Simulation of UHF PD Wave Propagation in Plug-in Cable Terminations

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Abstract- **The ultra-wide band partial discharge detection is successfully applied to assess on-line the insulation condition of plug-in cable connectors. To enhance the performance of this diagnostic method a series of numerical simulations on the detailed 3D model of the cable termination was conducted. 3D modelling of the UHF wave propagation was based on the Finite Integration Technique. The impacts of sensor's geometry and positioning on the UHF PD signal coupling were studied. The energy of the UHF PD pulse induced in sensor was used as a criterion for comparison. The eigenmode simulation was performed to match the working range of the sensors with the strongest resonance frequencies originating in the cable termination. The numerical results for capacitive and inductive sensors of different geometries were successfully verified by a series of laboratory measurements on a test setup using a built-in artificial PD defect or a UHF pulse generator.**

I. INTRODUCTION

A failure of a high voltage power cable causes a service interruption, costly location, repairs and loss of revenues. Modern plug-in cable connectors (terminations) for GIS and transformers are made from silicone rubber. The electrical life span of this high polymeric material normally exceeds 40 years, but only in absence of partial discharge (PD) activity that inevitably causes material degradation. Several IEC standards prescribe routine tests on the prefabricated components of HV cable accessories to be carried out by manufacturers. The conventional IEC 60270 method, which can be calibrated, is always applied during quality assurance testing on the components in the factory in those cases. An inaccurate assembly done under on-site conditions can strongly affect the long-term performance of the complete accessory. Therefore, to make sure that the assembly was done properly, a quality check on-site is often desired by utilities.

Partial discharge detection is a well established criterion for the condition assessment and quality control of the high voltage electrical insulation. The occurrence of PD in electrical insulation is always associated with the emission of electromagnetic pulses. A typical PD pulse has a rise time of less than 1 ns and a width of a few ns, implying in frequency-domain a bandwidth of several hundreds of MHz. The ultra-wide band PD (UHF PD) diagnosis is based on capturing those pulses. This method yields higher signal-to-noise ratio under on-site conditions comparing to the conventional IEC 602070 PD measurement.

Once excited, the electromagnetic emissions propagate in all directions from the PD source. Different materials impose different attenuation factors to the travelling waves. In general, the attenuation of the PD pulses is a function of frequency [1]. The higher frequency components will be attenuated rapidly when they travel along the cable. Therefore, detecting PD in the UHF band (300-3000 MHz), that has only a few known discrete interferences, also has the advantage of the distance selectivity of only several meters. This can be perfectly used for the diagnosis of the cable accessories.

Fig. 1 demonstrates the principle of UHF PD sensing in the plug-in cable connectors. A portable metallic housing is clamped on the cable behind the connector and fulfills two functions: firstly, as a housing for field couplers (antennas) and secondly, as a grounded screen against the disturbances from outside. To couple most effectively the electromagnetic UHF pulses originating in the cable termination, one needs to analyze the wave propagation through insides of the accessory. As a result of the complex nature of cable connector, this can hardly be done analytically or by means of equivalent circuits [2]. Instead, the numerical simulations presented in the paper were performed in order to optimize the PD extraction. Here we tried to evaluate some factors affecting the performance of the sensor, such as: its geometrical form, field component coupled (electric or magnetic), positioning of the coupler inside of a screening housing and an impact of the screening housing on sensor's performance. Finally, to verify the results received from the simulation, a series of lab experiments were performed on a test set-up in the lab.

II. SIMULATION

A. *Method*

Electromagnetic field analysis is based on the solutions of Maxwell's equations [3]. In this work a 3D modelling of the UHF wave propagation was performed using the commercial software Microwave Studio from CST [4]. The software can solve transient electromagnetic field tasks in time and frequency domains using a Finite Integration Technique (FIT). FIT discretizes volume and well suites for problems that contain many different, lossy dielectric materials as in the case of cable termination [3].

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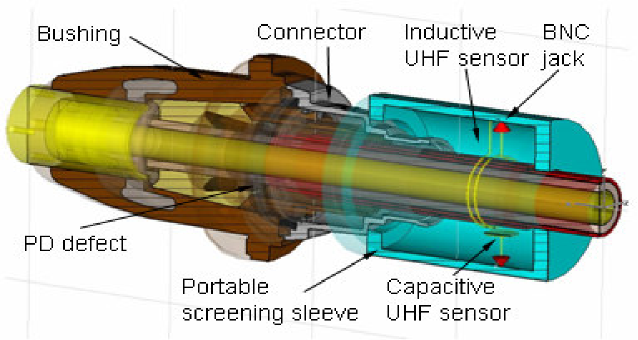

Fig. 1. Full 3D model of termination with the UHF diagnosis equipment

B. *Modelling*

The plug-in cable connector being modelled is a HV-Connex termination size 4 (up to 72.5 kV) made by Pfisterer for conductors in a range of 95-800 mm^2. The connection is part of a product family extending to 245 kV. A longitudinal cross section of a complete termination with a mounted portable housing and sensors is shown in Fig. 1. All sizes and material properties assigned during the modeling were taken from the CAD drawings, provided by the manufacturer. The capacitive sensor represents a copper disc with the diameter of 2 cm, placed about 2 cm above the cable sheath surface. The inductive sensor is a two-turn coil made from a copper wire and winded around the cable. In the model, each sensor is terminated with a 50 Ohm resistance (so called lumped element), which stands for an input impedance of the oscilloscope in the real set-up. The voltage curve across this resistor represents the output signal of the UHF sensor. Depending on the case, two excitation ways were used, such as a waveguide port (excitation signal sent directly to the conductor) or a lumped element port. The latter, a local “PD defect” in form of a small electrode (copper sphere of 1 mm radius) was placed into insulating silicon of the stress cone and terminated with 50 Ohm as well. The 50 Ohm value may seem unrealistic physically, but it is acceptable for the purposes of the parameter study. A Gaussian-shaped current pulse was injected into the excitation electrode. This transient input lasts a few nanoseconds only and excites frequency components in a range of 300-1500 MHz as shown in Fig. 2, i.e. referring to the time and frequency domains behaves very similar to the partial discharge in solid insulation.

After defining the frequency range for the calculation, the model is meshed automatically. Adaptive mesh refinement was tested as well, with no substantial result change though. Electric field free boundary conditions were applied to a cubic enclosure that contained the model. The transient solver was chosen. The sensor output in time domain simulated in respect of the known excitation pulse has a shape of a damped bipolar oscillating impulse and is very similar to the UHF sensor outputs picked up by an oscilloscope in the reality [5]. The energy of the UHF PD pulse induced in the sensor can then be an objective criterion for comparison among different variations. It is calculated according to a formula:

$$E = \frac{1}{50\Omega}\int u^2 dt \,. \tag{1}$$

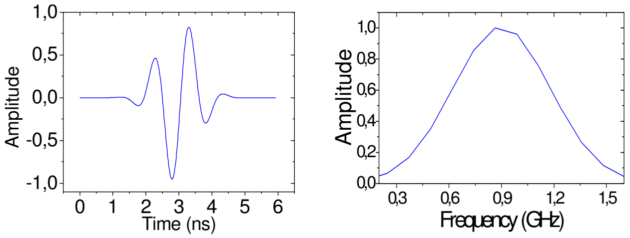

Fig. 2. Excitation signal in time and frequency domain applied to the PD defect electrode

III. EXPERIMENT

To conduct a comparative parameter study on the UHF sensors, the measurements have to be done under exactly same conditions, especially referring to the discharge intensity. Evidently, it is unachievable using a real discharge process, whose activity implies complex physics and always varies strongly in magnitude. An UHF pulse generator LDA-5/U from LDIC was used as the pulse excitation of constant magnitude as shown in Fig. 3. The UHF pulse generator is connected to the cable conductor of a single-phase XLPE insulated power cable.

On the receiving side of the setup already known screening housing with sensors was mounted on a connector plugged into the test joint filled with SF$_6$ at pressure of 420 kPa. The sensor signal was connected via high-pass filter (>200 MHz against radio noises) to a 50 Ohm input of Ch. 1 of the oscilloscope LeCroy WavePro 7100. No signal amplification was used for better comparability of results.

The normal statistical distribution for the pulse energy calculated acc. (1) over 1000 pulses is shown in Fig. 4. In the text below the term “measured energy” refers to a mean value over 1000 pulses.

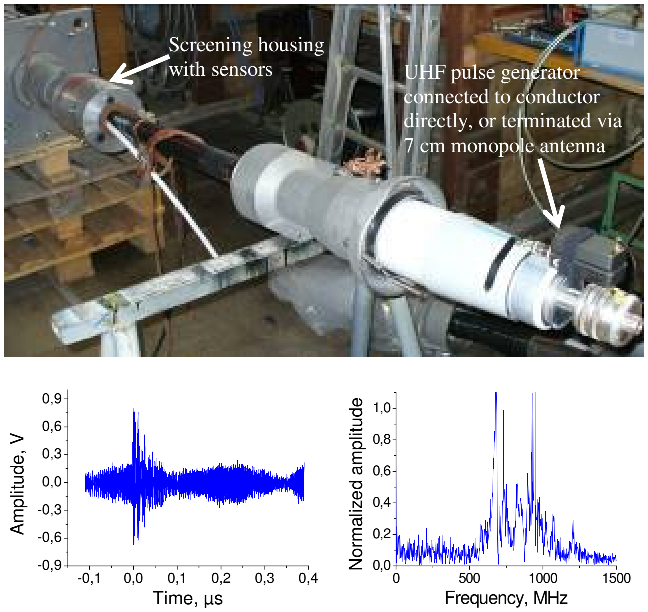

Fig. 3. Laboratory setup and excitation signal from LDA-5/U UHF pulse generator in time and frequency domains (picked up by the UHF sensor)

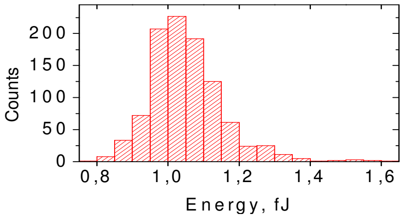

Fig. 4. Statistical distribution of 1000 pulses from UHF pulse generator picked up by a capacitive sensor

III. RESULTS

A. Varying of sensor's geometry

In the subchapters A-C, a direct connection of the UHF pulse generator output to the cable conductor was used during the experiment (ground loop of the UHF generator was disconnected to avoid a parasitic inductivity). In the simulation an excitation via waveguide port is used. In the beginning the diameter of the capacitive disc-shaped coupler is parameterized. Fig. 5(a) reveals that an induced energy in the UHF band increases with rising diameter of the disc coupler. The graph of Fig. 5(b) demonstrates that number of turns decisively impacts the energy induced in the inductive coil. Coils with 2, 6, 40 turns were simulated. The validation measurements were done on coils with 2, 5, 10 windings. The character of both curves is similar; however absolute values are hardly comparable due to different initial conditions in the simulation and experiment. Regarding the form of couplers, a diameter of the disc sensor, as well as a number of turns in the inductive sensor affects the performance of UHF wave coupling the most. The thickness and material of the sensor impact the measuring performance as well.

B. Varying of sensor's position in radial direction

In the parameter study shown in Fig. 5(c) the distance from the sensor to cable surface (sensor's radial coordinate) is varied. A clear decline in the induced energy with rising gap was revealed and verified by experiment.

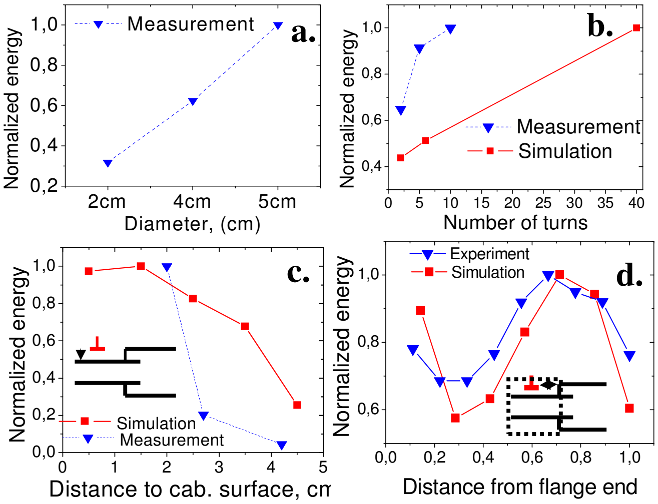

Fig. 5. Results of sensor's geometry and position parameterization: a. diameter of disc-shaped cap. sensor; b. number of turns in ind. sensor; c. radial coordinate of cap. sensor; d. axial coordinate of cap. sensor

C. Varying of sensor's position in axial direction

By varying the distance from the flange end to the sensor (sensor's axial coordinate), the sine-wave dependency of induced energy was found as shown in Fig. 5(d). This can be explained with an effect of a standing wave (resonance frequency) inside the screening housing. Fig. 7 will show later that the only possible cavity resonance frequency of the screening housing lies at 1.06 GHz, which approximately corresponds to a wave length of 28 cm (axial size of the screening sleeve).

D. Varying of sensor's position in azimuthal direction

In the vicinity of the PD source, the discharge pulses are carried by a small portion of the neighboring materials and they need some space until they will distribute uniformly along the circumference of the accessory or cable [1]. Therefore, to increase the spatial detection reliability of capacitive sensing one needs to put several sensors along the circumference or simply move the single sensor along the circle. To proof this effect a parameter study was done.

In the case of the sensor's azimuthal coordinate variation, the direct connection of the UHF pulse generator to the cable conductor used before would not make any difference for comparing the sensors, since the excitation would be at the center always. Therefore, a pulse source originating from the insulation is needed. For this purpose, a monopole antenna was connected to the UHF pulse generator and they together were taped to the surface on top of the stress cone, as shown in Fig. 3 (top).

Fig. 6 shows that both the simulation and the experiment revealed a non-uniform energy distribution along the circumference of the cable. For some reason simulation shows that sensors placed opposite to the defect's origin will get higher energy induced. The measurement confirms the opposite. In order to find more information some further measurements with different defect origins were conducted too. Unfortunately, no clear reproducibility of results during the measurements could be achieved.

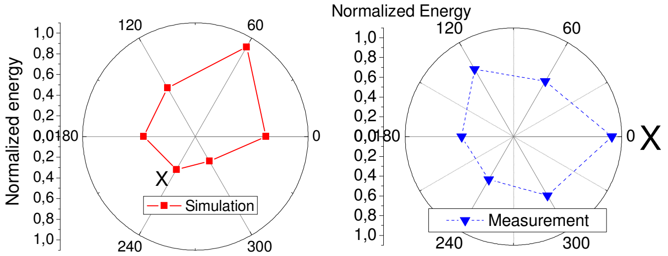

Fig. 6. Azimuthal sensor's position variation (PD source location is marked with X)

E. Cavity resonances and impact of screening housing

Since the presented UHF PD diagnostic concept implies the measurement of the radiated pulses outside the termination housing, it is of high interest to figure out what own resonance frequencies (eigenmodes) this body has. Because once excited, these frequencies will be resonated according to the well known physical phenomenon. Fig. 7 shows eigenmode simulation results for 2 cases: with and without screening housing. Comparing these two solutions to each other one finds that the only possible cavity resonance frequency of the screening housing lies at 1.06 GHz, which approximately corresponds to a wave length of 28 cm in the air (axial size of the screening housing). The calculation was done considering losses in materials. As a result, Q-factors, a ratio between the total signal power and power losses in materials of the model, were evaluated.

The eigenmode frequencies are almost uniformly distributed over the range of interest. The range of 550-850 MHz is densely occupied with eigenmode frequencies, which agrees perfectly with the working range of the sensors and hardware used.

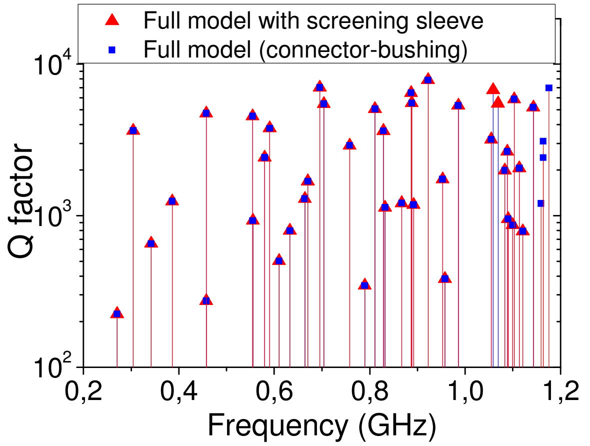

Fig. 7. Eigenmode frequencies with and without the screening housing

F. *Simulation of different PD defect sources*

Two different PD source locations, modelling some typical assembly faults, were simulated: first, on the outer surface of the stress cone and second, on the outer surface of cable's XLPE insulation. The defects were realized in form of spherical electrode as abovementioned and loaded with the Gaussian-shaped pulse in the frequency range of 300-1500 MHz. However, it should be mentioned that the Finite Integration Technique (FIT) used by MWS does not allow placing ports that touch objects with different material properties simultaneously, i.e. placing port electrode (defect) exactly on the border between two different components was hindered. Therefore, defects were placed inside one material possibly close to the contact border. In both cases a capacitive coupler of 2 cm diameter, placed at the same position was used. Namely, at 2 cm above the cable surface, and at the distance of ¾ screening housing size away from the flange as can be seen in Fig. 1.

The simulation results in the time domain did not reveal much of a difference: pulses originating from both sources had approximately same length and amplitude. But Fig. 8 (left) demonstrates clear differences in the FFT spectra. Two consequences can be concluded from the simulation: first, the energy of the signal is getting higher when defect's origin approaches to the cable conductor; second, proximity to the cable conductor facilitates transmission of higher frequencies.

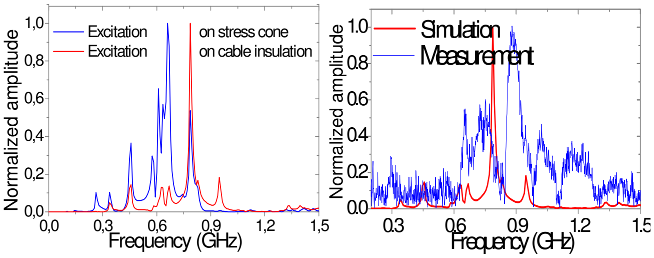

Fig. 8. Simulation results for two different defect locations (left), Comparison of the FFT spectra from the simulation and a real PD signal

In Fig. 8 (right) one can compare the results derived from the simulation (source located on the outer cable insulation) to the measurement done in the laboratory using an artificial PD defect. A push-in strip was introduced along the boundary between the cable insulation and the stress cone. Both FFT spectra have their heights in the middle of the frequency range. Unfortunately, this seems to be the only similarity. Of course it should be mentioned, that defects were not on the same place, design of connectors used for measurements and simulation slightly differs, also noise from GSM, DVBT and so on affected the measurement due to a non-shielded laboratory.

IV. CONCLUSIONS

The ultra-wide band partial discharge detection is successfully applied to assess the insulation condition of plug-in cable connectors in service. To couple most effectively the electromagnetic UHF pulses originating in the cable termination, one needs to analyze the wave propagation inside of the accessory.

The following was discussed in the paper:

- Parameter studies in respect of the sensor's size and positioning were done on the complete 3D model of the cable termination and verified experimentally using an UHF pulse generator,
- Resonance frequencies with and without screening housing were revealed as a result of simulations with an eigenmode solver. Good agreement between sensor's working frequency ranges and cavity resonances inside the termination was shown.

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