Modeling On-line Three-phase PD Monitoring System for MV Overhead Covered-Conductors

G. M. Hashmi, M. Isa, M. Lehtonen

***Abstract*--In this paper, EMTP-ATP simulation environment is used to model on-line three-phase partial discharge (PD) measuring system using Rogowski coil for the monitoring of falling trees on the covered-conductor (CC) overhead distribution lines. An on-line single-phase PD measuring system has already been simulated and experimentally verified. The previous model has been extended for a three-phase system to analyze and resolve the real problems faced by the utilities. The present model is investigated under various conditions with trees leaning on more than one phases. The model can be used to estimate the length of the practical CC line at which PDs due to falling trees can be detected; thus, deciding the number and positioning of the sensors over a particular length of the CC overhead distribution line.**

***Keywords*: keywords. Partial discharge, Rogowski coil, EMTP-ATP, covered-conductor, overhead distribution lines, sensors.**

I. INTRODUCTION

THE presence of the partial discharges (PDs) is one of the most prominent indicators of defects and ongoing degradation process of electrical insulation systems. Therefore, it has been widely recognized as the most effective diagnostic method for on-line condition assessment. For electric power distribution industries, continuous monitoring of installed and operating high voltage (HV) apparatus is of particular importance from safety and reliability point of view.

The CC lines have been used in MV networks throughout the world since long. One compelling reason to use CC lines is that they are more compact and environment-friendly than bare conductors. The CC line also withstands clashing and fallen trees for a considerable time without interruption to the power supply. In this way, the line can continue to function despite the tree contact and the removal of the trees can be scheduled appropriately. A drawback of CC lines in distribution networks is that falling trees on the line can neither be detected with normal protection relays nor be localized by advanced high impedance relays because the fault current is approximately nothing due to the CC insulation and tree resistances. However, these leaning trees produce PDs in the insulation of the CC lines, which may rupture after the passage of a certain time, resulting in different kind of faults being introduced into the network. By monitoring these PDs on-line, progressive deterioration of the insulation can be indicated. Early detection of developing faults leads to better power quality and increased customer satisfaction. PD monitoring involves an analysis of materials, electric fields, arcing characteristics, pulse wave propagation and attenuation, sensor spatial sensitivity, frequency response, calibration, noise, and data interpretation. For electric power distribution industries, continuous monitoring of installed and operating HV apparatus is of particular importance from the point of view of safety and reliability. The relatively new and challenging application is conducting on-line high frequency PD measurements for the monitoring of falling trees on the CC overhead distribution lines [1].

In CC overhead distribution networks, a wide application of on-line PD measurement as a condition monitoring technique has not practically or economically been possible. This is partly because of the high costs of the equipment and resources needed, compared to the cost of the components to be monitored. One way of reducing the costs of implementing an on-line PD measuring system is to use as simple sensors as possible (e.g., Rogowski coils) and to integrate the PD monitoring functions to advanced network automation [2]. The challenge for on-line PD measurements is to find the optimal locations for these sensors with respect to their sensitivity, interference level, signal distinction, and universal applicability. The advantage of on-line PD monitoring allows for CC insulation diagnostics during normal operation as well as when the trees are leaning on the conductors. Automatic detection of the falling trees will reduce visual inspection work after storms and it will improve reliability and safety of the distribution system. Recently, a great interest has been shown by electric utilities using CC system in distribution networks in Finland to develop an on-line automatic system that should be capable of detecting falling trees on the lines. The system can be planned to be integrated into the distribution automation system to reduce the overall costs of the CC lines [3].

The paper is organized in the following pattern. Section II presents the construction, working principle, and behavior of Rogowski coil for high frequency measurements. The experimental set-up is depicted in Section III. The validation of on-line single-phase PD measuring system model is carried out and three-phase PD measuring systems model is developed in Section IV. The conclusions are drawn in Section V.

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II. CONSTRUCTION AND OPERATING PRINCIPLE OF ROGOWSKI COIL

A Rogowski coil is basically a low-noise, toroidal winding on a non-magnetic core (generally air-cored), placed around the conductor to be measured, a fact that makes them lighter and smaller than iron-core devices.

To prevent the influence of nearby conductors carrying high currents, the Rogowski coil is designed with two wire loops connected in electrically opposite directions [4]. This will cancel all electromagnetic fields coming from outside the coil loop. The first loop is made-up of turns of the coil, and the other loop can be formed by returning the wire through the centre of the winding as shown in Fig. 1, where d_1, d_2, and d_{rc} are the internal, external, and net diameters of the Rogowski coil, respectively. The coil is effectively a mutual inductor coupled to the conductor being measured and the output from the winding is an electromotive force proportional to the rate of change of current in the conductor. This voltage is proportional to the current even when measuring complex waveforms, so these transducers are good for measuring transients and for applications where they can accurately measure asymmetrical current flows.

The Rogowski coil operates on the basic principle of Faraday’s law. The air-cored coil is placed around the conductor, where current pulses produced by PDs are to be measured. This variable current produces a magnetic field and the rate of change in current induces a voltage in the coil given as:

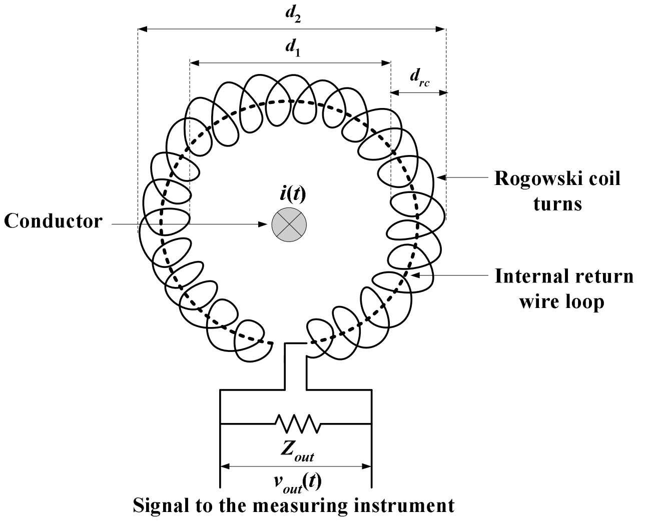

Fig. 1. Geometry and construction of the Rogowski coil.

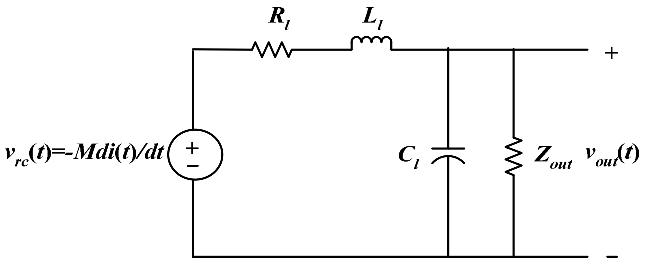

Fig. 2. The Rogowski coil equivalent circuit (lumped parameters model)

$$v_{rc}(t) = -M\,\frac{di(t)}{dt} \tag{1}$$

where $v_{rc}(t)$ is the voltage induced in the coil by the current $i(t)$ flowing in the conductor due to the mutual inductance M between the main current and the coil, which is practically independent of the conductor location inside the coil loop.

For simplified analysis, the behavior of the Rogowski coil with terminating impedance Z_{out} can be represented by its equivalent circuit of the lumped parameters as shown in Fig. 2 [5], where R_l, L_l, and C_l are the lumped resistance, inductance, and capacitance of the coil, respectively. The output voltage at the terminals of the winding wounded around the toroidal coil is proportional to the time derivative of the current flowing in a conductor passing through the coil. An integrator is incorporated with the coil, which integrates the output voltage $v_{out}(t)$ according to the following equation to convert it into the current flowing through the conductor as:

$$i(t) = -\frac{1}{M}\int v_{out}(t)dt \tag{2}$$

The frequency response of the Rogowski coil sensor is very wide. There is no conductive coupling between the coil sensors and the HV test circuits. Furthermore, the coil installation does not necessitate disconnection of the grounding leads of the test objects and therefore becomes a non-intrusive sensor which is a very important aspect for on-site, on-line monitoring. It has the advantage of possessing high signal to noise ratio (SNR) with wide frequency bandwidth. There is no saturation due to air-cored coil; therefore, it is not damaged by over current. It has very good linearity due to the absence of magnetic materials. The Rogowski coil based PD measurement system is a low cost solution and can be easily implemented on-site due to its light weight. These advantages are essential for on-line PD measurements; therefore, the Rogowski coils are preferred over conventional PD sensors to take measurements for detecting falling trees on CC overhead distribution lines.

III. EXPERIMENTAL SET-UP

An experimental set-up was arranged in the HV laboratory at Helsinki University of Technology (TKK). A single-phase CC line was laid at a certain height (≅3 m) above the ground level, and the return path was provided through the ground.

The experimental system consisted of:

- CC line having length of 29.2 m, 10 mm inner diameter of the stranded aluminum conductor, and 14.5 mm outer diameter along with HDPE (high density polyethylene) insulation
- Flexible Rogowski coil (without integrator) mounted around the CC line
- A pine tree leaning on the conductor to simulate a real world situation
- Pulse calibrator
- Digital oscilloscope, model Lecroy 9384TM
- Computing system (laptop) for data acquisition
- Grounding capacitor C_g of magnitude 500 pF, for connecting

conductor-end to the ground, and

- HV power supply, 20 kV (line-to-line) AC

The on-line single-phase PD measuring set-up is depicted in Fig. 3. The Rogowski coil is looped around the CC line to capture the PD signals produced by the pulse calibrator and due to a leaning pine tree when the line is energized. The PD signals are displayed on the oscilloscope and the data is stored for further processing and features extraction. The 20 kV AC power is supplied by a step-down transformer. The height of the CC line is not fixed at all points because it is hanged with the supporting ropes. Moreover, the CC line comes nearer to the ground at the point where the tree is leaning on it.

Two sets of PD measurements have already been performed on the CC line [1]. First, for calibrating the PD measuring system, a pulse of known magnitude is injected into the conductor by a pulse calibrator, and the Rogowski coil measurements are taken at points P_1 and P_2, as shown in Fig. 4 (a). Second, the conductor is energized with 20 kV distribution voltage, tree is leaned at point P_T on the conductor, and the Rogowski coil measurements are taken at point P_2 as shown in Fig. 4 (b). The distances of the measuring points P_1 and P_T from the sources have been taken randomly; these do not affect on the performance of the measurements in general.

It has already been determined by experiments (see Fig. 3) that PD magnitude produced due to the leaning of a pine tree on the CC line is around 3 nC [1]. This amount can vary depending upon the size, weight, and the species of the leaning tree as well as the prevailing environmental conditions. This amount propagates in both directions on the CC line; however 1.5 nC pulse propagating unidirectionally is equivalent to 3 nC pulse discharge in a real system. It is challenging to model a leaning tree in EMTP-ATP environment, which produces PDs, therefore, the pulse calibrator measurements and models are used to develop an on-line PD measuring system.

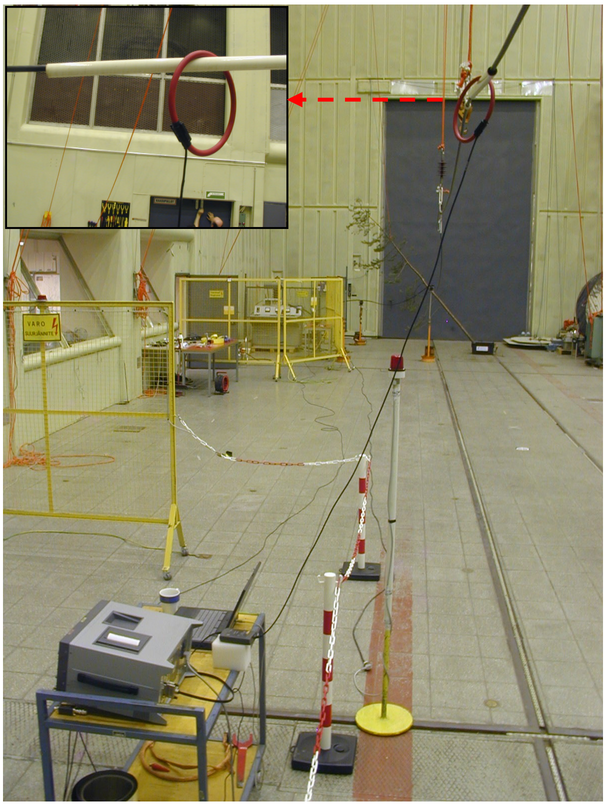

Fig. 3. On-line Single-phase PD measuring set-up

For the measurements, a calibrator pulse is sent from one end of the conductor and the Rogowski coil measurements are taken at points P_1 and P_2, at the distances of 6 m and 23.7 m from the point of insertion of the calibrator pulse, respectively, as shown in Fig. 4. The voltage pulses captured by the Rogowski PD transducer at point P_1 and P_2 for 5 nC calibrator pulse (which is equivalent to PD produced due to leaning of a single tree and this fact has been explained later) are shown in Fig. 5. The decreasing amplitude at point P_2 is the effect of the CC line attenuation during the propagation of the signal.

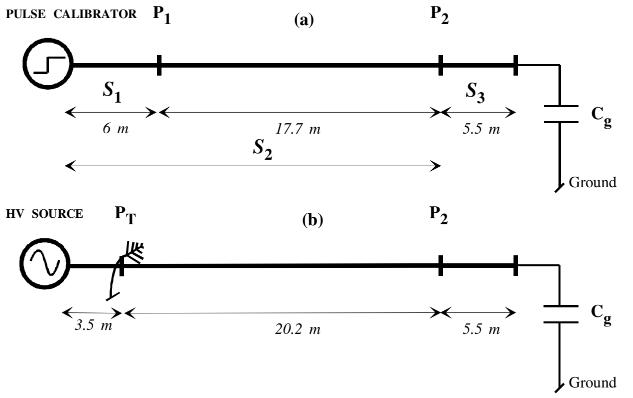

Fig. 4. Single-line diagram for on-line PD measuring system with: (a) pulse calibrator, (b) leaning tree while the line is energized with 20 kV supply

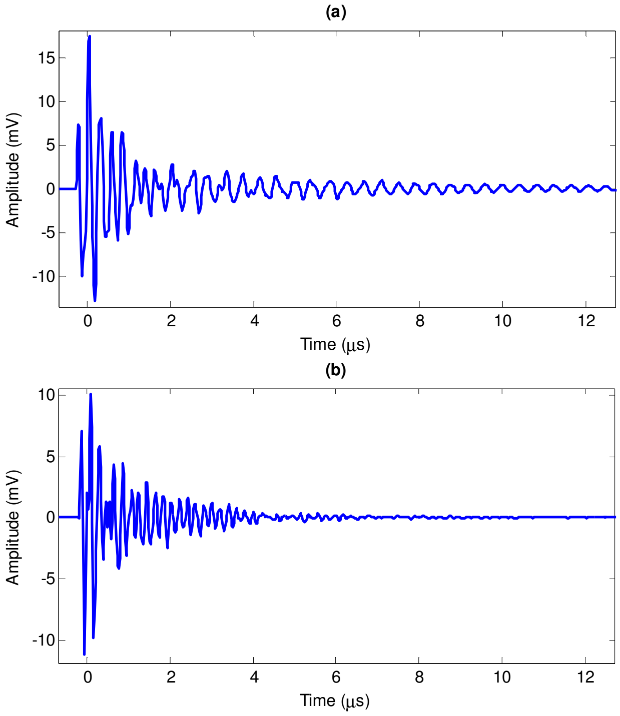

Fig. 5. Rogowski coil responses for 5 nC calibrator pulse at (a) point P_1, and (b) point P_2

IV. ATP SIMULATION RESULTS

A. *Validation of On-line Single-phase PD Measuring System Model*

The on-line single-phase PD measuring system is drawn using ATPDraw and the corresponding network of the PD measuring system including CC line and Rogowski coil is shown in Fig. 6. The calibrator pulse produces a simulated PD signal which is traveling down the CC line and is captured by the Rogowski coil at a certain distance over the line.

The measured parameters of the Rogowski coil lumped model are given as resistance (R_l) 0.11 Ω, inductance (L_l) 0.6 µH, capacitance (C_l) 50.3 pF, and terminating impedance (Z_{out}) 2 kΩ. The Rogowski coil parameters are measured at a frequency of 1 KHz with the help of Agilent 4263B LCR meter. The resonance frequency calculated using the Rogowski coil measured lumped parameters model is 29 MHz.

The distributed parameters can be calculated dividing the lumped parameters by the length of the coil. Using the distributed parameters values, the sensitivity of the coil can also be calculated, however, H is taken as 0.001 (V/A) from the manufacturer's data sheet [6]. In ATP simulations, H and N are used to model the Rogowski coil as a saturable current transformer having linear magnetizing characteristics [7]. These characteristics will simulate the behavior of an air-cored Rogowski coil. As the value of M is not given by the manufacturer, it is assumed to be 200 nH in this work, and N comes out to be 431 [8].

The CC line is mounted at an approximate height of 3 m above ground level in the experimental set-up. The frequency-dependent CC line characteristics can be calculated theoretically [9]. As the high frequency PD signals propagation is being investigated, the average values of the line characteristics at MHz frequency range are selected. The calculated CC line characteristics using the theoretical model are used in simulation as: resistance, 2 Ω/m; characteristic impedance, 350 Ω; and propagation velocity, 230 m/µs. The lengths of coaxial cable and Rogowski coil cable are 1 and 2.3 m, respectively. These lines are considered as lossless lines having zero resistance (due to shorter lengths) and 50 Ω characteristic impedance. All the transmission lines are represented using a distributed parameters Clarke model.

When a PD signal is traveling from the pulse calibrator towards the CC line through coaxial cable, there is a mismatch between the characteristic impedances of coaxial cable (50 Ω) and CC line (350 Ω) at the point of their connection (see Fig. 6). The signal is not totally transmitted to the CC line and a part of it is reflected back into the coaxial cable. The reflection coefficient Γ in this case is 0.75. Therefore, only 25% of the PD signal amplitude will reach the CC line and propagate inside it. If a 5 nC pulse is injected from the pulse calibrator, only 1.25 nC pulse will reach the CC line for further propagation; this amount is approximately equal to PD magnitude produced and propagating unidirectionally due to a leaning tree.

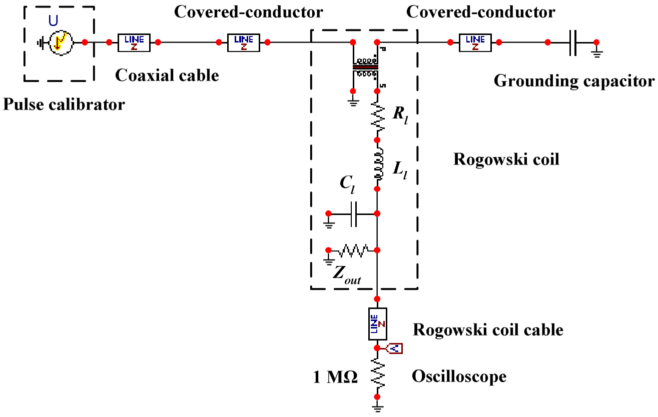

Fig. 6. ATPDraw circuit for on-line single-phase PD measuring system

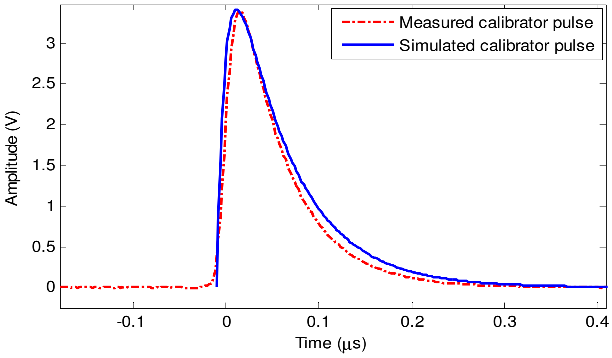

Fig. 7. Measured and simulated 5 nC calibrator pulses

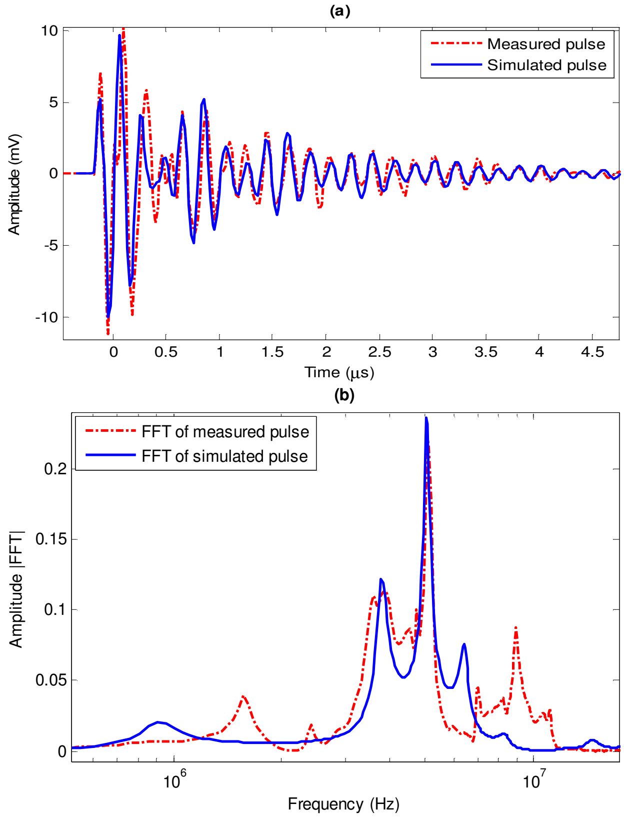

Fig. 8. The Rogowski coil response for 5 nC calibrator pulse at point P_2 in (a) time domain, and (b) frequency domain

Keeping in view above fact, an average value of 5 nC calibrator pulse is simulated in the PD measuring system to make the real analysis of a single pine tree leaning on the CC line. The measured and the simulated calibrator pulses are shown in Fig. 7 [8], [10]–[12].

A comparison of the measured and simulated voltage pulses captured by the Rogowski coil at point P_2, as shown in Fig. 4 (a), is given in Fig. 8. The comparison is carried out considering the time domain performance and fast Fourier transform (FFT) analysis. From Fig. 8, it is revealed that simulated PD measuring system response has a good agreement with the measurements, both in the time and frequency domain. It is further revealed that resonance occurs at 5 MHz. The resonance frequency of the Rogowski coil is 29 MHz; however, due to the effect of cabling, stray inductances are introduced into the system. This results in the lower value of the resonance frequency of the coil.

B. Modeling of On-line Three-phase PD Measuring System

In the previous sub-section, the on-line single-phase PD measuring system has been modeled for CC line mounted at an approximate height of 3 m above ground level (the same height in the experimental set-up). It would be interesting to analyze the PD measurements for practical three-phase CC lines that are normally mounted at a height of more than 10 m. The ATP simulated model for on-line three-phase PD measuring system is shown in Fig. 9 [for case (i)]. For this purpose, the CC line characteristics for a real situation (lines at a height of 15 m above ground level) can be calculated from the theoretical model, and are used in simulation as: resistance, 0.54 Ω/m; propagation velocity, 288 m/μs; and characteristic impedance, 475 Ω [9]. The Rogowski coil parameters for simulations are same as have been used in the modeling of single-line PD measuring system, however, sensors are mounted on each phase as RC1, RC2, and RC3 (see Fig. 9).

The simulated model can be used in order to estimate the maximum length of the real CC lines that can be monitored with a PD sensor. As the PD source (calibrator pulse) is of 5 nC, that is approximately equivalent to a pine tree leaning on the CC line, the maximum distance at which the falling trees can be detected on the CC lines from the point of measurement, can be determined.

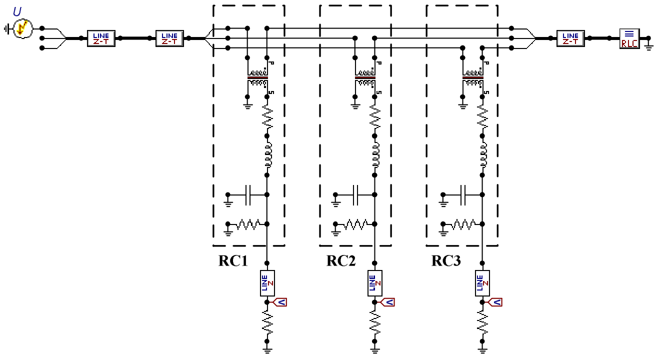

Fig. 9. ATPDraw circuit for on-line three-phase PD measuring system

In these simulations, the distance S_3 (see Fig. 4) is kept at 3.5 km to avoid the interference of any signal reflections from the termination of the CC line into the actual PD measurements [12]. The PD measurements are taken at a distance of 3.5 km from the leaning trees on the CC lines. In the simulations, following four scenarios are investigated and simulations results for first three cases are shown in Figs. 10, 11, and 12, respectively:

i. A tree is leaning on phase A (see Fig. 9)
ii. A tree is leaning on phases A and B
iii. A tree is leaning on each phase A, B, and C
iv. Two trees are leaning on phase A

For case (i), the PD pulse captured by the Rogowski coil at phase A initiates at t=12.18 μs as shown in Fig. 10 (a). The value of propagation velocity v used in simulations is 288 m/μs; therefore, the distance traveled by the signal until it reaches the point of insertion of the Rogowski coil is S_2=vt=3.508 km, which is in good agreement with the value used in simulation (3.5 km). This reveals that the simulated PD measuring system can be used to detect the PDs due to falling trees as well as localizing the falling trees on the CC lines.

The PD sensor signal at Phase A is stronger (0.5 mV) due to falling of a tree at the same phase, however, the signals captured at phases B and C are very weak (6 μV), because no trees are leaning on these phases. There are small amount of PD signals due to coupling capacitances of these phases. It reveals that PD sensors located at phases B and C cannot detect falling trees on the phase A.

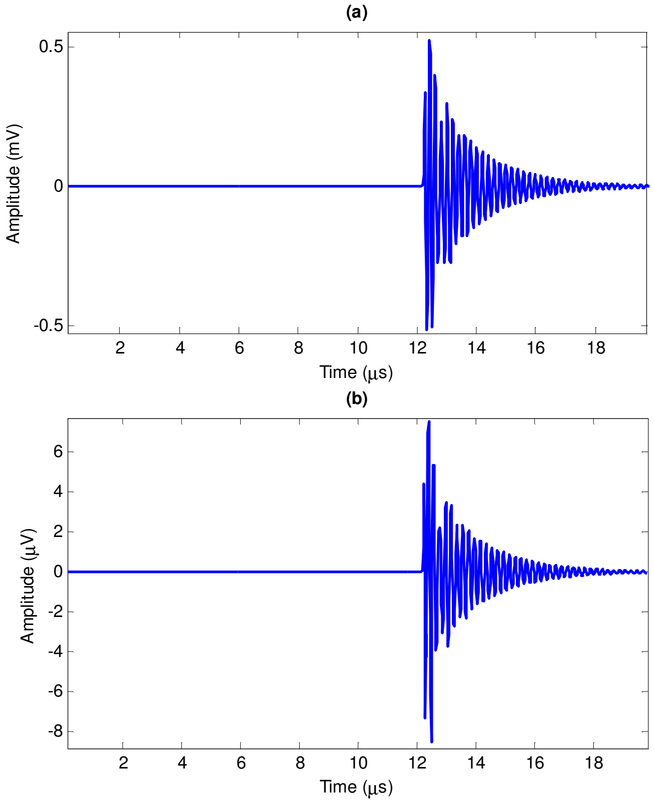

Fig. 10. Simulated Rogowski coil PD measurements due to leaning of a tree on phase A, keeping S_3=3.5 km; (a) phase A, (b) phase B and C

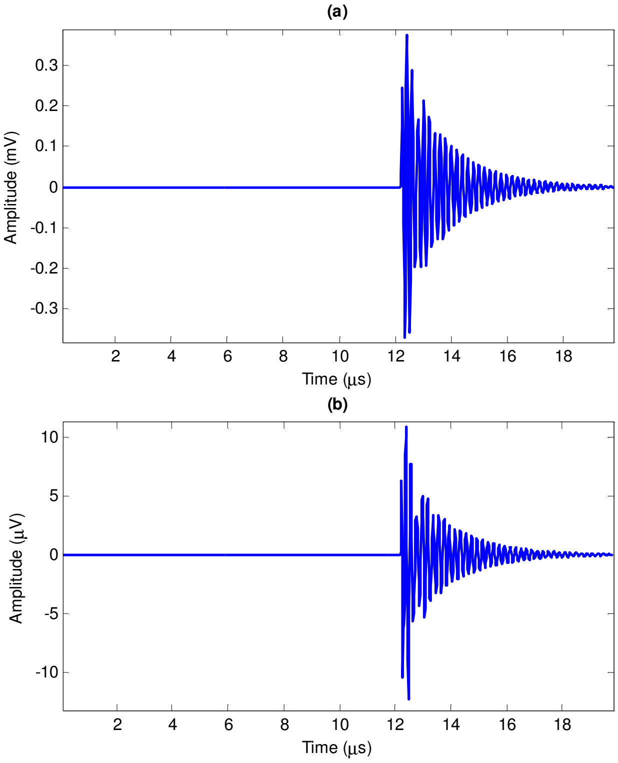

Fig. 11. Simulated Rogowski coil PD measurements due to leaning of a tree on phase A and B, keeping S_3=3.5 km; (a) phase A and B, (b) phase C

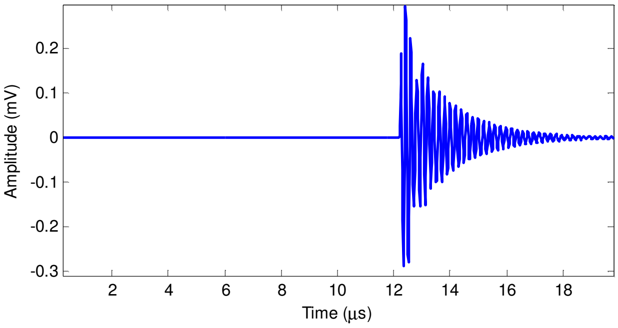

Fig. 12. Simulated Rogowski coil PD measurements on all phases due to leaning of a tree on phase A, B and C, keeping S_3=3.5 km

Similar results are also obtained for case (ii) where PD sensor mounted at phase C cannot detect falling trees on phases A and B as shown in Fig. 11. In case (iii), all PD sensors have almost similar measurements due to falling of a tree on each phase as shown in Fig. 12. It is worth mentioning that the quantity of PD magnitude detected by PD sensors reduces when trees are falling on more than one phases, i.e. PD magnitude is less when tree is leaning on phases A and B, and even lesser when a tree is leaning on each phase. The quanitiy of PD magnitude increases linearly if the number of leaning trees on the same phase increases as given in case (iv).

V. CONCLUSIONS

The on-line three-phase PD monitoring system is modeled in EMTP-ATP simulation environment. The ATP simulation results are verified by comparison with experimental results, which prove that PD measuring system has successfully been modeled that can be used to detect and localize the falling trees on the CC lines. The proposed model can be used to estimate the length of the line at which the PDs due to falling trees can be detected; thus deciding the number and positioning of the sensors over a particular length of the CC line, the design trade-offs that must be made, and the data processing algorithms that will be developed.

The amplitude of PD signal captured due to leaning of a tree on CC line at a distance of 3.5 km is around 1 mV and 0.5 mV in case of single-phase and three-phase PD measuring systems, respectively. It means we need more PD sensors in case of three-phase practical system. It is quite possible to detect PD signals beyond 4 km distance, provided there are a few trees leaning on the line or after the tree contact has violated the insulation so that the PD level starts to increase. Automatic detection of the falling trees will reduce visual inspection work after storms and it will improve reliability and safety of the distribution system. The proposed on-line three-phase PD monitoring system can be planned to be integrated into the distribution automation system in order to reduce the overall costs of the CC lines.

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