

MODELING OF ROGOWSKI COIL FOR ON-LINE PD MONITORING IN COVERED-CONDUCTOR OVERHEAD DISTRIBUTION NETWORKS

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ABSTRACT

In this paper, EMTP/ATP simulation environment is used to model the Rogowski coil for partial discharge (PD) monitoring due to leaning trees on the covered-conductor (CC) overhead distribution lines. The simulations are performed to obtain the Rogowski coil response at different lengths of the CC line and the results are compared with those obtained from the laboratory measurements. The results confirm that ATP simulations can effectively be carried out to model the transient behavior of the Rogowski coil for on-line PD detection.

INTRODUCTION

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. A relatively new application is conducting on-line high frequency partial discharge (PD) measurements for the monitoring of fallen trees on the covered-conductor (CC) overhead distribution lines [1]. Automatic detection of the fallen trees reduces visual inspection work after storms and improves the reliability and safety of the distribution system [2]. Rogowski coil is used as a PD sensor because it is non-intrusive and it provides the needed bandwidth for this application.

Extracting the features of PD from the measurements to detect and locate such faults on a complicated transmission line network is a challenging task. 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 [3]. Attenuation is an important parameter in order to estimate the maximum length of the line that can be monitored with a PD sensor; thus, deciding the number of sensors and their positioning. In this way, the CC lines will be more reliable and the costs related to visual inspection work will also be significantly reduced.

The attenuation of the CC line approximated from the Rogowski coil measurements is much higher than measured from the time domain reflectometry (TDR) method or calculated from the theoretical model of the line [1,4,5]. As the theoretical model of the line has already been experimentally verified using TDR measurements [5], the higher attenuation in Rogowski coil measurements is an issue that needs a deeper analysis. To resolve this matter,

the PD monitoring system (including Rogowski coil and CC line) is modeled in EMTP/ATP simulation environment to investigate the source of high attenuation. The ATP simulation results are verified by comparing with experimental results, which prove that the transient behavior of the Rogowski coil has successfully been modeled for on-line PD detection. The simulation results show that the CC line has very low attenuation; however, mostly the PD signal amplitude dies in the over damped resonant circuit of the Rogowski coil.

EXPERIMENTAL SET-UP

The experimental set-up is arranged in a HV engineering laboratory at Helsinki University of Technology (TKK), Finland as shown in Fig. 1. The experimental system consists of: CC line (≈ 29 m) having polyethylene insulation; flexible Rogowski coil (without integrator); pulse calibrator; digital oscilloscope; capacitor (500 pF) for connecting conductor-end to the ground; and the computing system (laptop) for data acquisition. A single-line diagram of the measuring set-up is shown in Fig. 2, where a calibrator pulse is sent from one end of the conductor and the Rogowski coil measurements are taken at points P₁ and P₂, at the distances of 6 m and 23.7 m, respectively, from the point of insertion of the pulse.

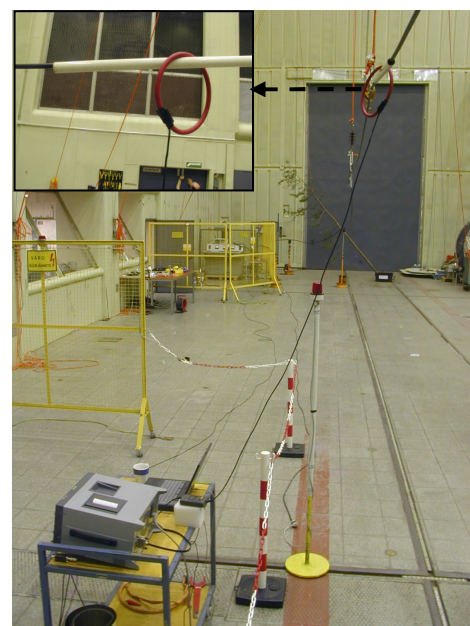


Figure 1. Experimental set-up

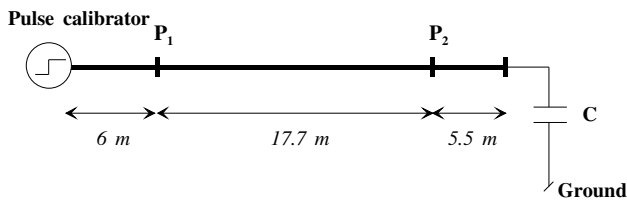


Figure 2. Single-line diagram for PD monitoring system

HIGH FREQUENCY BEHAVIOR OF THE ROGOWSKI COIL

In this study, Rogowski coil is used to measure PDs, which typically last few nanoseconds. Therefore, its high frequency behavior is of paramount importance. There is a trade-off between the bandwidth and the sensitivity of the coil. Moreover, the bandwidth and susceptibility of the coil to high frequency oscillations are significantly influenced by the termination impedance. If the coil geometry is not symmetrically positioned around the conductor, the experimental results are logically influenced, however, no significant effect has practically been found in the time or frequency domain behavior of the measurements [6].

Up to now, two different models of Rogowski coil have been developed; the distributed and the lumped parameter model [7-10]. The distributed model can help calculating the sensitivity H (V/A) of the Rogowski coil used in ATP simulations, and the transfer function can be extracted from the lumped model to analyze its bandwidth [6, 11].

SIMULATION PARAMETERS CALCULATION

Rogowski coil parameters

The Rogowski coil operates on the basic principle of the Faraday's law. The construction of the high frequency Rogowski coil is depicted in Fig. 3. The geometric characteristics of the circular cross section Rogowski coil are given in Table I. For a toroidal coil having circular cross section, the lumped parameters can be calculated as follows [6, 7, 11]:

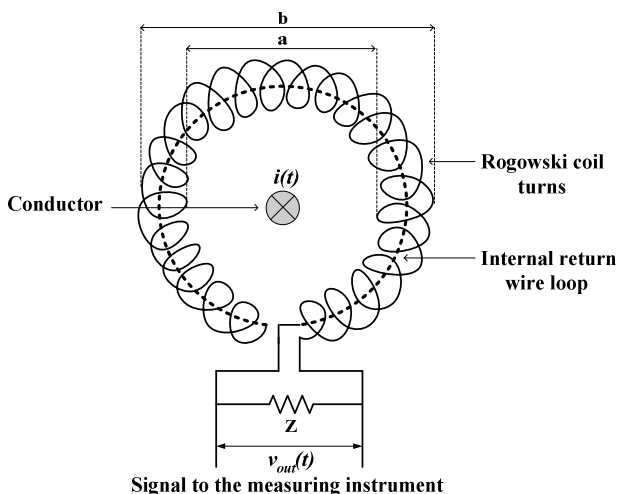


Figure 3. Construction of the Rogowski coil

TABLE I. GEOMETRY OF THE ROGOWSKI COIL

Rogowski coil dimensions	Specifications
Inner diameter a	162.4 mm
Outer diameter b	191mm
Transducer diameter d_{rc}	14.3 mm
Length of the wire l_w	25 m
Radius of the wire d	1 mm
Length of the coil l	600 mm

$$R_l = \rho_c \cdot \frac{l_w}{\pi d^2} \tag{1}$$

$$L_l = \frac{\mu_0 N^2 d_{rc}}{2\pi} \log \frac{b}{a} \tag{2}$$

$$C_l = \frac{4\pi^2 \epsilon_0 (b+a)}{\log \left(\frac{b+a}{b-a} \right)} \tag{3}$$

where R_l , L_l , and C_l are the lumped resistance, inductance, and capacitance of the coil, respectively. ρ_c is the copper resistivity; μ_0 and ϵ_0 are the air permeability and permittivity, respectively; and $N=431$, are the number of turns of the coil [6]. The terminating impedance of the Rogowski coil Z can be approximately calculated as given in reference [6, 7].

The equivalent circuit of the Rogowski coil, based on the lumped parameters, is drawn in Fig. 4, where $i(t)$ is the current flowing in the conductor, $v_{rc}(t)$ is the induced voltage in the coil, $v_{out}(t)$ is the coil output voltage, and M is the mutual inductance of the coil (200 nH).

The measured parameters of the Rogowski coil lumped model are given in Table II. The Rogowski coil parameters are measured at a frequency of 1 KHz with the help of Agilent 4263B LCR Meter. As the high frequency behavior of Rogowski coil is being investigated, the measured lumped parameters are preferred for reliable simulation results. The coil sensitivity is taken as 0.001 (V/A) from the manufacturer's data sheet [6]. H and N are used to model Rogowski coil as a saturable current transformer having linear magnetizing characteristics [12]. These characteristics will simulate the behavior of an air-cored Rogowski coil.

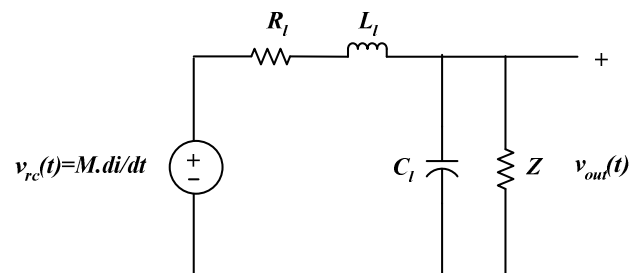


Figure 4. Equivalent lumped circuit of the Rogowski coil

TABLE II. MEASURED LUMPED MODEL PARAMETERS OF ROGOWSKI COIL

Lumped model parameters	Measured values
Resistance R_l	0.11 Ω
Inductance L_l	0.6 μH
Capacitance C_l	50.3 pF
Terminating impedance Z	2 k Ω

Covered-conductor line parameters

The CC 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 using theoretical model, and are used in simulation as: resistance, 2 Ω/m ; characteristic impedance, 350 Ω ; and propagation velocity, 230 $\text{m}/\mu\text{s}$ [5]. The transmission lines are represented using distributed parameters Clarke model.

ATP SIMULATION RESULTS AND DISCUSSION

The PD monitoring system is drawn using ATPDraw. The ATPDraw is used as a graphical interface and the corresponding network of the monitoring system including Rogowski coil and CC line is shown in Fig. 5. The measured and the simulated 5nC calibrator pulses are shown in Fig. 6. A comparison of the measured and simulated voltage pulses captured by the Rogowski coil at point P_2 (see Fig. 2) is given in Fig. 7.

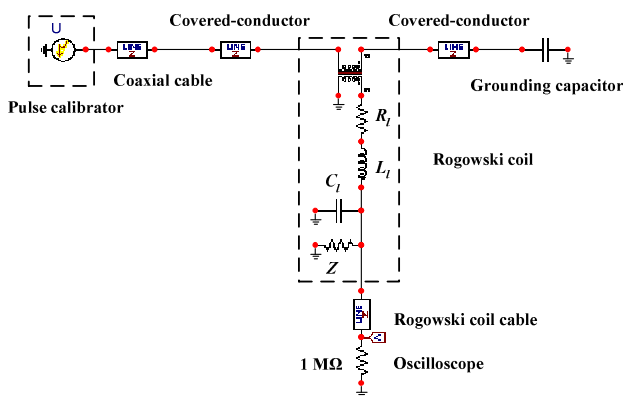


Figure 5. ATP Draw circuit for the PD monitoring system

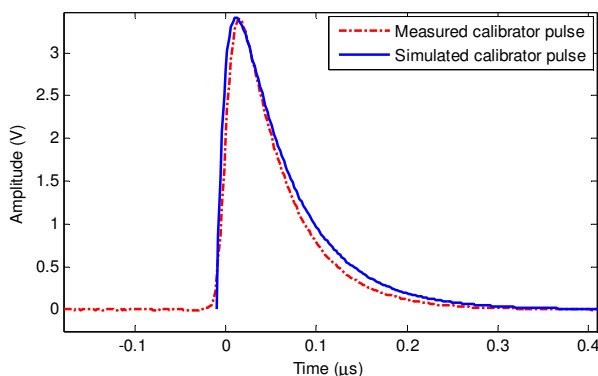


Figure 6. 5 nC calibrator pulses (measured and simulated)

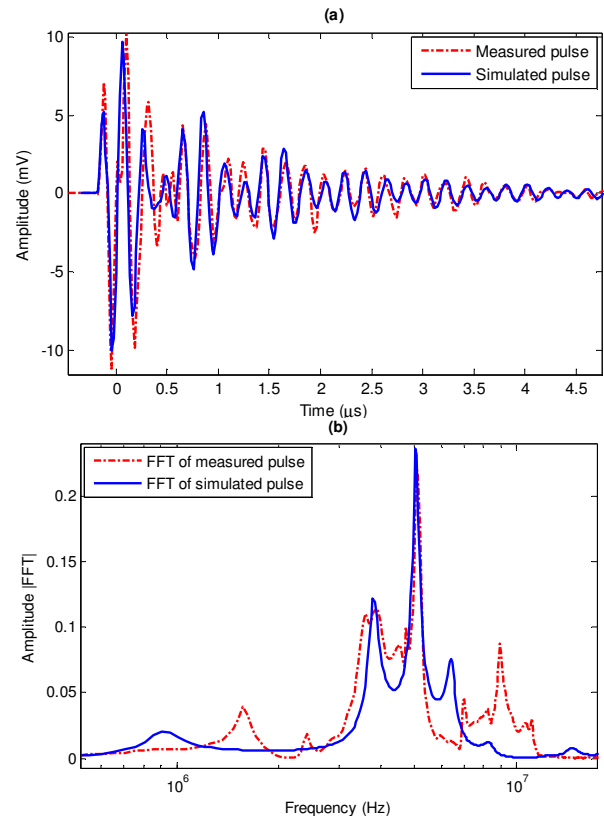


Figure 7. Rogowski coil response for 5 nC pulse calibrator charge at point P_2 in (a) time domain, and (b) frequency domain

The comparison is carried out considering the time domain performance and fast Fourier transform (FFT) analysis. From Fig. 7, it is clear that simulated PD monitoring system response has a good match with the measurements, both in the time and frequency domain. Although, the resonance frequency of the Rogowski coil is 29 MHz [6], however, due to the effect of cabling, stray inductances are introduced into the system, resulting in the lower value of the resonance frequency of the coil (5 MHz). The resonance effect can also be verified by determining the simulated transfer impedance function of the Rogowski coil [6].

The measured and the simulated voltage pulses captured by the Rogowski coil at point P_1 (see Fig. 2) are given in the time and frequency domain as shown in Fig. 8. The amplitudes of the measured and the simulated pulses are not closely matched in the first few cycles, and the pulses are also distorted in phase. It can be explained on the fact that the resonance frequency of the Rogowski coil has different values (in measurements) at different distances along the CC line. This can be due to the effect of stray capacitances introduced during the measurements taken at point P_1 , which is nearer to the exposed metal components lying in the laboratory. Another reason can be due to the unequal clearance of CC line above the ground at different locations, resulting in different values of the line capacitances. The higher attenuation calculated in the previous study from the Rogowski coil measurements can be due to the effect of its varying resonance frequencies at different distances [1].

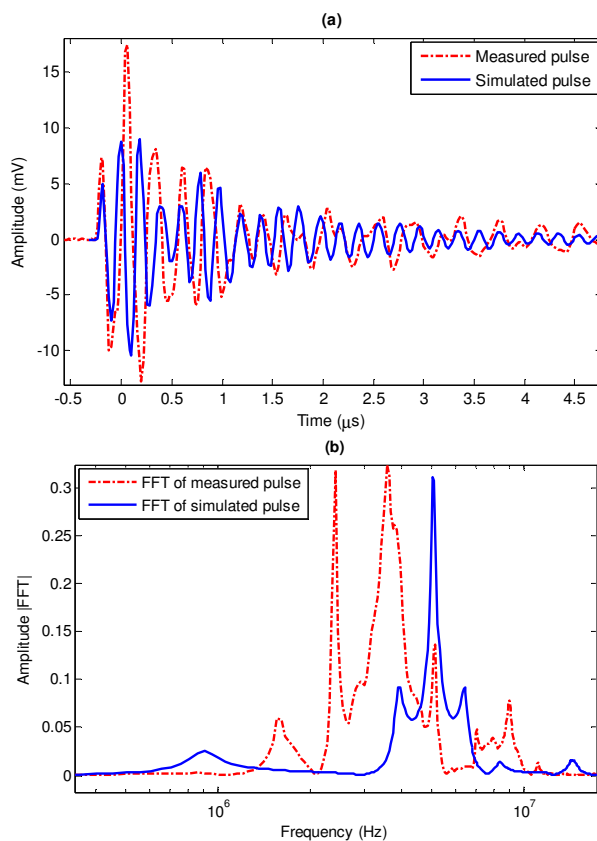


Figure 8. Rogowski coil response for 5nC pulse calibrator charge at point P_1 in (a) time domain, and (b) frequency domain

CONCLUSIONS

ATP simulations are performed to model the transient behavior of the Rogowski coil. The PD monitoring system, including Rogowski coil and CC line, is also simulated in ATP. The 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 simulation results show that the CC line has very low attenuation, and the higher amplitude pulse measured by the Rogowski coil near the source of PD is due to the effect of its varying resonance frequencies at different distances.

The Rogowski coil used in this study is not good for high frequency measurements beyond 5 MHz. Therefore, a higher bandwidth coil should be used for real time analysis of PDs produced by falling trees on the CC lines.

ACKNOWLEDGMENT

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