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Effect of Terminating Resistance on High Frequency Behaviour of Rogowski Coil for Transient Measurements

M. Shafiq[1], M. Lehtonen[1], L. Kütt[1], G. A. Hussain[1], M. Hashmi[2]
[1]*Department of Electrical Engineering, Aalto University, Finland*
[2]*VTT Technical Research Centre of Finland, Finland*
muhammad.shafiq@aalto.fi

***Abstract*—Partial Discharge (PD) current measurements have been widely used to assess the insulation condition of power components. Rogowski coil is a low cost current sensor specifically meant for high frequency transient diagnostics such as PDs in high voltage (HV) power apparatus. This paper presents the design of Rogowski coil for transient measurements. For the designed prototype of Rogowski coil, correct selection of terminating resistance is of high importance to calibrate its response for accurate measurement of the PD current waveforms. Effect of terminating resistance for the coil model is analysed based on theoretical, practical and simulated investigations. Simulated model of the coil is used to determine the behaviour of induced current through non-physical inductive and capacitive elements of Rogowski coil. The Electromagnetic Transient Program-Alternative Transient Program (EMTP-ATP) is used to implement and to analyze the model of Rogowski coil. The comparison of practical and simulated results validates the designed model of the coil. The paper explores EMTP-ATP as an efficient tool to analyze and modify the transient behaviour of Rogowski coil for high frequency pulse measurements.**

***Index Terms*—Partial discharges, Rogowski coil, calibration, diagnostic, transients, measurement.**

I. Introduction

Electrical power networks are always exposed to different types of faults that may harm the power supply continuity. One of most common faults in HV networks is insulation breakdown due to aging and operational stresses. It is however possible to detect the likelihood of this type of faults, as they usually provide significant measurable signs before their occurrence. When insulation deterioration is minor but with some effect, very short (nano-micro second duration) miniature breakdown events called partial discharges (PDs) may occur in the problematic location. PD is the process of localized dielectric breakdown event in defects (cavities, voids, cracks or inclusions) of a solid or a liquid electrical insulation which is under HV stress [1]. As a result of each such PD occurrence, fast transient current pulse is generated due to sharp collapse of voltage across the defective cavity of insulation. Voltage and current waveform together present an electromagnetic wave which travels along the power line at speed of light. Measurement of these extremely fast pulses can provide the information where the insulation degradation is happening, how far it has progressed and how fast it is progressing. If detected in prior to complete breakdown, it may help avoiding significant loss and customer dissatisfaction.

The duration and amplitude of these current (PD) pulses varies with change in operational voltage. Recent research points out that accurate assessment of PD faults requires complete information of pulse waveform and this step requires wider frequency band current sensors [2]. Currently, a comprehensive research on current sensors has been conducted, including shunts, current transformers (CT), Rogowski coils, Hall effect sensors, magneto impedance (MI) sensors, giant magneto resistive (GMR) sensors, pilot devices in power semiconductors, acoustic and optical current sensors. Based on some critical parameters of a sensor such as: cost, bandwidth, sensitivity, saturation, linearity, operating temperature, footprints, integratability, flexibility, isolation and material technology, Rogowski coil has been considered as a favourite tool for current sensing purposes [3]. Nowadays Rogowski coil is being used for measuring the currents under normal operating condition as well as under abnormal condition such as PD faults, ground faults, and relay protection tasks [4], [5]. Most of the available literature presents the design and performance of Rogowski coil based on practical analysis [6]. However, it is rare to find the simulation of a designed model of coil which can provide a deeper insight about the behaviour of Rogowski coil. This study presents effects of terminating resistance on the output of Rogowski coil using hardware as well as simulated model of Rogowski coil.

Although RC sensor is simple in construction but its behaviour and performance evaluation needs detailed investigation to calibrate its response for high frequency transient measurements. In this paper, a Rogowski coil having low number of turns is implemented and its performance is evaluated for low amplitude high frequency current pulses. Damping effect of terminating resistance on the output voltage of the coil is analysed in detail using theoretical, practical and simulated model of RC. Circuit

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model of the coil is simulated in EMTP-ATP environment and used for in-depth transient analysis. The designed model of the Rogowski coil is verified based on the simulated analysis. The comparison between real and simulated model validates the transient response of the coil.

II. DESIGNED MODEL OF ROGOWSKI COIL

Rogowski coil is composed of uniformly wound n number of turns on a nonmagnetic core (dielectric). Former of constant cross-sectional area A_c in toroidal fashion forms a closed loop, as shown in Fig. 1(a). The voltage $V_{rc}(t)$ induced within the coil can be expressed as

$$V_{rc}(t) = -\mu_0 A_c n \frac{di_p(t)}{dt}, \tag{1}$$

where μ_o is the permeability of free space and $\mu_o A_c n = M_c$ is the mutual inductance of the coil and also termed as sensitivity of RC.

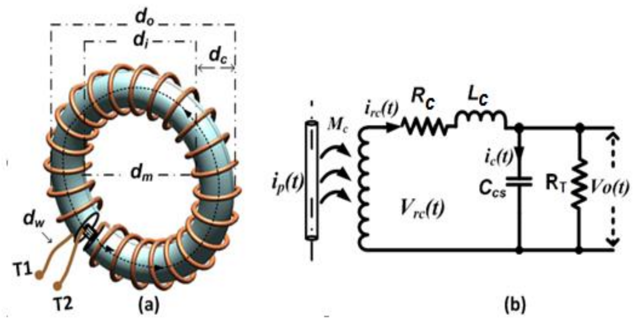


Fig. 1. Model of Rogowski coil. (a) Geometrical parameters model. (b) Lumped parameters model.

TABLE I. GEOMETRICAL PARAMETERS OF ROGOWSKI COIL.

Model Parameter	Symbol	Specification
Number of turns	n	30
Outer diameter of coil	d_o	16.1 cm
Inner diameter of coil	d_i	14.1 cm
Mean diameter of coil	d_m	15.1 cm
Core diameter	d_c	1.96 cm

TABLE II. ELECTRICAL PARAMETERS OF ROGOWSKI COIL.

Name of the Parameter	Symbol	Value of the Parameter
Self-resistance of coil	R_c	0.71 Ω
Inductance of coil system	L_c	1.19 µH
Capacitance of coil system	C_{cs}	14.7 pF
Mutual inductance	M_c	125 nH
Operating resonance frequency of coil system	f_{cs}	37.6 MHz

Core diameter is selected to fit the coil even for tight spaces during measurements. Selected coil diameter is considered to install the coil safely around the medium voltage (MV) lines. Keeping in view the basic factor of dielectric strength of 3 MV/m for air [7] added with insulation dielectric strength, this diameter is suitable for safety for the sensor and the measuring system at operating MV levels. Suitable number of turns (n) is selected to achieve the higher resonance frequency, necessary for faster response and acceptable output voltage signal even for smaller amplitude of pulsed currents.

Electrical parameters of Rogowski coil as shown in Fig. 1(b) are obtained using measurement based method [8] for better accuracy of the model and are given in Table II. C_{cs} is the capacitance of the coil system having the coil itself and the measuring system which includes the coil cable and active differential probe. This type probe allows reaching higher accuracy as it decouples the Rogowski coil from other circuitry. f_{cs} is the resonance frequency of the coil system, calculated using the parameters given in Table II, as

$$f_{cs} = \frac{1}{2\pi\sqrt{L_c C_{cs}}} \approx 37.6\ MHz. \tag{2}$$

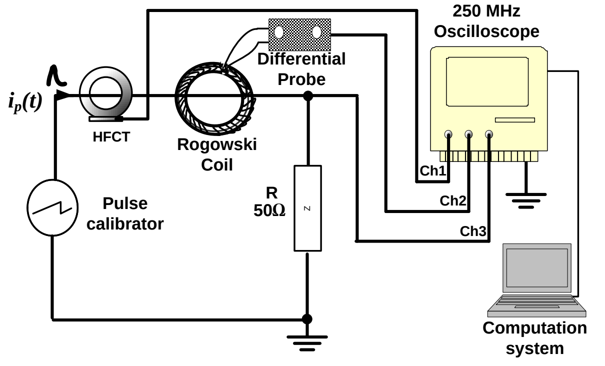


Fig. 2. Laboratory experimental setup for Rogowski coil measurements.

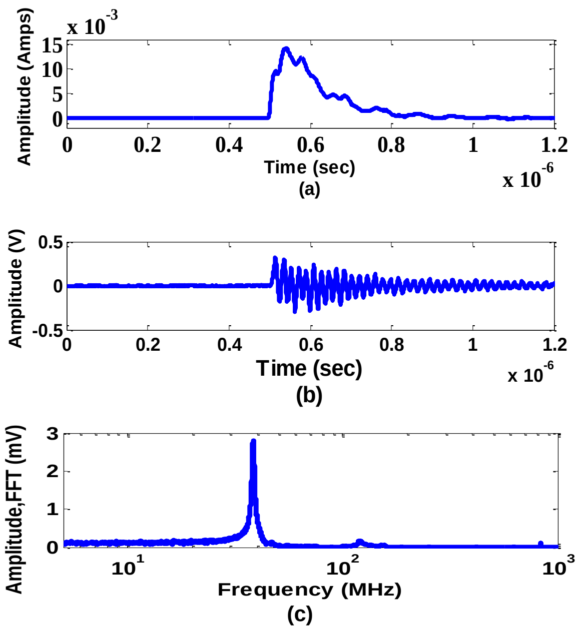


Fig. 3. Primary pulse in the test circuit measured by HFCT (a); output measured by RC along with measuring system configured for f_{cs} (b); FFT of the measured response (c).

To ensure the practical resonance frequency response of Rogowski coil, a laboratory test was made. A high frequency pulse was injected from a PD calibrator into a simple test circuit as shown in Fig. 2. The pulse current in the test line was measured by a commercial high frequency current transformer (HFCT), shown in Fig. 3(a). The data is captured at sampling time of $4 \cdot 10^{-10}$ sec. The captured output voltage of Rogowski coil for this primary current pulse is shown in time-domain plot in Fig. 3(b). The Fast Fourier Transform (FFT) of the captured response shown in Fig. 3(c) represents the frequency response of output which verifies 37.6 MHz (comparing with that in Table II) as the resonance frequency of designed coil. As resonance frequency reflects the LC parameters of the sensor [9] thus the determined parameters are also validated. The output is captured at oscilloscope across open terminal of coil (without terminating resistor), i.e. with R_T =1 MΩ which is input resistance of oscilloscope.

III. EMTP-ATP Simulation of Rogowski Coil

A high frequency transient signal shown in Fig. 4 is considered for measurement using the simulated model of coil in EMTP-ATP software. In the literature, pulse or impulse used in different simulation software is mostly based on the waveforms characterized by its mathematical model described as [10]

$$i(t) = A(e^{-\alpha_1 t} - e^{-\alpha_2 t}), \tag{3}$$

where A is the peak value of the pulse, $\alpha_1 t$ rise-time and $\alpha_2 t$ half of fall-time. In this work, a practical current pulse captured during testing is imported to EMTP to be sensed by the simulated model of RC. Both (mathematical and practical) current pulses are shown in Fig. 4. It can be clearly seen that practical current pulse contains high frequency variations during rise and fall time. This kind of variations or distortions (especially during rising front) in the pulse can significantly change the amplitude of output voltage of RC. To avoid any loss of high frequency components present in the practical pulse, the simulated model of RC is made to measure the same practical primary current. This verifies the validity of identified parameters of the coil for establishing an accurate model.

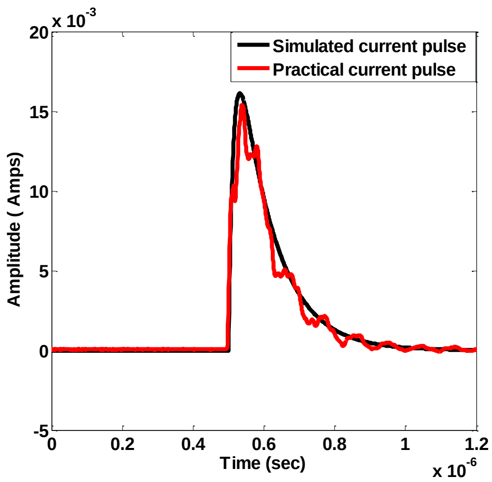


Fig. 4. Comparison of wave shapes for mathematical and practical current pulses.

The schematic diagram of the simulated model is shown in Fig. 5. The measured parameters (Table II) of the RC are used for simulation. Current carrying line is shown as circuit with source *B1* and resistance *R*.

Block *B1* in model represents the PD current pulse source shown in Fig. 5. The Transient Analysis of Control Systems (TACS) block "*T*" is for sensing the current flowing in the test circuit without disturbing the test circuit current. Block *B2* represents the time-derivative of the primary current while $V_{rc}(t)$ is measured as voltage induced in RC. Block *B3* shows the *R-L-C* equivalent of Rogowski coil. R_T represents the terminating resistance which is the external resistance connected across the terminal of the coil. Output voltage $V_o(t)$ is measured at the oscilloscope having 1 MΩ input resistance (in parallel with R_T).

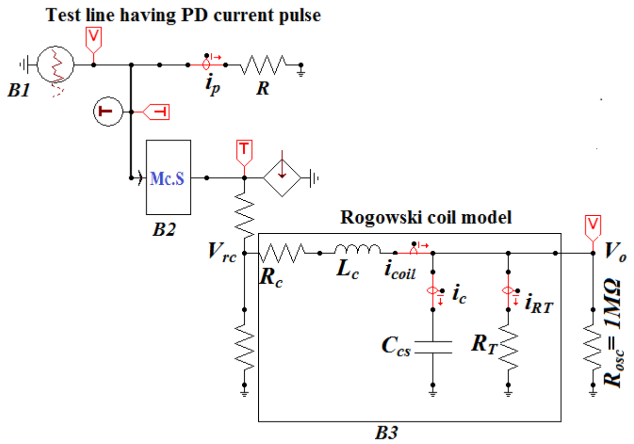


Fig. 5. ATP simulation model of non-compensated Rogowski coil using RLC equivalent circuit.

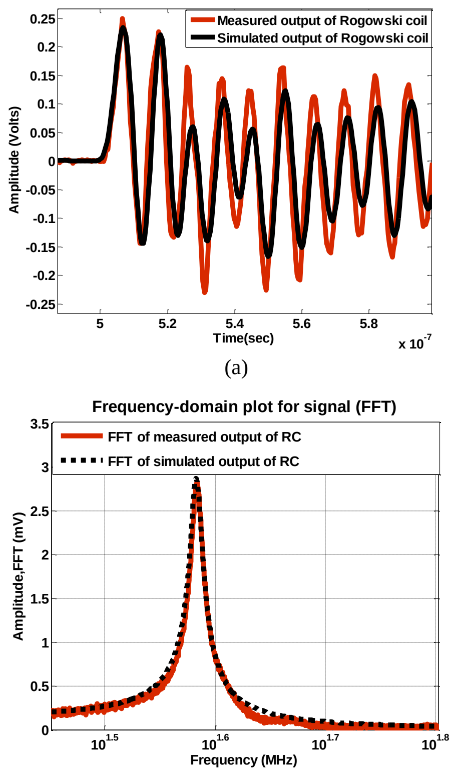


Fig. 6. Comparison of measured and simulated output voltage of Rogowski coil: a – time domain; b – frequency domain.

The comparison is carried out considering the time domain performance and FFT analysis of the measured and simulated outputs as shown in Fig. 6(a) and Fig. 6(b) respectively. The comparison shows a nice match between measured and simulated results which not only ensures the correct identification of the parameters of Rogowski coil but also validates the simulated model with enough accuracy to use it for further analysis.

In this work the *R-L-C*-based model (Fig. 5) will be used for further consideration. The advantage of using this model is the possibility to measure currents in the lumped components (R_c, L_c and C_{cs}) of the coil. This provides an opportunity to analyze the behavior of these components during any design modification. The current $i_{coil}(t)$ induced within the winding of Rogowski coil can be expressed as

$$i_{coil}(t) = i_c(t) + i_{R_T}(t), \quad (4)$$

where $i_c(t)$ and $i_{RT}(t)$ are the current through the C_{cs} and R_T of the coil system respectively as shown in Fig. 5.

The response of measurement head of RC to the pulse current is captured as oscillating voltage signal. For detection of a current pulse, this response can be considered sufficient as the 1st peak of the signal reflects the amplitude and polarity of the primary current pulse. For accurate measurement of the primary current pulse waveform, the oscillating output response needs to be compensated properly. For recreating the actual current waveform, the basic model of coil mentioned above requires certain modifications based on its transient behavior, namely termination and integration. The simulated model of the coil is analyzed in the next section to suggest the modification for the practically investigated prototype.

IV. TRANSIENT BEHAVIOUR DURING PULSED MEASUREMENTS

Observed from (1) the output of the RC is a time-differential of the primary current. To obtain the primary current, the coil's output voltage is needed to be integrated and then scaled by the reciprocal of the value of mutual inductance [11]. It can also be derived from (1) as

$$i_p(t) = -\frac{1}{M_c}\int V_{rc}(t)dt. \quad (5)$$

This is true for lower frequencies but for higher frequencies, integration of $V_{rc}(t)$ does not result in the measured primary current.

A. Transfer function of Rogowski coil

Electrically, Rogowski coil behaves as a *R-L-C* circuit as shown in Fig. 1(b). The output of RC can be represented by the transfer function (in *s*-domain) [8] as

$$V_o(s) = \frac{\frac{1}{L_c C_{cs}}}{s^2 + \frac{1}{L_c C_{cs}}(\frac{L_c}{R_T} + RC_{cs})s + \frac{1}{L_c C_{cs}}(\frac{R}{R_T}+1)} V_{rc}(s), \quad (6)$$

where

$$V_{rc}(s) \xrightarrow{L^{-1}} V_{rc}(t) = -M_c \frac{di_p(t)}{dt}. \quad (7)$$

For higher frequencies the significant presence of L_c and C_{cs} causes oscillations of frequency ω_n in the $V_o(t)$ as shown in Fig. 6. Based on circuit analysis theory [12] oscillatory response of RC can be expressed in terms of forced and natural response as

$$Vo(t) = V_{rc}(t) + V_{rc}(t)\cdot e^{-\xi\omega_n t}\sin\left(\omega_n\sqrt{1-\xi^2}\right)t \quad (8)$$

and

$$Vo(t) = -M_c\frac{di_p(t)}{dt} - M_c\frac{di_p(t)}{dt}\cdot e^{-\xi\omega_n t}\sin\left(\omega_n\sqrt{1-\xi^2}\right)t, \quad (9)$$

where ω_n is the natural (resonance) frequency of the coil and is calculated by (2) while ξ is the damping coefficient. Eq. (8) presents the output voltage of RC in terms of forced and natural response for *R-L-C* second order circuit of RC. Natural response is the response of coil's own circuit properties which hides the information of the original measured signal. As visible from (8), damping can be efficiently used to get rid of natural response from the output voltage of RC.

The transfer function given in (6) represents classical 2nd order behavior whereas characteristic equation can be written as

$$s^2 + 2\xi\omega_n s + \omega^2{}_n = 0\ . \quad (10)$$

Comparing with the transfer function, damping coefficient ξ can be expressed as

$$\xi = \frac{1}{2\omega_n\ L_c\ C_{cs}}(\frac{L_c}{R_T} + R_c C_{cs}), \quad (11)$$

where ξ depends on all the four parameters of the Rogowski coil (L_c,C_{cs}, R_c and R_T). As L_c, C_{cs} and R_c are fixed for a certain geometrical design of RC hence ξ is completely dependent on the terminating resistance R_T.

B. Effect of terminating resistance

It has been observed that for the higher value of terminating resistance i.e $R_T >> (1/\omega_n C_{cs})$ the RC behaves as *R-L-C* series circuit, with oscillations in the output of coil. In this case considering (4), $i_{RT} \sim 0$ and $i_{coil}(t)= i_c(t)$ as shown in Fig. 7(a). When R_T is decreased, $i_{RT}(t)$ increases and $i_c(t)$ decreases. This reduces the effect of charging and discharging of capacitance C_{cs} and takes the coil behavior closer to *R-L* inductive circuit. The current through the R_T represents losses in heat and oscillations are more damped as value of R_T decreases and share of i_{RT} increases. Fig. 7 shows the effect of R_T on current distribution inside RC using its simulated model given in Fig. 5.

Looking back at (8) there is a working point useful for the sensor application, when ξ =1:

$$\sin\left(\omega_n\sqrt{1-\xi^2}\right)t = 0, \quad (12)$$

$$M_c\frac{di_p(t)}{dt}\cdot e^{-\xi\omega_n t}\sin\left(\omega_n\sqrt{1-\xi^2}\right)t = 0. \quad (13)$$

This expresses the circuit operation when the oscillations due to the measured primary current are fully damped. In this case the RC output

$$Vo(t) \cong V_{rc}(t) = -M_c \frac{di_{in}(t)}{dt}. \tag{14}$$

Based on electrical parameters of Rogowski coil, the value of terminating resistance can be calculated using (11) as

$$R_T = \frac{L_c}{2\xi\omega_n L_c C_{cs} - R_c C_{cs}}. \tag{15}$$

Considering the values of high-frequency RC parameters

$$R_c C_{cs} << 2\xi\omega_n L_c C_{cs}. \tag{16}$$

Therefore the value of R_T can be calculated as

$$R_T = \frac{1}{2\xi\omega_n C_{cs}}. \tag{17}$$

For $\xi = 1$

$$R_T = \frac{1}{2\omega_n C_{cs}} = \frac{Z_c}{2}, \tag{18}$$

where

$$(1/\omega_n C_{cs}) = Z_c. \tag{19}$$

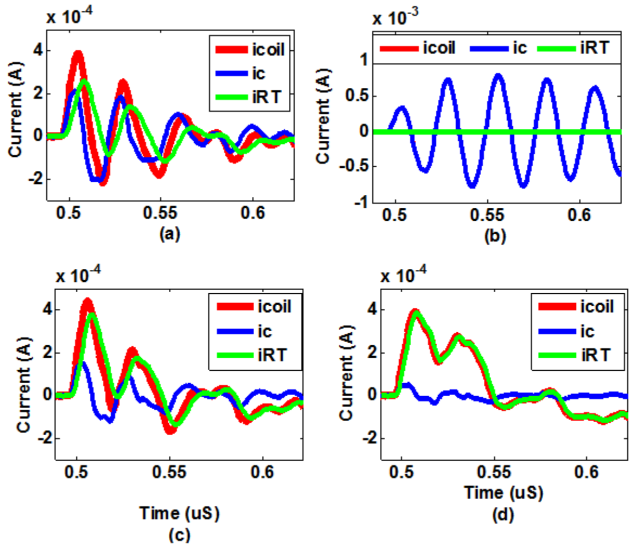


Fig. 7. Current i_{coil}, i_c and i_{RT} through the components of L_c, C_{cs} and R_T of Rogowski coil respectively for different value of R_T: (a) R_T = 1MΩ > Z_c; (b) R_T=Z_c; (c) R_T=Z_c/2; (d) $R_T \leq Z_c/2$.

V. INTEGRATION OF ROGOWSKI COIL OUTPUT

Integration of the output of Rogowski coil can be performed by one of two common means:

1) by use of an electrical or electronic integrator, or
2) by using numerical integration in software after the coil output voltage is digitized [11]. Numerical integration is selected and can be expressed as

$$i_p(t) = -K_c \int V_o(t)dt. \tag{20}$$

Integration is added in the simulated model of RC shown above as block "*B4*" in Fig. 9 having $K_c=1/M_c$.

The diagram shown in Fig. 8 represents the laboratory measurement setup with different values of terminating resistance connected to evaluate its effect on the output of RC. Fig. 9 represents the similar setup modeled in EMTP-ATP. Both, the output voltage $V_o(t)$ and (integrated and reconstructed) current $i_o(t)$ results of Rogowski coil for different terminating resistances are presented as measured values and compared to simulation results (Fig. 10). The comparison of measured and simulated results shows a nice match.

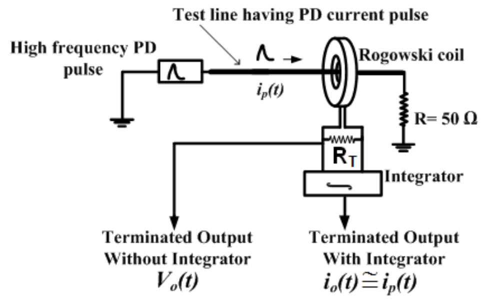


Fig. 8. Laboratory measurement setup to observe the effect of terminating resistance on Rogowski coil's output.

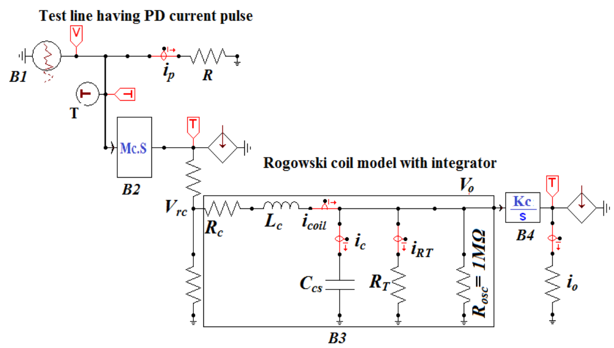
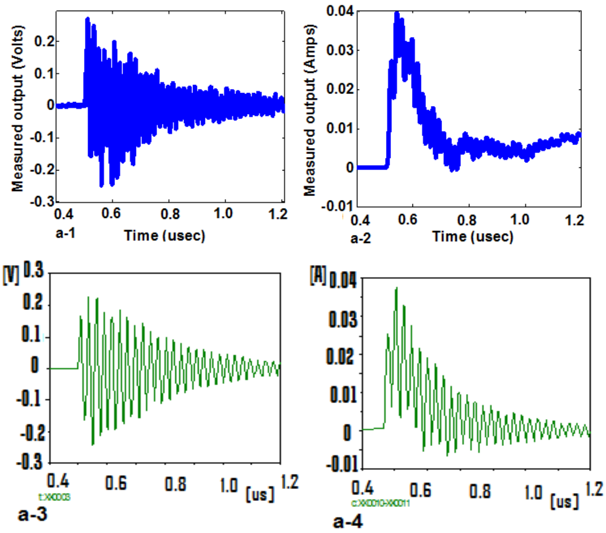
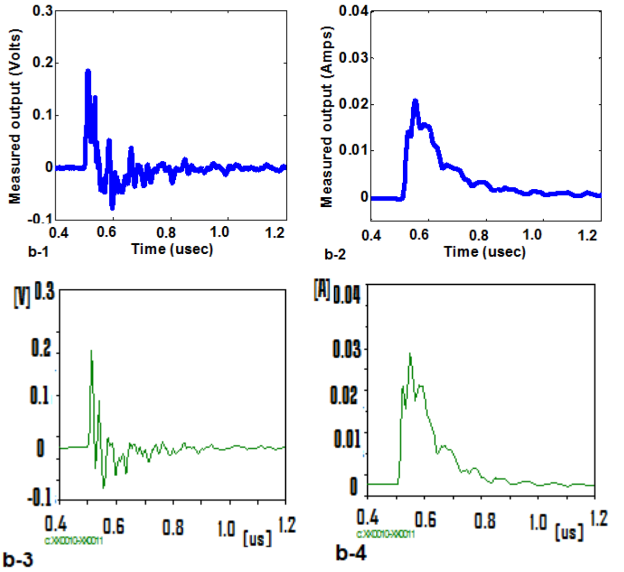


Fig. 9. ATP simulation diagram of Rogowski coil test setup.

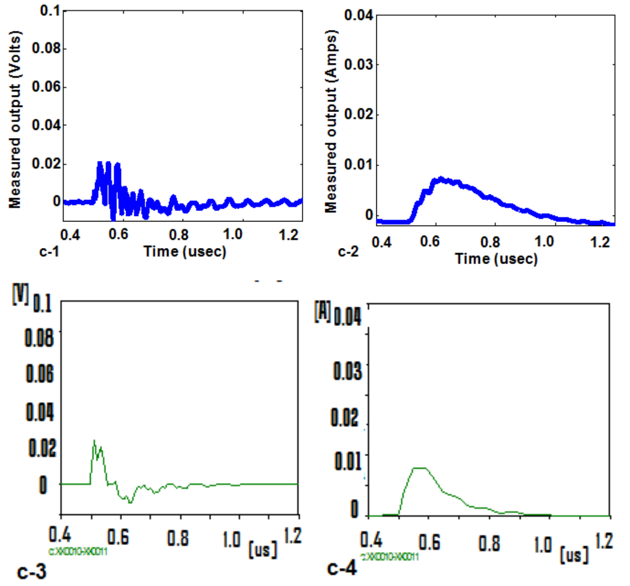
The oscillations are properly removed at R_T = *175 Ω* for our designed coil as shown in Fig 10(b). Lowering the R_T to *40Ω* (<Z_c) makes the response of coil over-damped and slow, which results in lower amplitude and increased pulse duration of the reconstructed primary current as visible in Fig. 10(c). Therefore the value of R_T considerably less than Z_c is not recommended for termination.



(a)



(b)



(c)

Fig. 10. (a): a-1 and a-2 shows $v_o(t)$ and $i_o(t)$ for real RC at $R_T\ (1M\Omega) >> Z_c$, a-3 and a-4 shows $v_o(t)$ and $i_o(t)$ for simulated RC at $R_T\ (1M\Omega) >> Z_c$, 10; (b): b-1 and b-2 shows $v_o(t)$ and $i_o(t)$ for real RC at $R_T\ (175\Omega)=Z_c/2$, b-3 and b-4 shows $v_o(t)$ and $i_o(t)$ for simulated RC at $R_T(175\Omega)=Z_c/2$, 10; (c): c-1 and c-2 shows $v_o(t)$ and $i_o(t)$ for real RC at $R_T\ (40\Omega) < Z_c$, c-3 and c-4 shows $v_o(t)$ and $i_o(t)$ for simulated RC at $R_T\ (40\Omega) < Z_c$.

VI. Practical Implementation of Rogowski Coil

In order to carry out in-depth transient analysis of RC using simulated model, the basic hardware model of the coil (given in Table I and Table II) is modified by adding the selected R_T and proposed integration technique for the output voltage of Rogowski coil. The measured non-oscillated output voltage of coil (measuring the calibrated PD pulse) is captured using a digital storage oscilloscope. LeCroy Wavesurfer 24Xs oscilloscope is used for this purpose where 8-bit built-in data acquisition system (DAS) is used to get the digital data with a sampling rate of 2.5GS/s. Here 8-bit resolution provides ($2^m = 2^8$) 256 vertical levels of the observed signal which means one level gives 0.4% of full scale. The maximum error during digitalization of the signal with 8-bit DAS is less than $\pm$0.2% which is sufficient in this application.

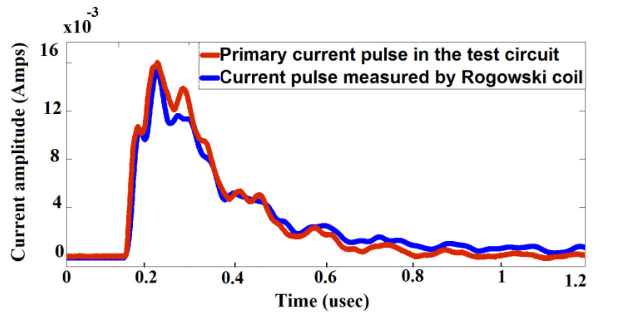


Fig. 11. Comparison of actually current pulse in the test line and current pulse measured by Rogowski coil.

The captured RC signal is integrated numerically to recreate the original (primary current) signal using Trapezoidal rule. Trapezoidal rule in general is considered as having faster convergence in particular cases of rougher signals (ones with weaker smoothness). Numerical integration is done using the same oscilloscope. Similar integration methods are provided also by Matlab software. This method is easy to include in a microcontroller based measurement system.

Comparison between the primary current pulse in simulated circuit and practically measured output current pulses are compared which shows a nice match as shown in Fig. 11. This confirms that the design of Rogowski coil for transient application. The final design of the coil is capable for measuring the real transient signal in electrical components.

VII. Conclusions

In this paper, the circuit behavior of Rogowski coil is investigated in detail for high frequency PD current pulse measurements. Analysis is made using real and simulated environments at different stages of construction of the coil model. Simulated model is verified for the measurement head of coil and then further used for developing the final design of the coil. The feature of using practically measured calibrated PD pulse instead of numerically generated pulse during simulation provides more reliable analysis of the simulated coil. During simulation it is necessary to keep the sampling rate of the measured and simulation system same.

Theoretically analyzed effects of terminating resistance are evaluated using the circuit model of the RC. During practical investigation, different values of R_T in the close neighborhood of $Z_c/2$ presented the acceptable damping to get the reconstructed primary current. However based on the availability of possibly pure resistance, R_T=175 $\Omega \approx Z_c/2$ is selected for better accuracy. The results show that the measured output voltage of Rogowski coil is closely matched with the simulated output. The slight mismatch is also observed in the output shown in Fig. 6a can also be seen in the reconstructed wave shape presented in Fig. 11. Reasons for mismatch can be stray inductance and capacitance of the RC itself, terminating resistance or other components in measurement circuitry. The terminating resistance used in simulated model is an ideal resistive component while the real resistance can have stray inductance effects at such high frequencies. The difference is not major thereby confirming the model applicability. The stray components of the terminating resistance are not modeled in this paper.

Simulated model has been used to verify the basic design of the coil for the assessment of expected behavior of coil during modification in design. Simulated model of coil can be used to propose better diagnostic techniques in cables, transformers and other electrical apparatus, before real implementation. In real-life application, there would be multiple RCs needed for the full diagnostics, as the diagnostic methods may require multiple coils for multi-end measurements. During research stages while the coil manufacturing is not done with the specialized equipment, multiple coils may not be perfectly identical even for the same design of coil. Non-uniform turn density, imperfect central position of the return loop and loose connections may result in ambiguities in measured signals. Simulating the diagnostics set-up with such a model, using parameters identified for each coil, will provide better accuracy and concurrency of the response.

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