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PARTIAL DISCHARGE DETECTION IN POWER CABLES: PRACTICAL LIMITS AS A FUNCTION OF CABLE LENGTH

Andrea CAVALLINI, DIE University of Bologna (Italy) andrea.cavallini@mail.ing.unibo.it
Chandrasekar SUBRAMANIAM, DEEE, Sona College of Technology, (India), chandrukvt@gmail.com
Gian Carlo MONTANARI, DIE University of Bologna, (Italy), giancarlo.montanari@mail.ing.unibo.it

ABSTRACT

Power cables behave as transmission lines as regards partial discharge (PD) pulse propagation. Attenuation and dispersion phenomena have, therefore, great influence on the detectability of PD pulses, particularly when long cable routes and detection from terminals are considered. This paper presents an approximate model to infer PD pulse waveform as a function of the distance travelled along the cable and shows results that can provide practical limits for PD detection in cable routes when using IEC 60270-compliant and/or ultra wideband detectors. Considerations on the effect of calibrator characteristics on sensitivity check procedures are, eventually, reported.

KEYWORDS

Partial discharge, bandwidth, detection sensitivity.

INTRODUCTION

Partial discharge (PD) pulses traveling along power cables undergo frequency-dependent attenuation and dispersion phenomena. Since attenuation increases with frequency, traveling pulses lose frequency content, as more as the distance between the PD source and the detection point (traveled distance) increases. As a consequence, depending on the spectral characteristics of background noise and interference, detection effectiveness decrease up to a point where detection can be practically unfeasible.

Modeling frequency-dependent losses (and, therefore, attenuation and dispersion constants) in power cables is, therefore, a key point for establishing (a) the optimum detection bandwidth to detect pulses coming from a given distance and (b) the maximum distance at which PD pulses can still be observed. In [1], a model based on the Advanced Transient Program (ATP) has been proposed and experimentally validated. Here, the model will be recalled shortly, being the focus of the paper on practical implications for PD testing.

CABLE MODEL

Propagation phenomena in cable systems are very difficult to model accurately. As a matter of fact, models that are commonly encountered in power system simulation packages (e.g., the ATP) take into account only skin effect losses. However, at frequencies larger than 1 MHz, those that generally are interesting for PD propagation issues, semicon losses become the predominant factor [2].

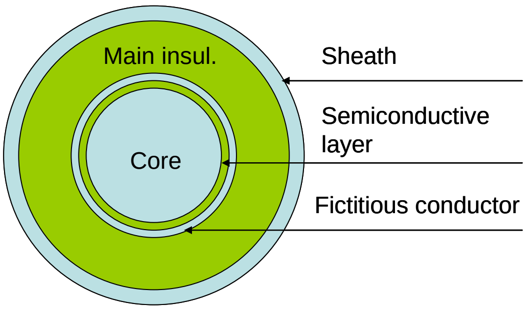

Figure 1. Structure of the cable model used simulation purposes.

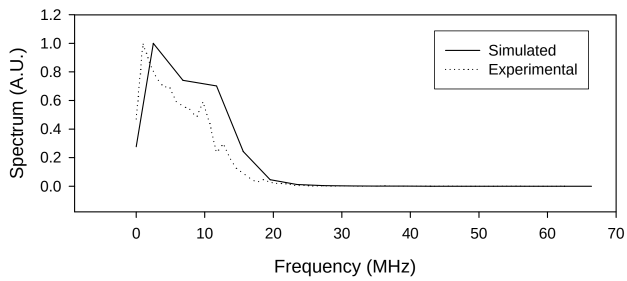

Figure 2. Comparison between experimental measurements and simulation results in the frequency domain. The distance between sending end and detection point is 360 m. Receiving end: open-circuited.

Modelling semicon characteristics is fairly complicated, as one needs to perform measurements through network analyzers and, moreover, the complex permittivity of semicon materials is subjected to change with frequency, pressure and temperature [3].

In order to obtain an approximate propagation model, tests were performed in the lab by injecting calibrator pulses into two MV cable rolls and by looking at the characteristics in the time and frequency domain of the propagating pulses. It was found that, with some approximation, the model reported in Figure 1 could be used properly. In particular, semiconductive layers were simulated through a layer having a relative permittivity equal to 1 and resistivity of 3 $\Omega \cdot$m (value obtained through DC measurements performed on the tested cable, neglecting the dependence of resistivity on frequency). A fictitious conductor around the semiconductive layer had to be considered due to the constraints of the ATP routine that evaluates transmission line parameters (i.e., RLGC parameters) as a function of frequency starting from the geometric characteristics of the cable. As shown in Figure 2, discrepancies between simulations and measurements were mostly at the largest frequencies (tens of MHz). Being attenuation phenomena slightly underestimated in the model [1], it will be considered as able to provide upper bounds for PD detectability when ultra-wide band detectors are employed.

Numerical filters reproducing the characteristics of an IEC60270-compliant quasi-integrator filter for wide-band detectors [4] were used to infer apparent charge. Calibration was performed through numerical procedures as explained in [1].

Following this approach, it is possible to simulate the detection of propagating PD pulses through ultra-bandwidth (UBW), as well as IEC 60270-compliant detectors. In the former case, it is assumed that the complete waveform of the PD pulse could be detected and recorded by the measurement system without any distortion.

PD propagation was inferred by injecting (through an appropriate impulse generator model of the ATP) 1 pC pulses into the cable. The cable itself was modelled by two lengths in series: PD pulses were measured by probing the voltage at the node connecting the two lines. The first line had a pre-selected length (from 50 m to 5 km); the second one, used to avoid reflection phenomena at the detection node, was 1 km long.

PD DETECTION AND SENSITIVITY FOR MV CABLES

The first analysis reported here concerns the simulation of PD apparent charge behaviour as a function of travelled distance. Owing to linearity, it is sufficient to trace the curve reporting apparent charge values recorded by a detector at a distance L from the source for a PD having an apparent charge of 1 pC. Clearly, for PD having a magnitude different from 1 pC, results can be scaled appropriately.
As it can be seen from Figure 3, attenuation phenomena can be an issue even in the frequency range for IEC 60270-compliant detectors. An attenuation of 50% can be expected for distances between source and detection point in a range of 300-800 meters. Indeed, as Figure 4 points out, attenuation is more marked when UWB detectors are used (the slope of the line that provides the best fit of magnitudes is -0.32 and -0.77 for the IEC 60270 and UWB detector, respectively). This attenuation is mostly associated with the effect of semicon layers, that attenuate large frequency components.
It is worthwhile observing, however, the behaviour of PD pulse peak in the UWB, prior and after IEC 60270 filtering, as reported in Figure 5. The Figure shows that, at short distances, the peak value after IEC filtering is much smaller than that prior filtering. However, as the travelled distance increases, the difference between the two peaks is reduced considerably. This means that, at dist6ances of some km, filtering does not affect remarkably pulse spectrum or, in other words, that the pulse spectrum tends to be more and more similar to the frequency response of the IEC 60270 quasi-integrator.

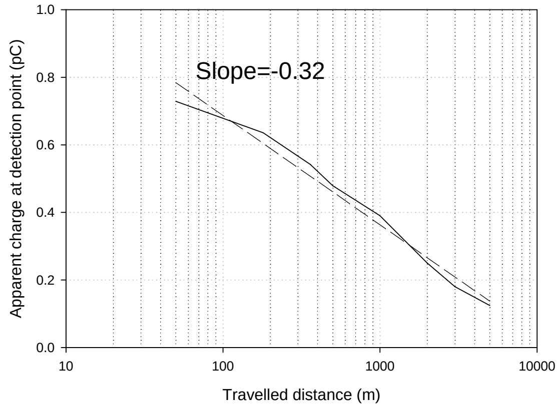

Figure 3. PD apparent (IEC 60270-compliant detector) charge as a function of travelled distance for a MV cable. The regression line fitting the data is also reported (dashed line). Simulation.

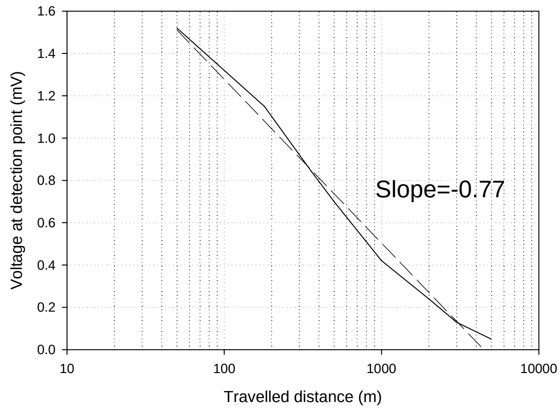

Figure 4. PD pulse peak value (UWB detector) as a function of travelled distance for a MV cable. The regression line fitting the data is also reported (dashed line). Simulation.

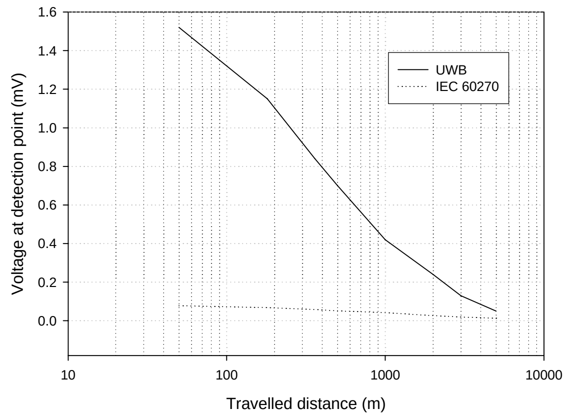

Figure 5. PD pulse peak value in mV for an UWB and an IEC 60270-compliant detector. Simulation.

The likelihood of PD detection depends very much on the spectral characteristic of noise and PD pulses. Generally speaking, noise energy decreases with frequency [5,6], thus detection performed in close proximity of the defect (i.e., by measuring PD at each cable accessory) using an UWB detector is in most case the solution providing the best Signal to Noise Ratio (SNR). When detection is performed very far from the PD source general conclusions cannot be drawn. Indeed, in some cases (as, e.g., when noise is

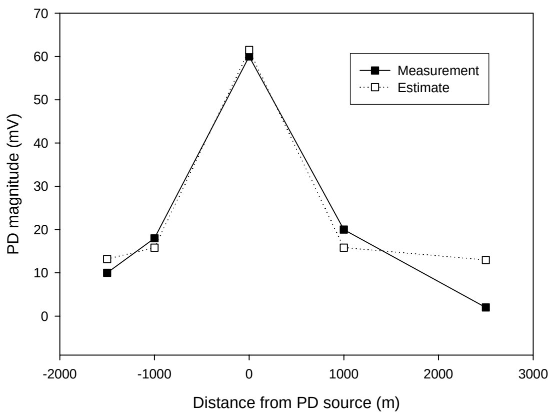

Figure 6. Comparison between measured and simulated PD height as a function of travelled distance. Measurements come from an after-laying test performed offline on a 220 kV XLPE cable system. PD height at the source has been assumed as the reference value

bounded in a range of frequencies close to those where IEC 60270-compliant must operate) UWB detectors can still provide a better SNR with respect to IEC 60270-compliant ones.

PD DETECTION AND SENSITIVITY FOR HV CABLES

Simulations were carried out also on a model of a 220 kV XLPE HV cable. The model used was similar to that employed for MV cables, i.e., semicon layers were described through a layer having relative permittivity equal to 1 and resistivity 3 Ω·m, same thickness as the one used for the MV cable. Since it was not possible to check extensively the accuracy of the model for a HV cable in the lab, measurement results performed at each joint of a 220 kV XLPE cable system during after laying test were compared with simulations. Due to the fact that high frequency current transformers had been used on field to pick up the PD signal, measured and simulated data were normalized by using the amplitude at the PD site as a reference value. The comparison between measured and simulated PD amplitudes shown in Figure 6 emphasizes that the model can provide satisfactory results even for quite low propagation distances.

After model checking, simulation similar to those presented earlier for MV cables were carried out. By comparing Figs 3 and 7 it comes out that MV and HV cables behave in a similar way when IEC 60270-compliant detectors are used to detect PD (the regression line slopes are: -0.32 and -0.29, respectively, both characteristics provide 0.8 pC observed at 50 meters). In the case of UWB detection, HV cables seem to propagate PD with less attenuation than MV cables, at least at a distance up to about 1 km (see results for both type of cables reported in Figure 8). For cable lengths exceeding 1 km, the two cable types seem to behave in a similar way.

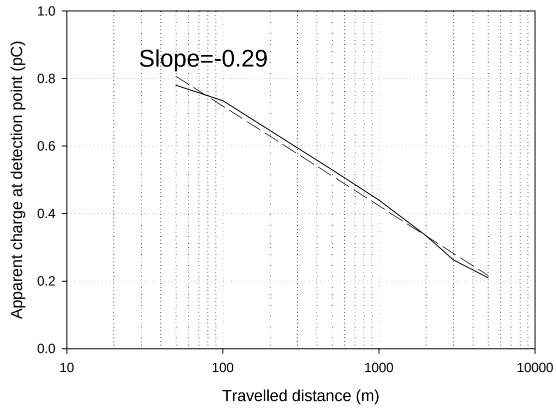

Figure 7. PD apparent charge (IEC 60270-compliant detector) as a function of travelled distance for a XLPE HV cable. The regression line fitting the data is also reported (dashed line). Simulation.

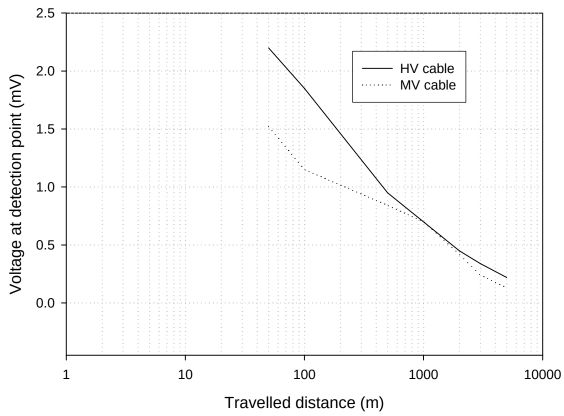

Figure 8. Comparison between PD pulse UWB detection sensitivity as a function of travelled distance for an XLPE HV cable and a MV cable. Simulation.

EFFECT OF CALIBRATOR CHARACTERISTICS ON SENSITIVITY CHECK

Sensitivity check (rather than calibration) is becoming the standard test to prove the effectiveness of the detection chain (sensors, filters, detector and, when available, post processing tools). Sensitivity check is carried out by injecting calibrator pulses of decreasing magnitude into the cable system, up to a point where detection is not anymore possible.

It should be noted, however, that calibrator pulses with low frequency content can travel large distances with negligible attenuation, while pulses with large frequency content can experience fast energy loss as they travel along the cable route. Thus, the sensitivity of the detection system is dependent on calibrator pulse characteristics, particularly when measurements with UWB detectors are carried out. In spite of that, the only requirement for calibrator rise time, t_{rise},(when using wide band detectors) is that [4]:

$$t_{rise} < 0.03 / f_{upper} \quad [1]$$

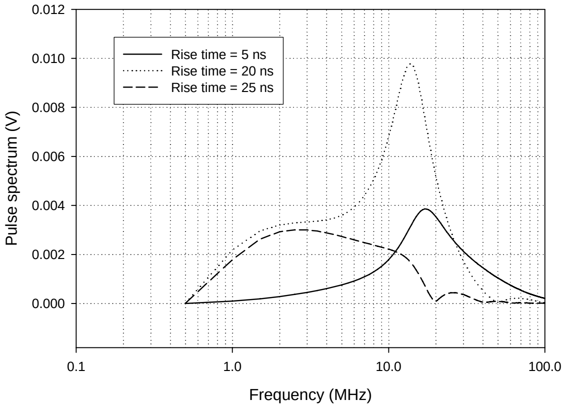

Figure 9. Measured spectra for calibrator pulses having rise times of 5, 20 and 25 ns.

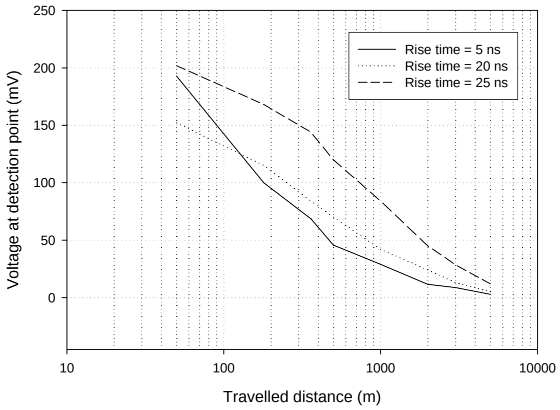

Figure 10. Simulated PD pulse peak value as a function of travelled distance and for different values of PD pulse rise time. UWB simulation.

being f_{upper} the upper cut-off frequency of the detector. In practice, for a detector with f_{upper}=500 kHz, the rise time should be below 60 ns.

In order to quantify the dependence of sensitivity check procedure on calibrator characteristics, simulations with calibrator pulses having different rise times (i.e., 5, 20 and 25 ns) were carried out. The spectra of the calibrator pulses are shown in Figure 9 and put in evidence that calibrators with different rise times can have, at the largest frequencies, similar spectra. This is associated with resonance peaks due to, e.g. stray inductances and calibrator capacitance, and affects sensitivity check results, as shown in Figures 10. In particular, when detection is made through UWB instruments, the 5 ns and 20 ns calibrator pulses, which present similar resonance peaks in the 10-20 MHz range, provide similar effects, while the 25 ns calibrator pulse behaves in a different way with respect to the 20 ns one. When apparent charge is the measured quantity, the similarities at frequencies in the IEC 60270 range for apparent charge measurement become prevalent at longer distances (results not shown here).Thus, the 20 and 25 ns pulses provide close results for cable lengths larger than about 1 km.

These results underline that sensitivity check is affected significantly by calibrator choice and, therefore, they warrant a deeper investigation and stricter requirements in standards for PD measurements in power cables.

CONCLUSIONS

ATP simulations can provide useful considerations regarding PD detection sensitivity limits. First of all, simulations confirm the obvious differences between UWB and IEC 60270 compliant detectors, emphasizing that localized detection can be performed best by UWB detectors. When measurements from terminations are concerned, UWB and IEC 60270 can become equivalent on long distances (depending on noise band), being UWB detectors favored on short distances.
With some analytical modeling, detection limits (in terms of maximum cable length) can be established, allowing to draw adequate decisions regarding the possibility of detection from cable termination based on given limits of PD amplitude and of the level of noise. These procedures are very important in order to determine PD detection strategies.
Eventually, some considerations regarding the effect of calibrator characteristics on sensitivity check can be drawn. In particular, calibrator pulse rise time can affect noticeably the maximum distance at which calibrator pulses can still be detected, thus influencing sensitivity check procedures. This topic should be considered carefully while preparing new standards on cable system testing.

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