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Investigation of the Influence of electrical parameters on dynamic property of Self-integrating Rogowski coil

***Abstract**. Rogowski coil as the special mutual inductor is often applied to measure high amplitude and transient currents in electrical industry. Since there are no iron core, they cannot be driven into saturation. In this paper, the transfer function of the self-integrating Rogowski is proposed based on the analysis of the Rogowski coil. According to the transfer function, bode diagram simulates the effect of changing some of these parameters. Also, the influences of self-inductance, sampling resistance and stray capacitance are disussed in details. Moreover, a high-frequency current transducer for measurement of PD is developed based on the self-integrating Rogowsk,and the actual dynamic response are performed by adopting function generator. Based on the transducer, measurements of PD of needle-plate model under impulse voltage is identical to the results of theory analysis. Finally, the method to obtain an optimum dynamic property in self-integrating Rogowski coil is suggested.*

***Streszczenie.** W artykule wyznaczono charakterystykę przetwarzania paska Rogowskiego bez układu całkującego. Wyznaczono charakterystyki częstotliwościowe czujnika prądu a następnie sprawdzono parametry na przykładzie badania wyładowań niezupełnych. (**Badania wpływu parametrów elektrycznych na właściwości dynamiczne paska Rogowskiego**)*

Keywords: self-integrating Rogowski coil; transfer function; electrical parameters; dynamic property.
Słowa kluczowe: pasek Rogowskiego, charakterystyki częstotliwościowe, właściwości dynamiczne.

Introduction

A Rogowski coil is a toroidal solenoid wound on a non-magnetic core form. Behaving as a specially designed mutual inductor; it is one of the most useful current measuring devices in power industry to measure high amplitude and transient currents[1]. The Rogowski coils have no iron core, so they can not be driven to saturation, and have good linearity. Also, the coils exhibit a strong resistance to interference thanks to the isolating and non-instrusive measurement.

Its use has been usually associated to an external circuit for intergrating the measured signals. However, previous papers[1] has shown that the Self-integrating Rogowski coil has wider frenquency band than external- integrating Rogowski coil, also the former has less response time than the latter. So the main aim in this paper is to introduce the structure theory of the Self-integrating Rogowski coil, and to discuss the dynamic property when electrical parameters are different. Besides, the method to obtain an optimum dynamic property coil is suggested.

Principle of the Self-integrating Rogowski coil

The coil is made of copper wire that is wound in a spiral around a ring-type air-core and then returns to the original points. It is placed around the conductor to couple the pulse signals.

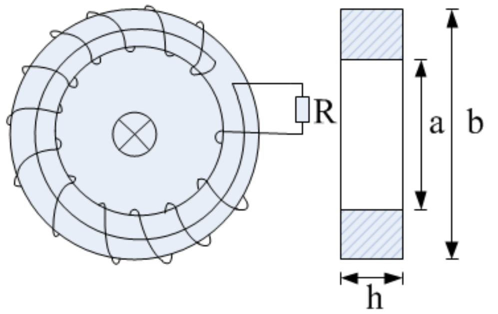


Fig.1. Schematic diagram of the self-integrating Rogowski coil (a, inner diameter of Rogowski coil; b, the outer diameter of Rogowski coil; h, the thickness of Rogowski coil; R, the sampling resistance)

Up to present, two different models have been developed: the lumped parameter model which represents the basic theory in the design of the Rogowski coil, and the distributed parameter model which is specially used in the design of a Rogowski coil with a perfect high frequency response [2]. The lumped parameters model is adopted in order to simplify this study. A schematic diagram of the Self-integrating Rogowski coil is shown in Fig.1 [3].

Fig.2 shows the equivalent circuit diagram of the coil based on the lumped parameter model.

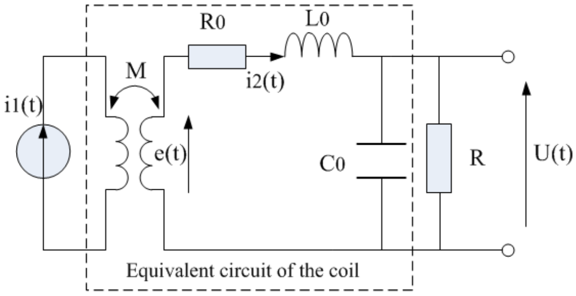


Fig.2. The equivalent circuit of the lumped parameter model

Parameters shown in Fig.2 are described as follows: M is the mutual self-inductance of the Rogowski coil; R_0 - is the equivalent resistance of coil; L_0 - is the self-inductance; C_0 - is the stray capacitance; $i_1(t)$ - is the original current; $i_2(t)$ - is the secondary current, $u(t)$ -'is the output voltage of the coil.

Based on Faraday's law, the voltage induced in the coil is defined by Equation 1.

$$e(t) = -M\frac{di_1(t)}{dt} \tag{1}$$

The mutual self-inductance in this case is[4]:

$$M = \frac{\mu_0}{2\pi} nh \ln\frac{b}{a} \tag{2}$$

where: n – the number of coil winding turn, μ_0 – the permittivity of air which equals $4\pi \times 10^{-7}$ (H/m).

The following equations can be deduced from Fig. 2:

(3)
$$\begin{cases} e(t) = L_0 \dfrac{di_2(t)}{dt} + R_0 i_2(t) + u(t) \\ i_2(t) = C_0 \dfrac{du(t)}{dt} + \dfrac{u(t)}{R_0} \end{cases}$$

The resistance R_0 depends on the wire dimensions and on the material and is given by[5]:

(4)
$$R_0 = \rho \frac{4l}{\pi d^2}$$

where: l –the wire length, d – diameter, ρ – the resistivity of the wire.

R_0 and R determine the damping of the circuit commonly. This is a critical constraint in the design to keep the output of the coil away from oscillation.

The self-inductance (L_0) and the stray capacitance (C_0) can be calculated respectively by[5]:

(5)
$$\begin{cases} L_0 = \dfrac{\mu_0}{2\pi} n^2 h \ln \dfrac{b}{a} \\ C_0 = \dfrac{2\pi^2 \varepsilon_0 (b+a)}{\log \dfrac{b+a}{b-a}} \end{cases}$$

where: ε_0 –the dielectric constant in vacuum.

The self- inductance plays an important role in the dynamic behavior of the probe together with the stray capacitance.

Combining equations (1) and (3), so the transfer function is given by equation (6):

(6)
$$H(s) = \frac{u(s)}{I_1(s)} = \frac{Ms}{L_0 C_0 s^2 + (\frac{L_0}{R} + R_0 C_0)s + \frac{R+R_0}{R}}$$

then

(7)
$$H(\omega)_{\max} = K = \frac{R}{N}$$

where : K –the sensitivity of the coil.

From the equation (6), f_L, f_H and BW are deduced as follows:

(8)
$$\begin{cases} f_L \approx \dfrac{R}{2\pi L_0} \\ f_H \approx \dfrac{1}{2\pi R C_0} \\ BW \approx \dfrac{1}{2\pi} (\dfrac{1}{RC_0} - \dfrac{R}{L_0}) \end{cases}$$

where: f_L and f_H – the lower and upper frequency limits respectively, BW – the bandwidth of the Rogowski coil.

It can be found through the theory analysis above that L_0 , C_0 and R can determine the dynamic property of the Rogowski coil.

Simulation and Analysis

The dynamic property of the Rogowski coil mainly includes its step response, the amplitude and phase frequency characteristics , which determines the coil's performance.

In this section, the influences of these parameters on dynamic property are discussed.

A The influence of C_0

The results obtained in the frequency and step response of the coil as C_0 vary are shown in Fig.3 and Fig.4.

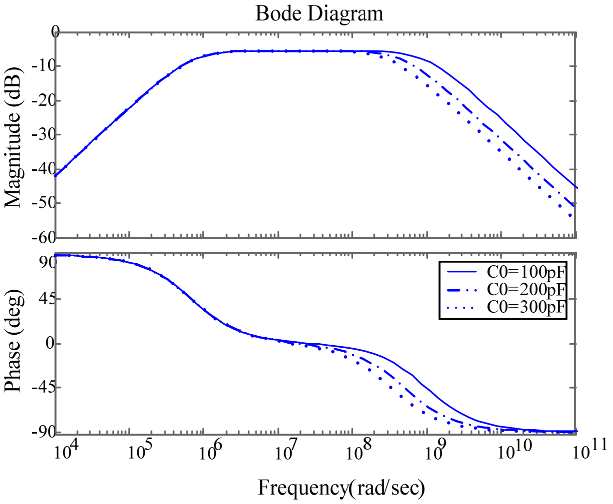


Fig.3. The frequency response of the coil as C_0 changing

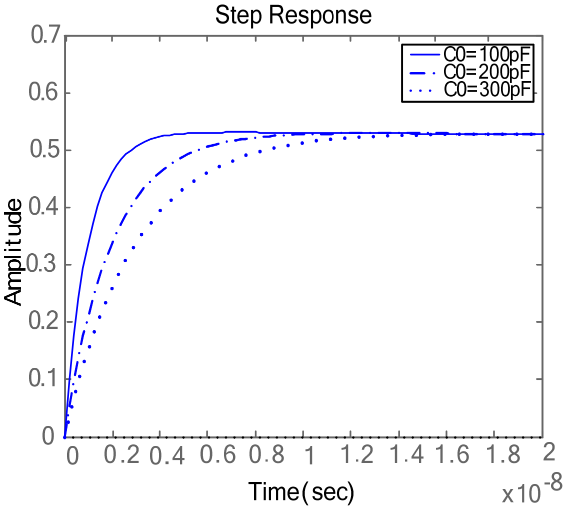


Fig.4. The step response of the coil as C_0 changing

From the Fig.3, it can be seen that the upper limiting frequency is decreasing with C_0 increasing, and no influence can be found on the low limiting frequency. This indicates a reduction of the BW of the coil. Special care should be put in the fabrication of the coil. The capacitance has to be kept as low as possible to prevent the drop of the upper limiting frequency that would destroy the main advantage of the coil.

Fig.4 describes the step response of the coil in function of the stray capacitance. The rise time of the step response becomes longer with C_0 increasing. In order to meet the requirements of measurement in rapid current pulses, the optimization of the coil geometry to achieve the purpose of reducing the stray capacitance is necessary.

B The influence of L_0

Fig.5 draws the evolution of the frequency response of the coil in function of the self-inductance. Although the low limiting frequency is decreasing and BW is extended when the self-inductance is increased by adding turns, a decrease of sensitivity in the frequency band of the interest is seen. On one hand, this is beneficial to read currents at lower frequencies. On the other hand, the self-inductance could be decreased to get a higher sensitivity of the coil.

Fig.6 shows that the rise time of the step response is increasing and the amplitude of the step response is decreasing with the self-inductance increasing. So the stability of the coil is falling.

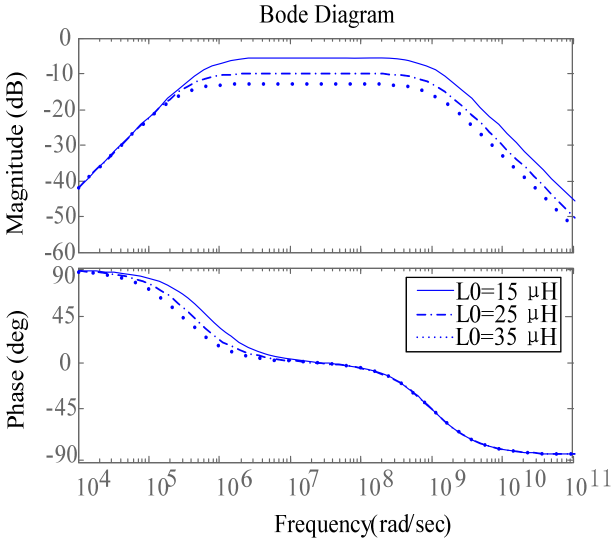


Fig.5. The frequency response of the coil as L_0 changing

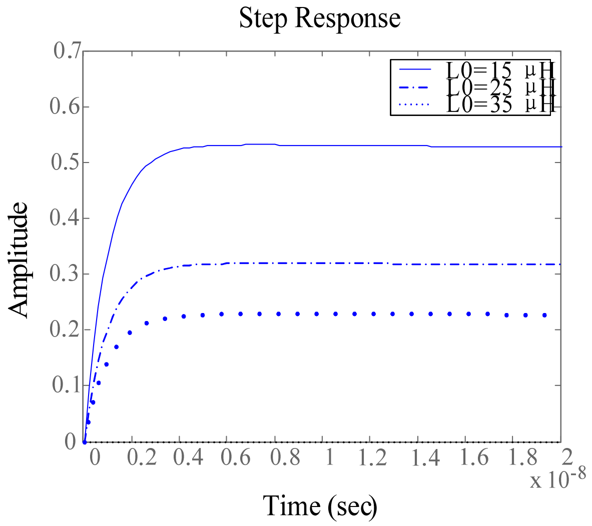


Fig.6. The step response of the coil as L_0 changing

C The influence of R

In Fig.7, it can be seen that the sensitivity of the coil is dependent on the parameter of R. With increasing R, a increase of the sensitivity can be observed. However, the low limiting frequency increases while the upper limiting frequency decreases. Thus, BW can be diminished with a high value of R. It is necessary to optimize the value of R to meet the requierments of appropriate sensitivity and BW.

From the Fig.8, With increasing R, it can be seen that the rise time of the step response is minishing while the amplitude is increasing. Accordingly, the stability of the coil can be enhanced.

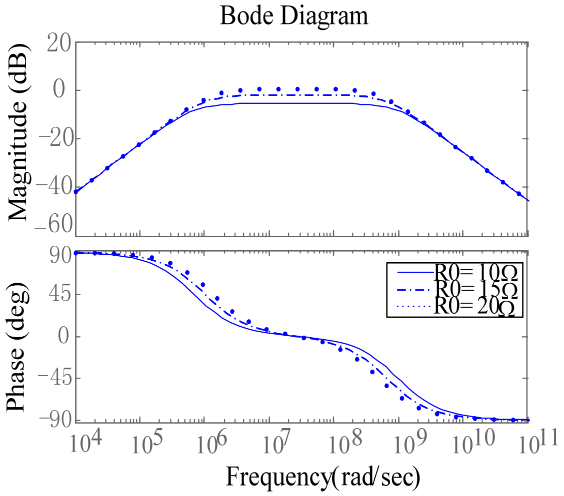


Fig.7. The frequency response of the coil as R changing

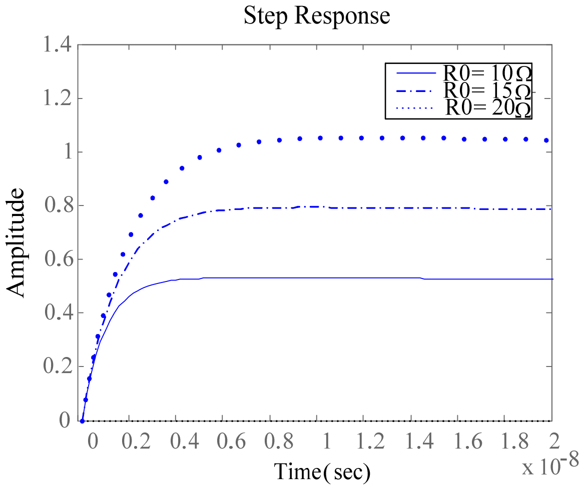


Fig.8. The step response of the coil as R changing

Design of the high frequency current transducer

A Selection of the magnetic core

Form the formula (8), we know that BW of the current transducer can reach the desired range by changing R, L_0 and C_0. However, the frequency range and configuration parameters of the magnetic core play an important role in determining BW of the current transducer. The studies of frequency response characteristics of different magnetic cores have been presented in literature[6], experiment results show that a type of ferrite of nickel-zinc material with high resistivity and low coercive force can be used to obtain the performance of broadband and lower loss. Therefore, nickel-zinc core is selected in the design of transducer, and the parameters of core as: $a = 26mm$, $b = 45mm$, $h = 15mm$, μ (magnetic permeability)=10. There is no need to consider the saturation problem of the magnetic core owing to the measured PD current at the level of milliampere.

B Selection of R and N

R and N are the main parameters that have a great effect on BW besides of magnetic core. According to Eqs.(4), (7) and (8), it can be found that the sensitivity is enhancing by increasing R. However, the low limiting frequency increases while the upper limiting frequency decreases. Thus, BW can be diminished with a high value of R. It can also be found that the BW becomes larger with the increase of N, but the sensitivity becomes lower. Therefore, it is necessary to optimize the values of R and N to meet the requirements of appropriate sensitivity and BW.

The instrument for experiments is an arbitrary waveform generator AWG2021, which can generate a sine wave from 10Hz to 125Hz with amplitude of 0 to 5V and a calibrating square wave and impulse wave from 10Hz to 2.5MHz with amplitude of 0 to 5V. All the data are measured with a 200MHz digital storage oscilloscope of DPO2022B. Based on the experimental results, the best parameters are as follows: $N = 20$, $R = 50\Omega$ for the wide bandwidth of 800 kHz~105MHz and high sensitivity of 2.4VA^{-1}. Fig. 9 and 10 show the photograph and the amplitude-frequency response characteristic of the current transducer, respectively.

Fig. 9. The designed current transducer

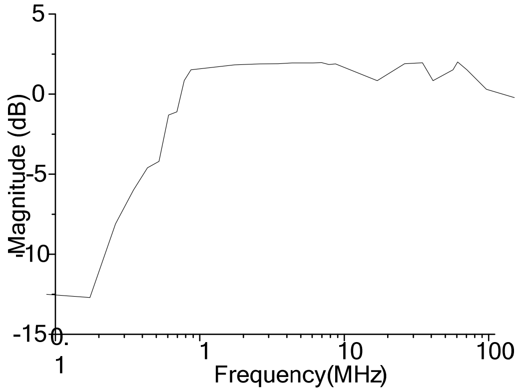


Fig.10. The amplitude-frequency response of the current transducer

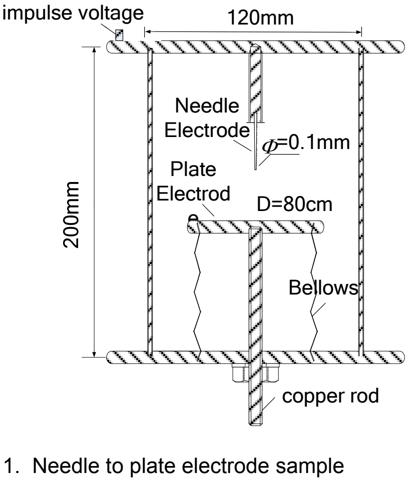


Fig.11. Needle to plate electrode sample

Measurement of PD signals under impulse voltage

The needle-plate electrode sample is shown in Fig.11. The gap length of the needle-plate electrode is 30mm. The experiment system is shown in Fig.12. Positive lighting impulse voltage ($1.2/50\mu s$) was applied to the needle electrode and generated PD. The elaborated high frequency current transducer is used to measure a PD pulse.Fig.13(a) shows the applied voltage (CH1) and PD current (CH2) waveforms for positive impulse voltage application of 25KV, respectively. From the Fig.13(a), it can be seen that the high amplitude capacitive Current was measured owing to the short rise time of the applied voltage. Moreover, the high frequency interference was caused by the overshoot of the source. The single PD current waveform is shown in Fig.13(b). The experimental results reveal that by using the designed high frequency current transducer an accurate waveform of the PD pulse can be obtained. Furthermore, it can be used to measure the small amplitude pulse signals without an amplifier, which can also avoid noise interference.

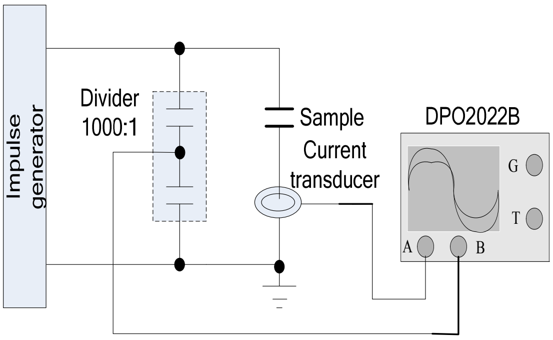
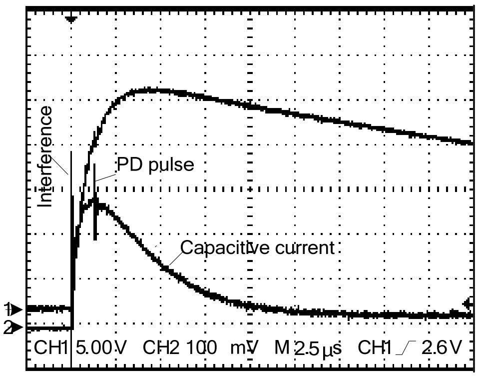
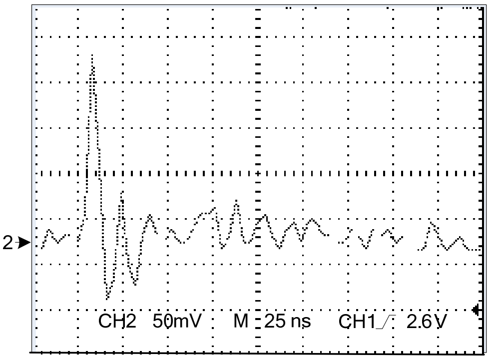


Fig.12. Measurement system



(a) PD signal measured by the current transducer under positive lighting impulse voltage



(b) Single PD current transform

Fig.13. Measurement of PD pulses

Conclusion

Based on the present analysis of the influence of electrical parameters on dynamic property of Self-integrating Rogowski coil, one may draw the following conclusions:

1. The capacitance of the coil have to be kept as low as plssible to improve the upper limiting frequency and to widen the BW to measure rapid current pluses.

2. A limited number of turns are required for reducing the self-self-inductance which jeopardizes sensitivity and stability of the system.

3. The value of R should be properly chose for the purposes of providing high sensitivity and preventing the system oscillation.

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