Rogowski Coil Transient Performance and ATP Simulations for Applications in Protective Relaying

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***Abstract*- This paper presents ATP modeling of Rogowski coils for protection system applications. Characteristic test cases have been developed and the results presented. Simulation results were also compared to conventional current transformer transient behavior.**

***Keywords*: Rogowski Coil, Current Transformer, Protective Relaying, Transient Study, Digital Simulation**

I. INTRODUCTION

Traditional electromechanical and microprocessor protection relays process signals provided by iron core voltage and current transformers (VTs and CTs), requiring a number of protective and control devices, measuring equipment and extensive wiring. These designs are inflexible if adjustments are needed to accommodate load and power system configuration changes. In addition, complex periodic testing and maintenance procedures are necessary. In spite of best engineering efforts, at times relay system misoperation occurs due to the complexity of the protection scheme (e. g., wrong wiring after periodic testing, wrong relay setting), the effects of external magnetic fields, and CT saturation, especially in differential schemes. Even protection systems using multifunction relays are susceptible to these problems. When a protection device becomes inoperative and does not initiate breaker tripping during the fault, backup protection is provided locally by a redundant or breaker failure relay and remotely by upstream protection devices. Traditional schemes employ intentional time-delays to ensure the primary relay has ample time to clear a fault before the backup relay operates. This delay in fault removal causes higher equipment stress and a power outage to larger areas, affecting more customers.

Advanced protection and control systems can be designed using new Rogowski coils (RCs) and multifunction relays. These schemes require fewer relays and current sensors than conventional designs, response times to faults are faster, and adjustments to load and/or power system configuration changes can be easily made. Since RCs are very accurate and do not saturate, protection levels can be set to lower thresholds increasing the sensitivity of the scheme without affecting reliability of operation. This reduces the stress on protected equipment during faults. The system is immune to external magnetic fields, is simple, user friendly, requires less wiring and space, and can provide metering class accuracy.

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II. CURRENT TRANSFORMER TRANSIENT PERFORMANCE

Iron-core transformers (power, voltage, and current instrument transformers) have non-linear magnetizing reactance. Power and voltage instrument transformers are connected in parallel with the load while CTs are connected in series with the load. Since power systems are operated within a range of ±5% nominal voltage, power and voltage instrument transformers are designed to operate close to the saturation voltage (Figure 1). However, under some operating conditions, voltages can increase and cause saturation. Ferroresonance can be initiated when overvoltages occur.

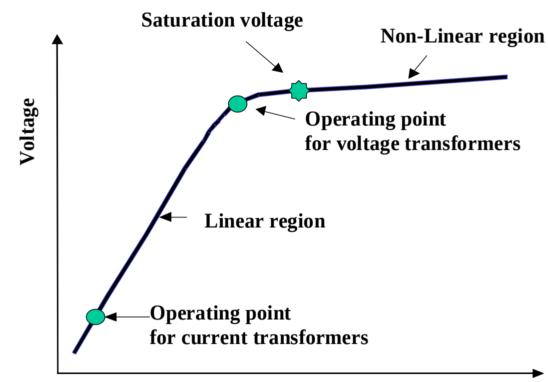
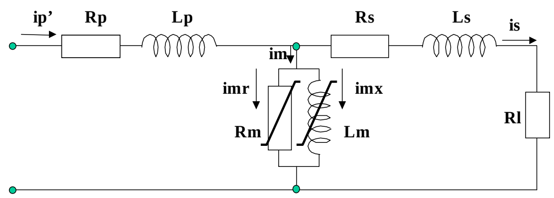


Figure 1. V-I Curve and Operating Points for Current and Voltage Transformers

CT primary currents can change from load currents to high fault currents. To avoid saturation, CTs are designed to operate at load currents on the lower portion of the magnetizing branch V-I curve's linear region (Figure 1). It is desirable that CTs operate on the linear region without exceeding the saturation voltage even for fault currents. Nevertheless, under some conditions, CTs saturate.

CT performance characteristics are specified by ANSI/IEEE Standard [1]. However, this standard only covers CT behavior under steady state and symmetrical fault conditions. In an actual power system, short circuit currents may have a significant DC offset, which may saturate CTs that would not saturate under symmetrical fault conditions. Remanence in the CT core can also contribute to CT saturation. Therefore, it is necessary to use additional techniques to estimate CT performance under fault conditions. The Alternative Transients Program (ATP) was used for to simulate the CT transient behavior. ATP simulations have been useful in solving actual electric power system problems. Computer simulations are particularly effective when investigating CT transient behavior in the current range not convenient for testing in the high power laboratory [2]. CT equivalent circuit is shown in Figure 2.



Rp, Rs, Lp, Ls	-	primary and secondary winding resistance and leakage inductance
Lm	-	magnetizing inductance
imx	-	magnetizing current, reactive component
imr	-	magnetizing current, resistive component
Rl	-	CT burden including lead resistance
Rm	-	iron loss equivalent resistance

Figure 2. Current Transformer Equivalent Circuit

The CT equivalent circuit of Figure 2 can be simplified as shown in Figure 3 and will provide adequate transient behavior for the relay transient studies.

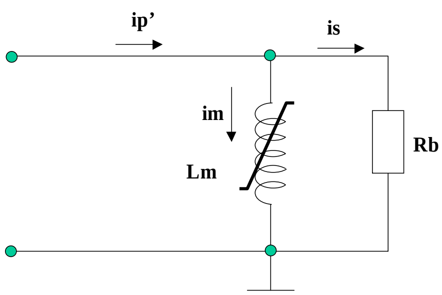


Figure 3. Current Transformer Modeling for the Relay Transient Studies

The CT V-I curve can also be simplified, simulated with only two sections, providing realistic CT transient behavior [3]. Figure 4 shows measured and simulated V-I curve for a 1200/5 A CT (curves are slightly offset for visual comparison). The non-linear magnetizing branch can cause the CT saturation at fault currents. This CT saturates during an asymmetric fault of 10 kA_{RMS}, tested in a high power laboratory (Figure 5).

Rogowski coils are linear (do not saturate) and provide advanced solutions for applications in protective relaying.

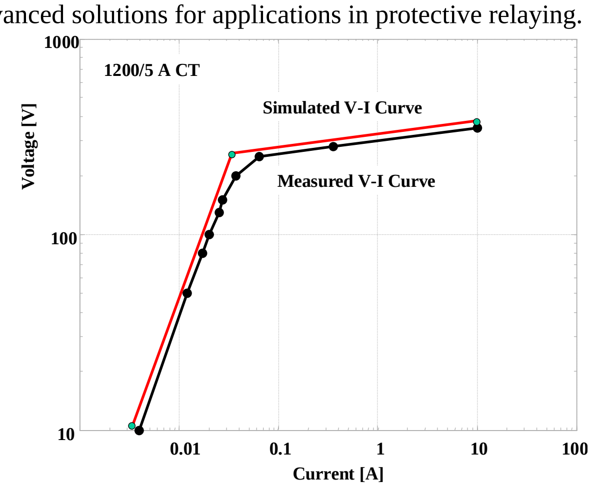


Figure 4. 1200/5 A Current Transformer V-I Curve

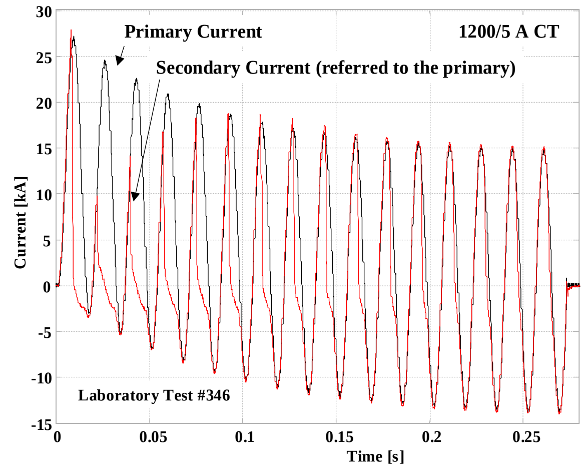


Figure 5. 1200/5 A Current Transformer Transient Performance

III. Rogowski Coil Characteristics

A. Theory of Operation

Rogowski coils consist of wire wound on a non-magnetic core ($\mu = \mu_0$). The coil is placed around the conductors whose currents are to be measured as shown in Figure 6a [4]. Rogowski coil equivalent circuit is shown in Figure 6b.

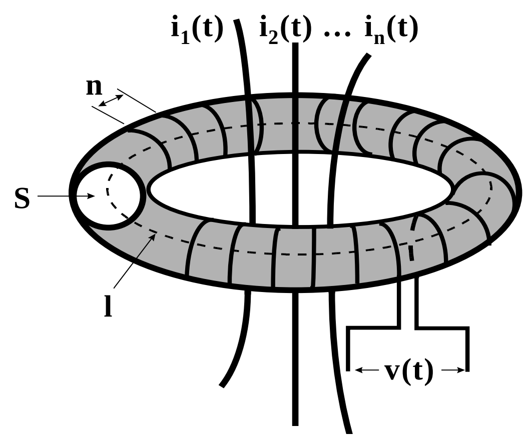
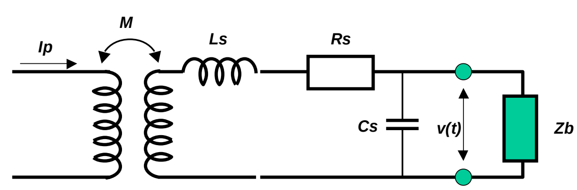


Figure 6a. Principle of Rogowski Coil Design



Rs, Ls	-	secondary winding resistance and leakage inductance
M	-	mutual coupling
Cs	-	stray capacitance (for power applications can be neglected)
Zb	-	RC burden (>50 kΩ)

Figure 6b. Rogowski Coil Equivalent Circuit

The voltage induced in the coil is defined by Equation 1.

$$v(t) = -\frac{d}{dt}\left(\sum_{j=1}^{N} \Phi_j\right) \qquad (1)$$

, where ϕ_j is instantaneous flux for the j-th turn of the total N turns. The total flux in the coil is given in Equation 2.

$$\Psi = \oint_l dl \int_s \vec{H} n d\vec{S} \qquad (2)$$

, where

ψ - total flux,
l - core length,
n - winding density (windings per unit length),
S - core cross-section, and
H - magnetic field.

If the core has a constant cross-section and the wire is wound perpendicular on the middle line l with constant density, then Equation 3 applies.

$$d\vec{S} dl = dS d\vec{l} \qquad (3)$$

Now, Equation 2 can be rewritten as:

$$\Psi = \mu_0 n \int_s dS \oint_l \vec{H} d\vec{l} = \mu_0 n \int_s \sum_j i_j(t) dS = \mu_0 n S \sum_j i_j(t) \qquad (4)$$

, where

$$\oint_l \vec{H} d\vec{l} = \sum_j i_j(t) \qquad (5)$$

The coil output voltage is then:

$$v(t) = -\mu_0 n S \frac{d}{dt}[\sum_j i_j(t)] = -M \frac{d}{dt}[\sum_j i_j(t)] \qquad (6)$$

, where

$$M = \mu_0 n S \qquad (7)$$

Coil mutual reactance M is independent of the conductor location inside the coil loop. Rogowski coil output voltage is proportional to the rate of change of the measured current. To prevent the influence of nearby conductors carrying high currents, Rogowski coils must be designed with two wire loops connected in the electrically opposite direction. This will cancel all electromagnetic fields coming from outside the coil loop. This other loop can be formed by returning the wire through the center of the winding as shown in Figure 7 or by adding an additional winding wound in the opposite direction over the existing one.

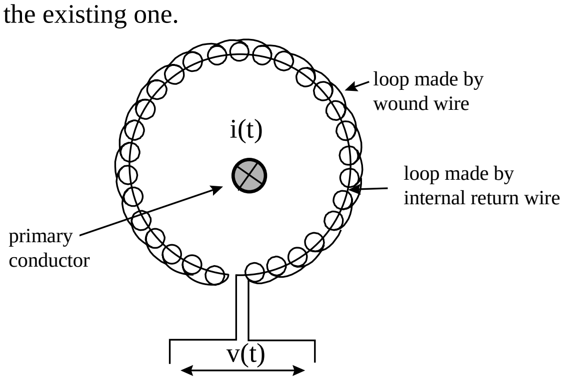


Figure 7. Rogowski Coil with the Return wire Through the Winding Center

To obtain a voltage proportional to the measured current, the coil output voltage must be integrated. Output voltage integration can be performed using a RC integrator or an operational amplifier. The integrated voltage is proportional to the sum of the measured currents as given by Equation 8.

$$v(t) = \frac{M}{RC} \sum_j i_j(t) \qquad (8)$$

If the measurement is restricted to single frequency sinusoidal currents (50 or 60 Hz), it is not necessary to integrate the coil output voltage. This is because the differentiation of sinusoidal currents results in sinusoidal waveforms shifted by 90°. This shift does not affect measurement results if only currents are measured. The coil output voltage is given by Equation 9.

$$V_{rms} = \mu_0 n S \omega \mathrm{I_m} = \mu_0 n S \omega \sqrt{2} I_{rms} \qquad (9)$$

B. Designs

Papers [5-7] present conventional RC designs. Paper [8] presents an innovative and patented design of RCs that use PCBs. In that design both RC windings are imprinted on the same PCB. High precision Rogowski coils presented in this paper consist of two printed circuit boards (PCBs) located next to each other (Figure 8) [9-10]. Each PCB contains one imprinted coil wound in opposite directions (clockwise and counter-clockwise). The top and bottom sides of each PCB are imprinted to form a coil around the center of the board. The conductive imprints on the upper and lower sides of the PCB are interconnected by conductive-plated holes. High precision is obtained because the manufacturing process is computer controlled, providing accurate geometry of the coils. New RC designs use multi-layer PCBs, which provides higher accuracy and more proficient manufacturing.

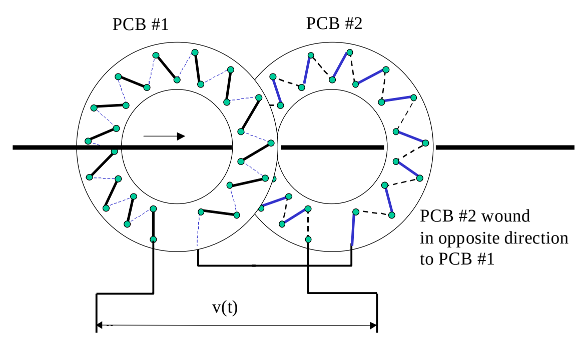


Figure 8. Principle of the PCB Rogowski Coil Design

PCB Rogowski coils can be designed with different shapes to adjust for the application and be designed in split-core styles for installation without the need to disconnect primary conductors. Figure 9 shows a bushing type encapsulated circular shape RC implemented on multi-layer PCBs. These RCs were used for differential protection of mobile substation power transformers. Figure 10 shows principle of design of oval shape split-core style RC designed to embrace all three-phase conductors (for measurement of residual currents) or to embrace parallel conductors that carry heavy currents. The split-core style RC consists of four half loops. The first two half loops are constructed with two PCBs with imprinted windings wound in opposite directions, located next to each other. The remaining two half loops are constructed in the same way, but wound in opposite directions and connected. Figure 11 shows the PCB split-core style RC design implemented for differential protection of electric arc furnace (EAF) transformers.

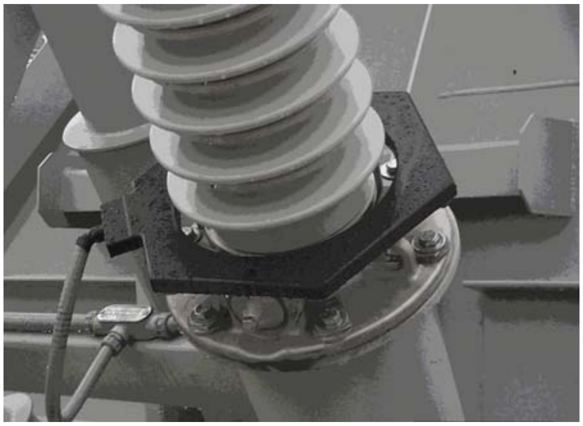


Figure 9. Bushing Type Multi-layer PCB Rogowski Coil Design (installed around bushings of a mobile substation power transformer)

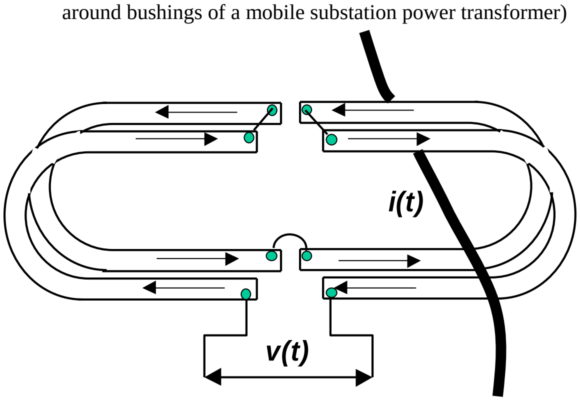


Figure 10. Principle of the Split-Core Style PCB Rogowski Coil Design

Figure 11. Split-Core Style PCB Rogowski Coils (installed around water-cooled secondary conductors of an EAF transformer)

C. PCB Rogowski Coil Performance

The PCB Rogowski coil has the following characteristics: measurement accuracy reaching 0.1 %; measurement range from 1 A to over 100 kA; frequency response linear up to 700 kHz; unlimited short-circuit withstand; galvanically isolated from the primary conductors; can be installed around bushings or cables, avoiding the need for high insulation. Rogowski coils can be connected in series to increase output signal.

Linearity was tested from $1A_{RMS}$ to 190 kA_{peak}, representing the extremes of RC applications. The coil has linear characteristic over the whole current range.

Frequency response was estimated using computer simulations. To verify the model, the coil impedance as a function of frequency was measured. The same measurement was then simulated. Differences between simulated and test results were evident only at 5 MHz (resonant conditions) due to modeling difficulties at high frequencies. However, this frequency is much higher than the expected range of RC applications. The simulated frequency response for integrated output signals is linear up to 700 kHz as shown in Figure 12.

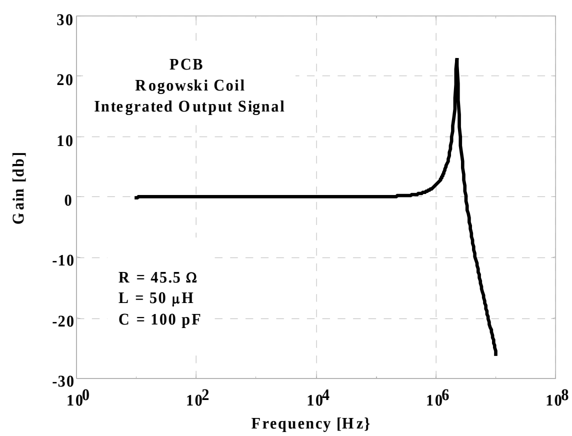


Figure 12. PCB Rogowski Coil Frequency response (integrated signal)

D. ATP Simulations

Rogowski coils were modeled based on their equivalent circuits. The ATP saturable transformer model was used to model RCs. Since RCs are linear, saturable transformer model was adjusted to represent linear magnetizing branch by selecting only one point for flux-current characteristic. The flux-current slope was adjusted to the actual RC slope as shown in Figure 13.

Transient response of Rogowski coils was simulated and compared to a conventional CT (Figure 14). The following simulations were performed: symmetric faults, asymmetric faults, and capacitor energizing.

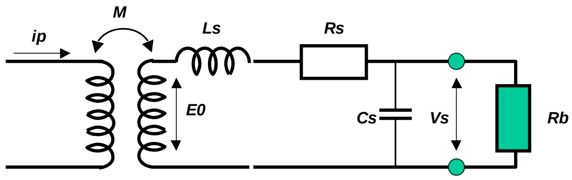


Figure 13a. Rogowski Coil Equivalent Circuit

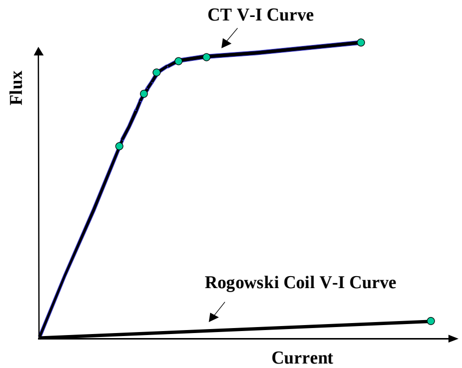


Figure 13b. Rogowski Coil and Current Transformer Flux-Current Characteristics

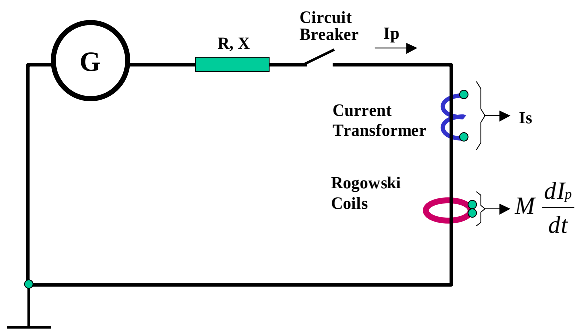


Figure 14. ATP Model for Simulation of CT and RC Transient Responses

Symmetric current faults. Figure 15 shows the RC non-integrated secondary signal for a symmetric fault. The secondary signal is shifted 90°. However, when signal is integrated, it becomes identical to the primary current waveform.

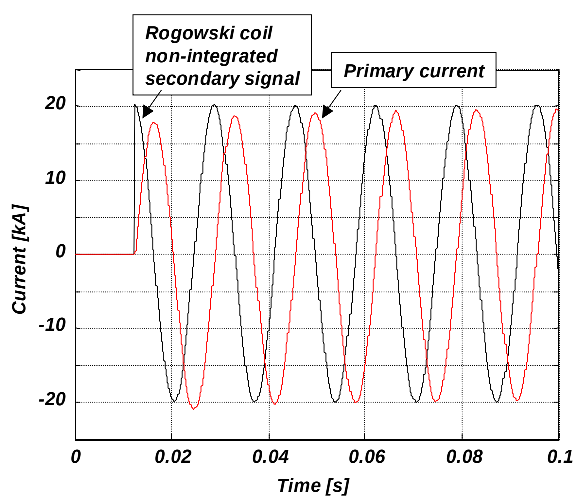


Figure 15. RC Transient Response to Symmetric Faults (non-integrated RC secondary signal)

Asymmetric current faults. Figure 16 shows the RC non-integrated secondary signal for an asymmetric fault. DC offset is attenuated. However, when signal is integrated, it becomes identical to the primary current waveform (Figure 17).

Figure 18 shows that 1200/5 A current transformer heavily saturates for this asymmetric fault and could cause relay misoperation.

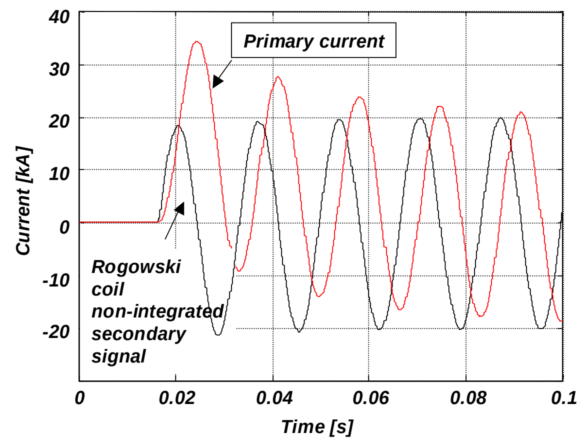


Figure 16. RC Transient Response to Asymmetric Faults (non-integrated RC secondary signal)

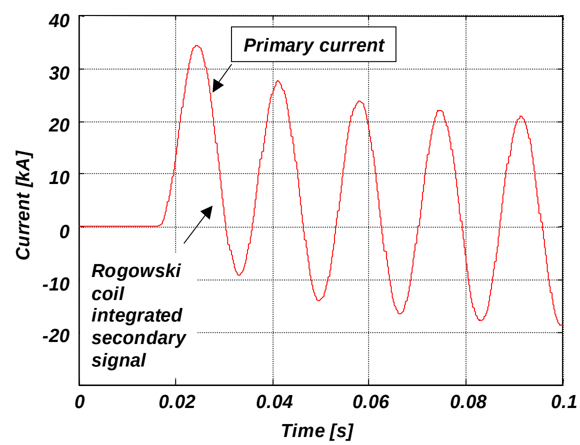


Figure 17. RC Transient Response to Asymmetric Faults (integrated RC secondary signal overlaps the primary current waveform)

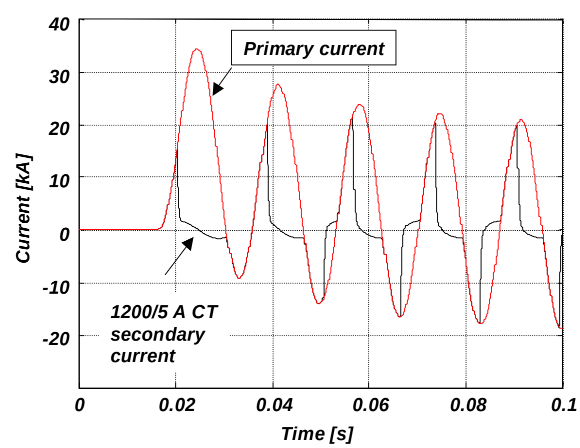


Figure 18. Current Transformer Transient Response to Asymmetric Faults

Capacitor switching. Figure 19 shows capacitor current waveform during the capacitor energizing. High frequency current is dominant during the first half cycle. Figure 20 shows the RC non-integrated secondary signal during this capacitor energizing. The RC waveform is significantly different than the primary current waveform. However, integrated signal becomes identical to the primary current waveform shown in Figure 19.

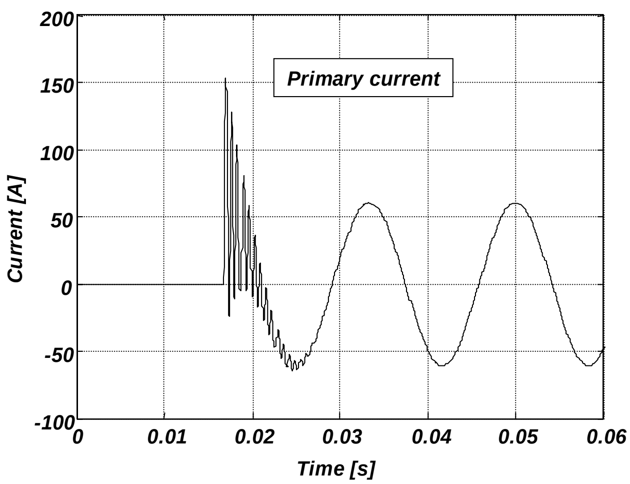


Figure 19. Capacitor Energizing (primary current)

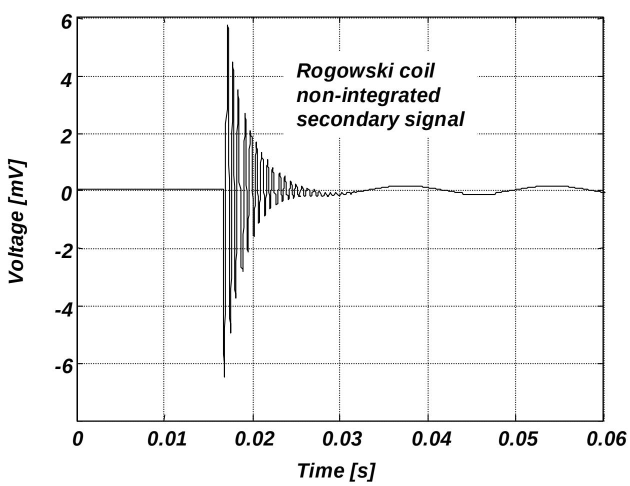


Figure 20. RC Transient Response to Capacitor Energizing (non-integrated RC secondary signal)

IV. CONCLUSIONS

The Rogowski coil (RC) output voltage is proportional to the rate of change of measured current. To obtain measured current, coil output voltages must be integrated. Strict design criteria must be followed to obtain a coil immune from nearby conductors and independent of conductor location inside the coil loop. The most important design criteria is to prevent the influence from nearby conductors, which is achieved by designing the coil with two-wire loops connected in electrically opposite directions. This cancels the electro-magnetic fields coming from outside the coil loop.

ATP simulations were performed modeling RCs based on their equivalent circuits. The results confirmed that ATP can effectively be used to simulate the RC transient behavior for applications for protective relaying.

V. REFERENCES

[1] C57.13-1993 ANSI /IEEE Standard, “Requirements For Instrument Transformers”.

[2] Lj. A. Kojovic, “CT Modeling Techniques for Relay Protection System Transient Studies”, International Conference on Power Systems Transients – IPST 2003, New Orleans, September 2003.

[3] Lj. A. Kojovic, “Comparison of Different Current Transformer Modeling Techniques for Protection System Studies”, IEEE/PES Summer Meeting, Chicago, Illinois, July 2002.

[4] Lj. A. Kojovic, ”Rogowski Coils Suit Relay Protection and Measurement”, Computer Application in Power, IEEE Magazine, July 1997.

[5] J. M. Sohn, W. J. Choe, B. W. Lee, I. S. Oh, H. S. Kwon, “Development of current and voltage sensor for distribution switchgear”, T&D Conference and Exhibition 2003, Dallas, USA, 2003.

[6] G. Schet, F. Engler, F. Jaussi, K. Pettersson, A. Kaczkowski, “The Intelligent GIS - A Fundamental Change in the Combination of Primary and Secondary Equipment”, CIGRE ’96, Paris, France, 1996.

[7] G. Reiter, T. Looser, D. Fischer, M. Ilar, “Digital Protection and Control Systems in Substations using Sensor Technology”, CEPSI 2000, The 13th Conference of the Electric Power Supply Industry, Manila, Philippines, October 23–27, 2000.

[8] E. Thuries, J. P. Dupraz, C. Baudart, J. P. Gris, “Contribution of Digital Signal Processing in the Field of Current Transformers”, CIGRE ’96, Paris, France, 1996.

[9] Lj. A. Kojovic, V. Skendzic, S. E. Williams, “High Precision Rogowski Coil”, Patent Number: 6,313,623; Date of Patent: November 6, 2001.

[10] Lj. A. Kojovic, “Measuring Current Through An Electrical Conductor”, Patent Number: 6,680,608 B2; Date of Patent: January 20, 2004.

VI. BIOGRAPHIES

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