Frequency Response Characteristics of Rogowski Coil with Active Integrator for Lightning Measurement

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ABSTRACT

This paper presents frequency response characteristics of a Rogowski coil which is developed with an active integrator. Experiments are performed in a laboratory with a frequency function generator as a source. The frequency responses of the Rogowski coil and the integrator are recorded with both magnitude and phase in order to verify the capability in measuring lightning current waveshapes. For availability in lightning current measurement in the electrical system, the developed Rogowski coil is specifically designed as a clamp on device. The standard lightning current waveshape of the positive first stroke impulse (10/350 μs) is simulated to investigate the measuring system. It is found that the frequency bandwidth of the Rogowski coil with the integrator developed in this paper is proper in lightning current measurement.

Keywords: Active Integrator, Frequency Response Characteristic, Lightning Current Waveshape, Rogowski Coil

1. INTRODUCTION

A lightning current is a kind of transient current in a power system. The lightning current can lead to the interruption of the operation in the power system. There are many types of lightning which can cause variation in lightning current waveshapes. Winter lightning causes much damage in power generation such as wind turbine, failures of surge protection devices in control systems and power transmission systems [1–2]. The areas, where winter lightning occurs frequently, are the coastal areas of the Sea of Japan, when cold air from Siberia moves over the Sea of Japan where the stream of warm Tsushima Current flows to the north [3]. According to IEC 62305-1:2010, a lightning current consists of one or more different strokes [4]. Moreover, it determines the parameter of lightning current separately as impulses with duration less than 2 ms and long strokes with duration not longer than 2 ms. The front duration (T_1) of lightning current is in the range of 2 to 10 μs. For the time of half value (T_2) of lightning current, a positive lightning stroke has longer T_2 than T_2 of a negative lightning stroke. In the winter, positive lightning discharges are more frequent than in summer and the time to half value of positive lightning discharge is considerably longer [3]. Hence, it is necessary to design proper frequency responses of a lightning measuring system in a wide frequency band so that a lightning current waveshape can be detected accurately.

From the sources mentioned above, the lightning current waveform (10/350 μs) has characteristics of high and low frequency components [5]. Therefore, the characteristics of the measuring system for lightning current measurement should have a wide bandwidth for covering the frequency content of the lightning current waveform. Currently, many measuring systems [6-8] have been developed with a wide bandwidth for the standard lightning impulse current (8/20 μs). These systems are not sufficiently capable of the measurement of the lightning current (10/350 μs) that contains low frequency components. To overcome such a problem in measurement of the low frequency components, a measuring system with a wide bandwidth frequency is proposed in this paper.

For measurement of the positive first stroke lightning current, a Rogowski coil with an active integrator should accurately measure an impulse current with fast rise time in a range of a few microseconds and with long duration time in a range of a few milliseconds. In this paper, experimental tests are performed to confirm design efficiency and to verify the lightning measuring system by frequency responses and impedance characteristics of the measuring system consisting of a Rogowski coil and an active integrator. The performance of the developed lightning measuring system is determined by simulation with injected lightning waveforms to the measuring system

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using a computer program.

2. DESIGN AND CONSTRUCTION OF A MEASURING SYSTEM

In this research, the measuring system of lightning measurement has been organized in three major components: a sensing part, an integrator and a recording device as shown in Fig. 1.

2.1 Rogowski coil

A cross section of Rogowski coils is in a square/rectangular form as shown in Fig. 2. The winding of a Rogowki coil is in a counter-wound compensation form [9], which is that the compensation coil is retuned in the opposite direction to the main coil. The winding of the Rogowski coil is shown in Fig. 3. With such configuration, the measured current will be induced on the main and compensation coils with different directions, so that the total induced voltage of the coils will be nullified. Therefore, the undesired magnetic field will not affect the measured current waveform.

The air cored coil is placed around the conductor where a high fast current signal produced by lightning current generator is to be measured. The developed Rogowski coil is shown in Fig. 4.

The values of electrical parameters depend on the physical design of the coil. Table 1 represents the measured electrical parameters of the Rogowski coil.

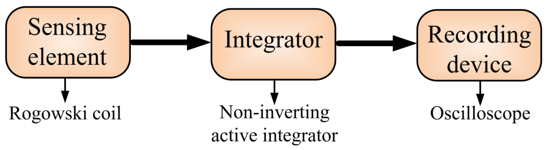


Fig.1: *The important components of a lightning current sensor.*

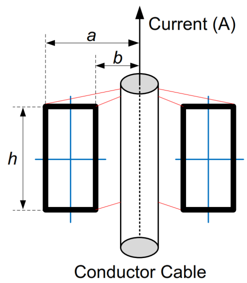
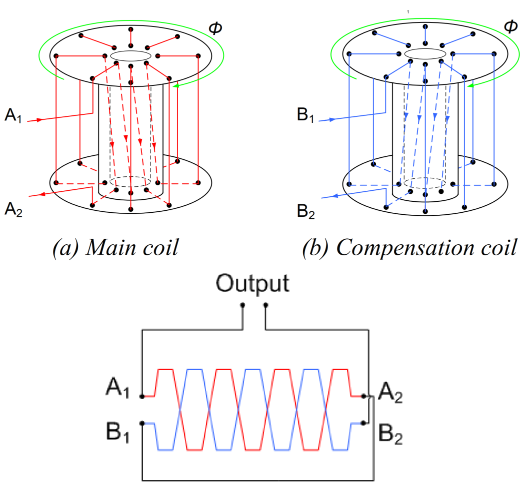


Fig.2: *Model of a lightning current sensor.*



(a) Main coil *(b) Compensation coil*

(c) Diagram of counter wound compensation

Fig.3: *Diagram of a Rogowski coil winding.*

Fig.4: *The lightning current sensor.*

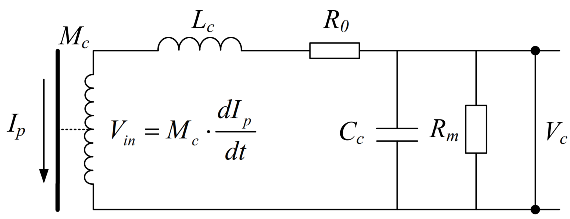


Fig.5: *Lumped parameters model of the Rogowski coil.*

Table 1: *Geometrical and electrical parameter of Rogowski coil.*

Parameter	Symbol	Specification
Number of turns	N	16
Center to outer of coil	a	5.5 cm
Center to Inner of coil	b	1.5 cm
Thickness	h	7.5 cm
Resistance of coil	R_0	0.3 Ω
Inductance of coil	L_c	7.07 μH
Capacitance of Rogowski coil	C_{Row}	136.5 pF
Capacitance of cable	C_{cab}	5.8 nF
Capacitance of oscilloscope	C_{osc}	20 pF
Capacitance of system	$C_c = C_{Row} + C_{cab}$	5.94 nF
Matching resistance	R_m	75 Ω

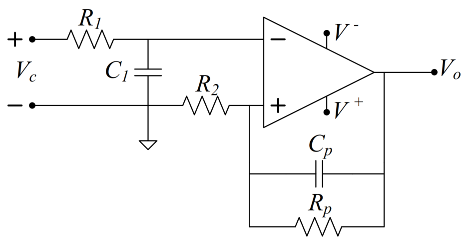


Fig. 6: *The equivalent circuit of active integrator.*

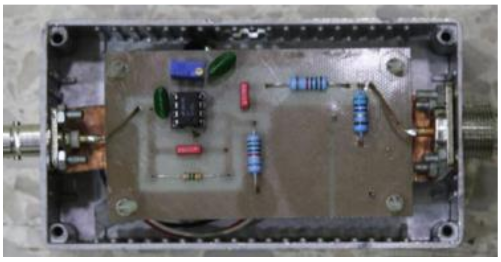


Fig. 7: *The constructed active integrator.*

The lumped parameters (RLC) equivalent electrical model [10] is as Fig. 5.

The transfer impedance has been derived from the lumped parameters model to analyze a bandwidth. The transfer impedance of the Rogowski coil [11] lumped parameters model can be calculated as:

$$G_R = \frac{V_c}{I_p} = \frac{\dfrac{M_c}{L_c C_c}}{s^2 + \left(\dfrac{R_0}{L_c} + \dfrac{1}{R_m C_c}\right) s + \dfrac{R_0 + R_m}{L_c C_c R_m}} \tag{1}$$

The Rogowski coil operates on the fundamental principle of Faraday's Law. The air-cored coil is installed around the conductor for which lightning current is measured. This variable current generates a magnetic field and a rate of change in the current induces a voltage in the coil given as in Eq. (2)

$$V_{in}(t) = M_c \frac{dI_p(t)}{dt} \tag{2}$$

where $V_{in}(t)$ is the voltage induced in the coil by the current $I_p(t)$ flowing in the conductor due to the mutual inductance M_c between the primary current and the coil, which is practically independent of the conductor location inside the coil loop.

2.2 Integrator

From the Eq. (2), the induce voltage at the terminals of the winding wound 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 $V_o(t)$ according to the following equation to convert it into the current following through the conductor [12]:

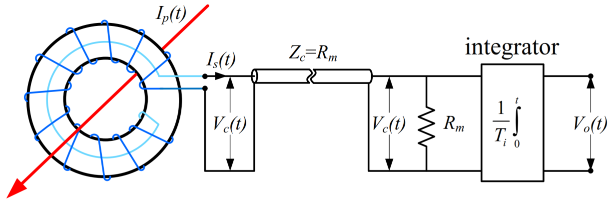


Fig. 8: *Configuration of Rogowski coil with integrator.*

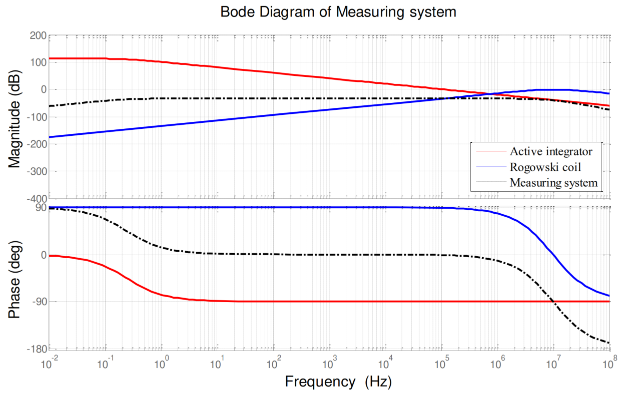


Fig. 9: *The simulation magnitude and phase plot of Rogowski coil with active integrator.*

$$I_p(t) = -\frac{1}{M_c} \int V_o(t) dt \tag{3}$$

To obtain a voltage signal corresponding to the current waveform, integration of inducing voltage is required. Several options for integrating are such as:

- Electronic passive or active (using op-amp) integration networks,
- Digital integration with DSP or data acquisition,
- Self-integration by specially designed coil, as explained in the following section.

In this paper, an electronic integrator (active integrator) is applied to the measuring system. The equivalent circuit and developed integrator are illustrated in Figs. 6 and 7. The circuit parameters of R_1, R_2, R_p, C_1 and C_p were set to be 15 $k\Omega$, 15 $k\Omega$, 15 $M\Omega$, 110nF and 110nF, respectively. The transfer function of the integrator is shown in the Eq. (4).

$$G_i = \frac{V_o}{V_c} = \frac{1}{1 + R_1 C_1 s} \times \frac{s + \dfrac{R_2 + R_p}{R_2 R_p C_p}}{s + \dfrac{1}{R_p C_p}} \tag{4}$$

From the transfer impedance of Rogowski coil in Eq. (1) and the transfer function of the integrator in Eq. (4), the transfer impedance of the whole measuring system is shown in Fig. 8, and can be calculated by Eq. (5)

$$G_M = G_R G_i = \frac{V_o}{I_p}$$
$$= \frac{\dfrac{M_c}{L_c C_c}}{s^2 + \left(\dfrac{R_0}{L_c} + \dfrac{1}{R_m C_c}\right) s + \dfrac{R_0 + R_m}{L_c C_c R_m}}$$
$$\times \frac{1}{1 + R_1 C_1 s} \times \frac{s + \dfrac{R_2 + R_p}{R_2 R_p C_p}}{s + \dfrac{1}{R_p C_p}} \qquad (5)$$

The transfer impedance of the Rogowski coil, the transfer function of the integrator, and the transfer impedance of the measuring system (the Rogowski coil with the integrator) are plotted in Fig. 9. It is noticed that the lower cutoff frequency (f_L) of the measuring system is about 1 Hz and the high cutoff frequency (f_H) is about 2 MHz.

3. EXPERIMENTS AND RESULTS

A Rogowski coil is a type of current sensor which is used as a component in a measuring system such as a lightning current waveform recorder. Lighting current is a transient current which consists of high frequency components. The Rogowski coil, then, must have proper frequency response characteristics so that the coil can give accurate results in lighting current measurement. In practice, a Rogowski coil may be employed with an additional integrator which can be either active of passive depending on the purpose. In this paper, three experiments were performed to verify the Rogowski coil and an active integrator. In the first experiment, frequency response characteristics of the Rogowski coil were investigated by injection of a current with frequency from 80 Hz to 2 MHz and measurement of the output voltage of the coil. In the second one, the frequency response characteristics of the active integrator were investigated in a similar manner to the first experiment. In the third one, the frequency response characteristics of the measuring system (the Rogowski coil with the integrator) are investigated in the same frequency range of the first and second experiments. In addition, the overall performance of the measuring system in lightning measurements is observed by injecting lightning currents on the basis of computer simulations.

3.1 Frequency response characteristics of a Rogowski coil

In this part, the characteristics of the developed coil were investigated. The output voltages from the Rogowski coil were measured by injection of input sinusoidal currents with the frequency varied from 80 Hz to 2 MHz. The experimental set up is shown in Fig. 10, where, 1: Function generator (NF-30MHz MULTIFUNCTION GENERATOR WF1947), 2: Power amplifier (NF-HIGH SPEED BIPOLAR AMPLIFIER DC-10MHz/50VA HSA 4101), 3: Shunt resistor (50 Ω), 4: Oscilloscope (Tektronix-TPS2012B 100 MHz, 1 GS/s), 5: Devel-

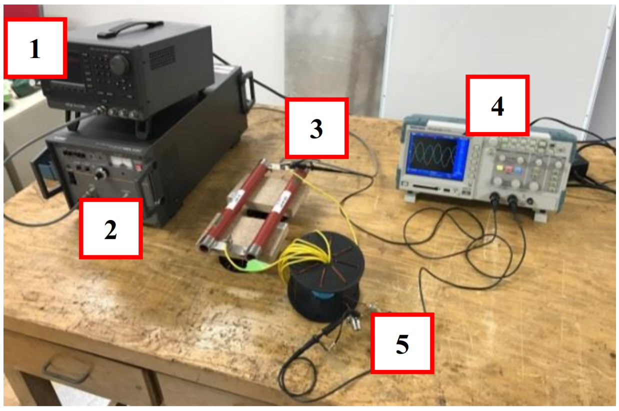
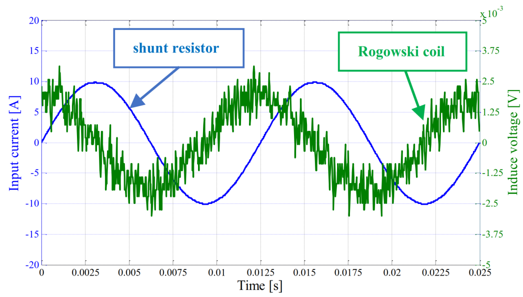
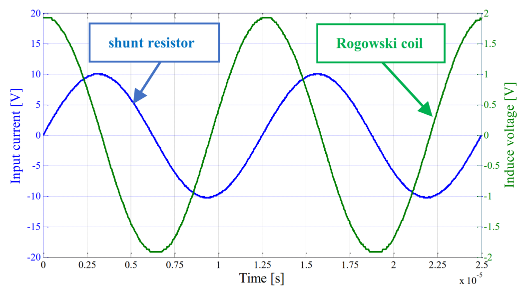


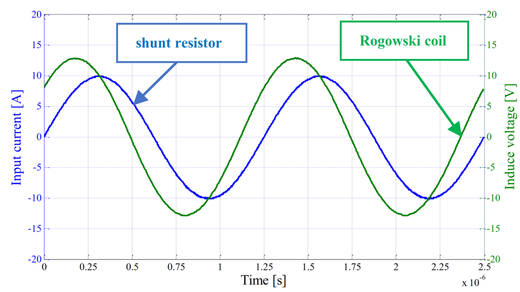
Fig.10: *The experimental set up of frequency response test of the Rogowski coil.*



(a) The sinusoidal current waveform at 80 Hz



(b) The sinusoidal current waveform at 80 kHz



(c) The sinusoidal current waveform at 800 kHz

Fig.11: *The sinusoidal waveform results of the Rogowski coil compared with shunt resistor.*

Table 2: *The experimental results of the developed Rogowski coil.*

Frequency of sinusoidal [Hz]	Gain [dB]	Phase shift of Rogowski coil
8.00×10^1	–84.021	90.144
1.00×10^2	–80.787	90.144
3.00×10^2	–74.425	90.720
5.00×10^2	–70.641	90.720
8.00×10^2	–67.555	90.432
1.00×10^3	–65.567	90.000
3.00×10^3	–56.851	91.584
5.00×10^3	–52.338	90.720
1.00×10^4	–46.393	90.360
3.00×10^4	–36.681	88.992
5.00×10^4	–32.418	86.400
8.00×10^4	–28.335	84.096
1.00×10^5	–26.396	81.720
3.00×10^5	–17.443	65.664
5.00×10^5	–14.042	52.920
8.00×10^5	–11.687	38.592
1.00×10^6	–10.883	30.600
2.00×10^6	–9.320	9.360

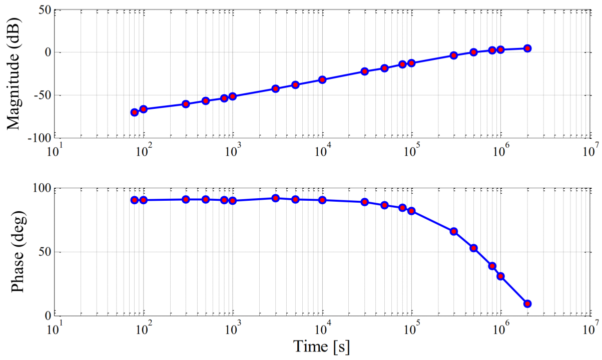


Fig.12: *The frequency response characteristics result of the Rogowski coil.*

oped Rogowski coil.

Experimental results of the input current and the output voltage of the Rogowski coil are presented in Fig. 11 and Table 2.

From Table 2, the frequency response characteristics of Rogowski coil are plotted in Fig. 12. It is confirmed that the Rogowski coil can be used in the frequency range higher than 1 MHz.

3.2 Frequency response characteristics of an active integrator

The integrator was tested with sinusoidal voltage waveforms with frequencies from 80 Hz to 2 MHz to investigate the characteristics of the developed active integrator. The experimental set up is shown in Fig. 13, where, 1: Function generator (NF-30MHz MULTIFUNCTION GENERATOR WF1947), 2: Power amplifier (NF-HIGH SPEED BIPOLAR AMPLIFIER DC-10MHz/50VA HSA4101), 3: Oscilloscope (Tektronix-TPS2012B 100 MHz, 1 GS/s), 4: Active integrator.

Experimental results, input and output voltages of the developed integrator are shown in Fig. 14 and Table 3.

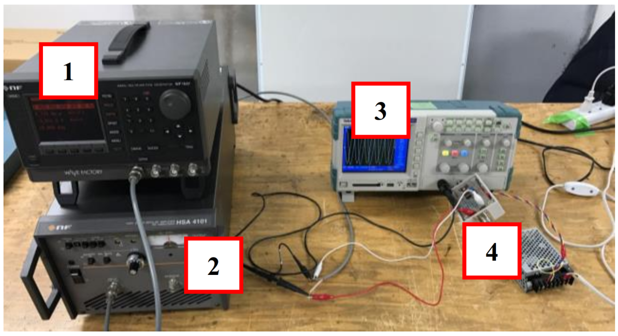
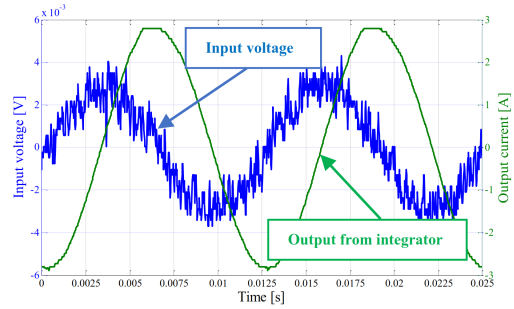
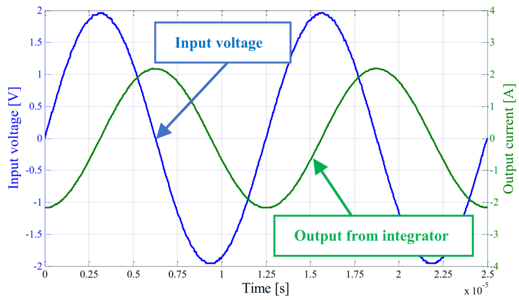


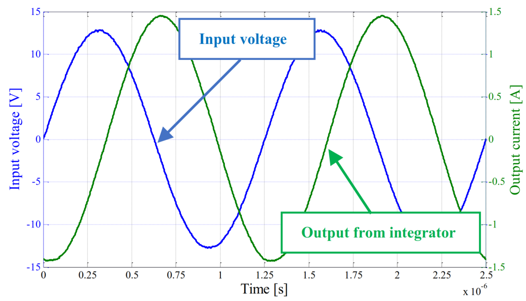
Fig.13: *The experimental set up of frequency response test of active integrator.*



(a) The sinusoidal current waveform at 80 Hz



(b) The sinusoidal current waveform at 80 kHz



(c) The sinusoidal current waveform at 800 kHz

Fig.14: *The sinusoidal waveform results of the active integrator compared with input voltage.*

Table 3: *The experimental results of the developed integrator.*

Frequency of sinusoidal [Hz]	Gain [dB]	Phase shift of integrator
8.00×10^1	55.229	–89.856
1.00×10^2	55.761	–90.720
3.00×10^2	47.549	–89.424
5.00×10^2	43.580	–90.720
8.00×10^2	39.911	–89.856
1.00×10^3	39.645	–90.720
3.00×10^3	28.983	–88.992
5.00×10^3	25.889	–90.180
1.00×10^4	20.066	–88.920
3.00×10^4	9.388	–90.504
5.00×10^4	6.047	–88.380
8.00×10^4	0.931	–90.432
1.00×10^5	0.087	–89.280
3.00×10^5	–10.501	–91.152
5.00×10^5	–13.662	–89.280
8.00×10^5	–18.904	–89.280
1.00×10^6	–19.665	–89.640
2.00×10^6	–26.761	–93.600

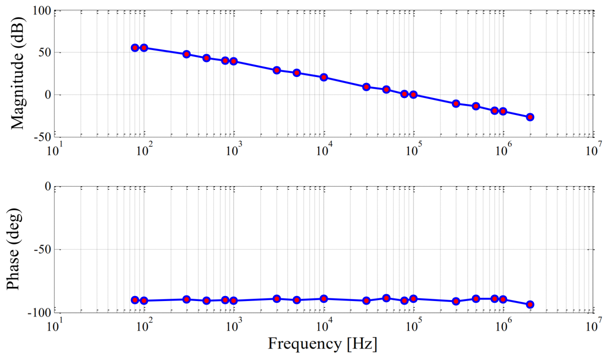


Fig.15: *The frequency response characteristics result of the active integrator.*

From Table 3, the frequency response characteristics of the developed integrator (the transfer function) is plotted in Fig. 15.

3.3 Frequency response characteristics of Rogowski coil with active integrator

The combination of a Rogowski coil and an active integrator are named as a whole measuring system. The whole measuring system was tested with the input sinusoidal currents with frequencies from 1 Hz to 2 MHz to investigate the characteristics of the developed measuring system in comparison with a reference measuring system (a non-inductive shunt resistor). The experimental set up is shown in Fig. 16. where, 1: Function generator (NF-30MHz MULTIFUNCTION GENERATOR WF1947), 2: Power amplifier (NF-HIGH SPEED BIPOLAR AMPLIFIER DC-10MHz/50VA HSA4101), 3: Shunt resistor (50 Ω), 4: Oscilloscope (Tektronix-TPS2012B 100 MHz, 1 GS/s), 5: Measuring system.

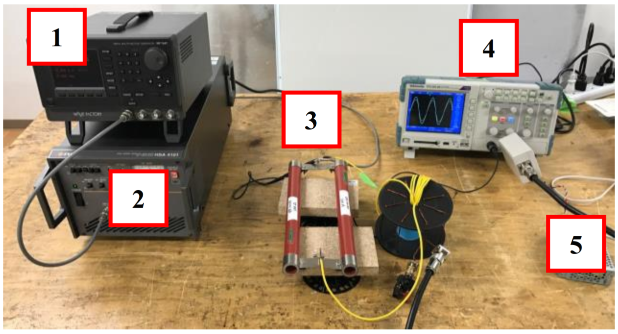
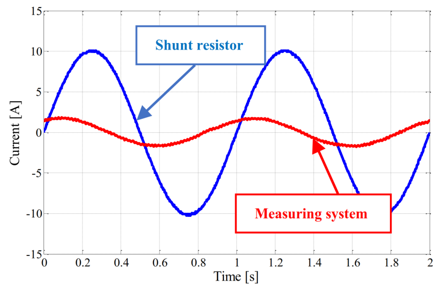
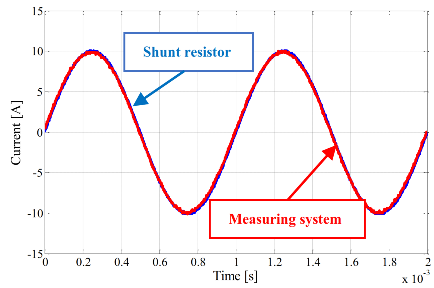


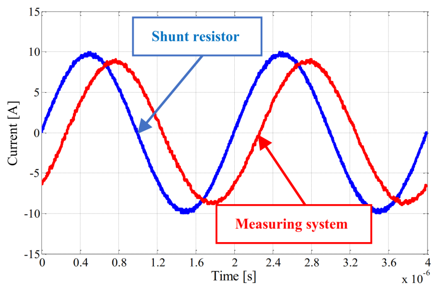
Fig.16: *The experimental set up of frequency response test of measuring system.*



(a) The sinusoidal current waveform at 1 Hz



(b) The sinusoidal current waveform at 1 kHz



(c) The sinusoidal current waveform at 500 kHz

Fig.17: *The sinusoidal waveform results of the Rogowski coil with active integrator compared with shunt resistor.*

Experimental results of Rogowski coil with active integrator are compared with shunt resistor. Some experimental results are shown in the Fig. 17 and Table 4.

From Table 4, the frequency response characteristics of the measuring system (Rogowski coil with

Table 4: *The experimental results of the measuring system (Rogowski coil with active integrator).*

Frequency of sinusoidal [Hz]	Gain [dB]	Phase shift of Rogowski coil
1.00	–14.77	59.76
3.00	–7.49	58.75
5.00	–4.70	49.32
8.00	–2.32	37.44
1.00×10^1	–1.86	33.84
5.00×10^1	–0.20	7.92
8.00×10^1	0.06	5.18
1.00×10^2	0.01	4.32
3.00×10^2	–0.02	3.02
5.00×10^2	0.08	1.44
8.00×10^2	0.00	1.44
1.00×10^3	–0.06	2.52
3.00×10^3	–0.11	0.86
5.00×10^3	–0.08	1.80
8.00×10^3	–0.02	0.58
1.00×10^4	–0.02	0.54
5.00×10^4	0.32	–1.44
1.00×10^5	0.25	–8.82
3.00×10^5	–0.35	–29.81
5.00×10^5	–0.80	–47.97
8.00×10^5	–2.65	–69.70
1.00×10^6	–3.69	–81.72
1.50×10^6	–6.47201	–106.11
2.00×10^6	–8.5355	–121.68

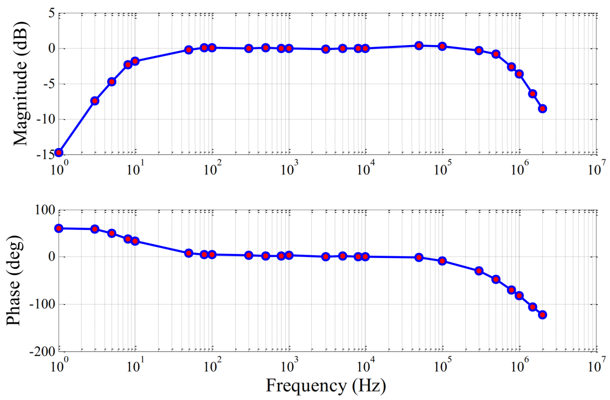


Fig.18: *The frequency response characteristics result of the measuring system (Rogowski coil with active integrator).*

active integrator) is plotted in Fig. 18. It is noticed that the lower cut-off frequency (f_L) of measuring system is about 7 Hz and the high cut-off frequency (f_H) is about 1 MHz.

3.4 Lightning current waveform simulation of the measuring system

It has been shown that the developed measuring system which consists of the Rogowski coil and the integrator can achieve the designated frequency band-

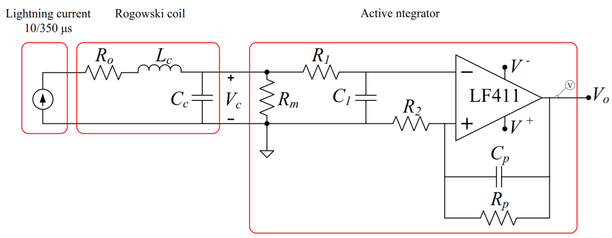


Fig.19: *The simulation scheme on PSpice.*

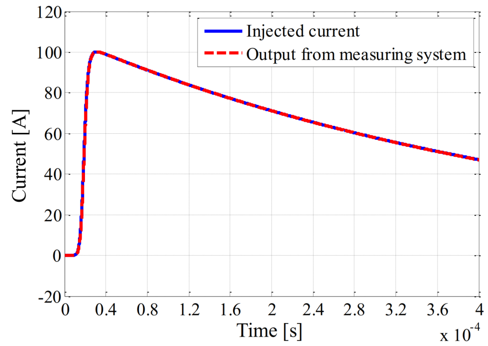


Fig.20: *The simulation results of the measuring system (Rogowski coil with active integrator).*

width that is proper to be employed in lightning current measurement. To confirm validity of the measuring system, simulations on PSpice were performed. The simulation scheme on PSpice is shown in Fig. 19. There are three parts in the scheme. The first part is a current source representing the 10/350 μs impulse current. The second part is the RLC equivalent circuit for a Rogowski coil, and the third part is an active integrator. The response of the measuring system which is obtained from computer simulations shows that the current waveform as an output of the measuring system is in a correct waveshape with a good agreement to the injection of the 10/350 μs current waveshape. This is as depicted in Fig. 20.

4. CONCLUSION

This paper has presented the development of the Rogowski coil and the integrator for use as a positive first stroke current (10/350 μs) measuring system. The purpose of the measuring system is to be employed in recording positive first stroke lightning current waveshapes. It has been shown that the measuring system should have a wide frequency bandwidth in order to reproduce correctly the lightning current waveshape as an output of the system. Frequency response characteristics of the developed Rogowski coil and the integrator have been studied, and it has been found that the bandwidth of the measuring system in this paper is proper in lightning current measurement. Computer simulations using a 10/350 μs waveform have been performed to verify the correctness of the output of the measuring system. It has been shown that the measuring system, developed in this paper, can provide an accurate output lightning current waveshape.

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