuation and dispersion for different cable types.

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