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Design of Rogowski Coil with external integrator for measurement of lightning current up to 400kA

***Abstract**. Lightning is one of the most serious disasters in the electrical power grid, especially in the ultra-high and extra-high voltage power systems. The measurement of the lightning current parameters is of great importance for the investigation of lightning protection. The literature shows given its significant advantages over equivalent current transducers, the Rogowski coil is an increasingly popular method for current measurement of high amplitude and high frequency. However, there is little report focus on the lightning measurement on the transmission lines. In this paper, the lumped parameter model of the Rogowski coil with an external integrator is established to deduce the transfer functions as well as the bandwidth of the coil. Relationships between the sensitivity and coil parameters, such as coil dimension, integral parameters and number of turns of the coil, are investigated. Results show that the sensitivity of the coil increases with the increase of the sectional area and number of turns, or with the decrease of effective magnetic path, resistance and capacitance of the integrator. Based on the analysis of the experimental results, a Rogowski coil of the bandwidth from 2 kHz to 2 MHz and average sensitivity of 0.1144V/kA is developed for the measurement of lightning current up to 400kA. Furthermore, it is found that the measuring uncertainty is always caused by the off-center position of the current flowing through the coil. Combined with the affiliate circuit, the lightning current transducer is used to measure and locate the lightning current on the transmission line based on the designed Rogowski coil with external integrator.*

***Streszczenie.** Pomiary prądów wyładowań atmosferycznych odgrywają dużą rolę w zabezpieczeniach. Obecnie pasek Rogowskiego staje sioę coraz popularniejszym narzędziem pomiaru prądów o dużej amplitudzie i dużej częstotliwości. W artykule przedstawiono cewki Rogowskiego w zastosowaniu do pomiarów w liniach przesyłowych. Zaprojektowano czujnik o pasmie częstotliwości 2 kHz – 2 MHz i czułości 114 mV/kA. (**Projekt cewki Rogowskiego z zewnętrznym układem całkującym do pomiaru prądów wyładowań do 400 kA**)*

Keywords: Rogowski Coil, lightning current, sensitivity, external integrator
Słowa kluczowe: pasek Rogowskiego, prądy wyładowań, układ całkujący.

Introduction

Lightning is a discharge process caused by the accumulation of electric charges in thunderclouds. Being a natural disaster, lightning can damage electrical equipments, cause electrical power outage, and bring about personnel casualties [1]. More than 70% power system outage is caused by the lightning overvoltage which is generated by the lightning current striking on the structures of power grid, such as transmission lines, towers and substations, especially in extra-high and ultra-high voltage power systems [2-4]. In general, the peak value of lightning current is tens to hundreds kilo Ampere, and the wave-front frequency is about hundreds kilo Hertz. The determination of the lightning protection level is based on the precise measurement of the lightning current. Therefore, the lightning current measurement is significant to the lightning protection of power system [5].

Since the 1970s, various methods have been used to measure peak current and location of the lightning, including magnetic links, magnetic garnet, lightning protection systems (LPS) and lightning location systems (LLS). Via the above methods, however, the waveforms can not be fully recorded though the peak values and rate-of-rise of the lightning current are recorded and investigated [6-9]. The current shunt could record the full waveform of the current [10-11], but it is inconvenient in the measurement of lightning current due to the indeterminacy of the peak value of lightning current, which will causes damage to the measurement equipments.

Rogowski coil is a special mutual inductor that is often used to measure AC and transient currents, especially high frequency current like gas discharge current, plasma current and high lightning current [12-14]. For the measurement of lightning current up to hundreds kiloamperes, the main difficulty in achieving a wide bandwidth is the conflicting constraints on the coil when operating at the high frequency of several megahertz. Improvements have been made to both Rogowski coil and the integrator over the past ten years, for example, the core based on the PCB board [15-17], magnetic core [18-19] and multiple-level compensated integral circuit [14, 20]. An added active integral circuit with an op-amp and (or) filter(s) is usually employed to make output waveform more accurately in the ultra-high frequency current measurement [21-23]. However, for the measurement of lightning current up to several hundred kilo Ampere, the transducer output always shows a transient reverse pre-shot with oscillation as well as the waveform distortion due to the abrupt change of dI/dt and high amplitude current.

In this paper, the Rogowski coil with an external integrator is designed to measure the lightning current. The transfer function and the bandwidth of the Rogowski coil with external integrator are deduced through the lumped parameter model. The effect of the conflicting constraints on response characteristics, such as the dimensions of the core, integral circuit parameters of the and the number of turns of the coil, are investigated to analyze and explain external integral behavior. Based on the results of the experiment and simulation, a Rogowski coil with external integrator is developed for the measurement of high lightning current up to 400kA and output voltage below 50V, giving a high frequency up to 2MHZ. At last, the Rogowski coil with external integrator and affiliated circuit are installed on the transmission line for lightning current parameters measured.

Structure and principle of Rogowski coil

The principle of the current measured by Rogowski transducers has been known since 1912 [24]. The traditional structure of Rogowski coil is shown in Fig. 1, in which the coil is wound uniformly as a continuous helix on a magnetic or non-magnetic core whose cross sectional area forms a closed loop. The coil has a single-layer winding or multiple-layer windings. As for the single-layer winding coil, a central return-loop should be placed inside the helical winding in the opposite direction to compensate for the undesired electromagnetic effect.

In order to prevent unwanted electromagnetic interference, an electrostatic shield which is made of copper or aluminum is often wrapped around the coil, as shown in Fig. 2. A slot along the inner circumference should be made to ensure the shielding box is not completely closed, so that the eddy current induced by the magnetic flux can be prevented.

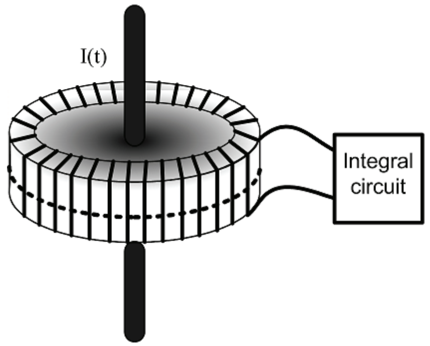


Fig. 1 Schematic diagram of the current transducer

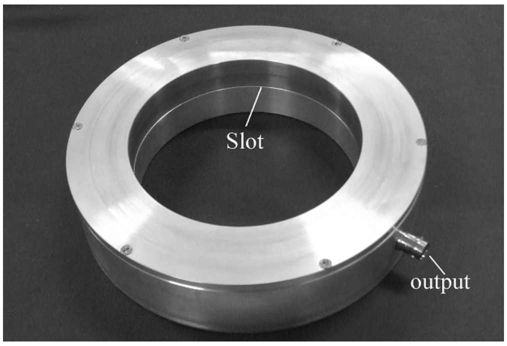


Fig. 2 Picture of shielding box and the slot

The equivalent circuit diagram of the lumped parameter model based on the external integral Rogowski coil is shown in Fig. 3. Where, M and L_s are the mutual inductance and self inductance of the coil, respectively, C_p is turn-to-turn capacitance, C_s is stray capacitance; R_s is equivalent resistance of the coil, R_0 and C_0 are the integral parameters of the coil, integral resistance and capacitance, respectively, and R_t is the matched resistance of the coil. $U_i(t)$, and $U_o(t)$ are the induced voltage and output voltage of the coil, respectively.

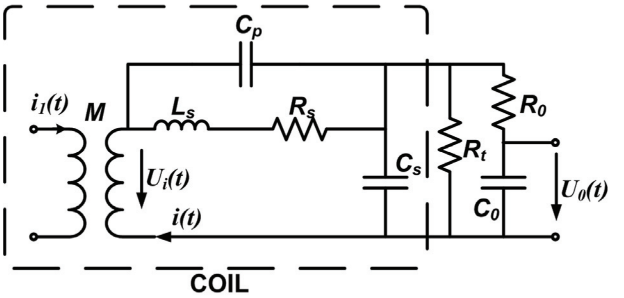


Fig. 3 Equivalent circuit diagram of the lumped parameter model

In Fig. 3, C_p could be ignored compared with C_s, so the following formulas can be deduced. The bandwidth of the

The transfer function and the bandwidth of the integral coil are deduced from Fig. 3 by the Laplace and Fourier transformation which are mentioned in our previous study [18-19], as shown in Eq.1 to 2.

$$H(s) \approx \frac{M}{R_0 C_0} \tag{1}$$

$$BW = f_h - f_l = \frac{1}{2\pi}\left(\frac{1}{\sqrt{L_s C_s}} - \frac{1}{R_0 C_0}\right) \tag{2}$$

where: $H(s)$ - transfer function, BW – bandwidth, f_h – upper frequency, f_l – lower frequency.

Influence of coil parameters

As indicated by the formulas last section, it can be seen that, to achieve accurate measurement of lightning currents, the frequency bandwidth of the coil should be wide enough. Which means, f_l should be as low as possible while f_h as high as possible. Therefore, R_0C_0 should be as high as possible while the L_sC_s as low as possible. Since L_s and C_s are parameters determined by the dimension and number of turns of the coil itself, the correlative influence parameters should be investigated carefully to improve the design of Rogowski coil. In this section, the influences of the coil parameters on the response characteristics are investigated to give an analytical method of external integral parameters (R_0 and C_0), number of turns (N) and magnetic path (l).

The maximum peak value of the positive and negative lightning current to be measured by the designed coil is about 400kA while the output voltage of the coil should be below 50V, so the sensitivity should be below 0.125V/kA. In order to gain a correct measurement result, the coil should have better response characteristics at the bandwidth from 5kHz-1MHz, which corresponds to the range of the lightning current. A standard lightning current (8/20μs) is generated to investigate the response characteristics of the coil in the laboratory.

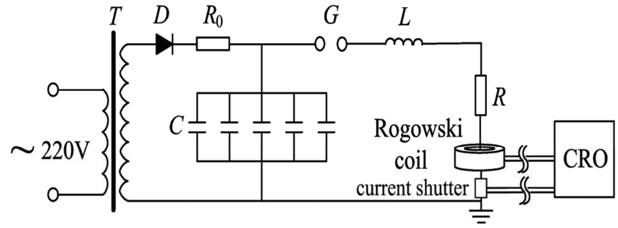
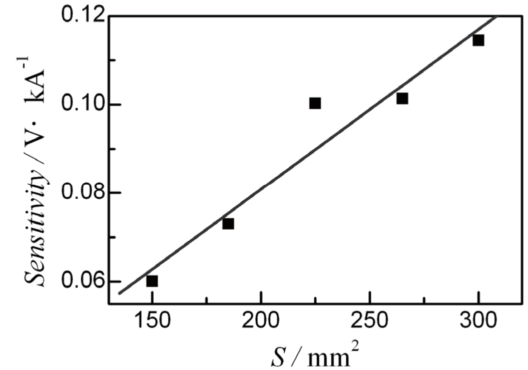
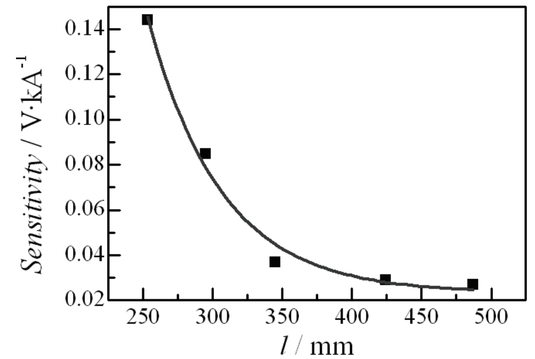


Fig. 4 The calibration circuit: T: regulator, D: silicon stack, R_0: protection resistance, C: charging capacitor, G: gas switch, L: stray inductance, R: wave-front resistance



(a) Sectional area (N=600, R_0=490kΩ, l=457.95mm and C_0=10nF)



(b) Effective magnetic path (N=300, R_0=200kΩ, S=100mm^2 and C_0=10nF)

Fig. 5 Relationships between sensitivity and dimension of coil

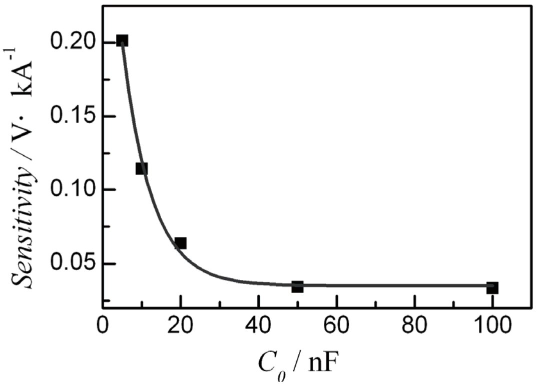
The experimental circuit is shown in Fig. 4. The lightning current is also measured by the standard current shunt with a resistance of 0.1824mΩ to be as the calibration signal. The output signals measured by the Rogowski coil and the current shunt are both recorded and stored by a digital storage oscilloscope of TEK 4054.

It is known that the sectional area and effective magnetic path of the coil are main influence factors on the coil response characteristics. When the number of turns and the integral parameters are fixed, the sensitivities of the coil with different sectional areas and effective magnetic paths are shown in Fig. 5, respectively.

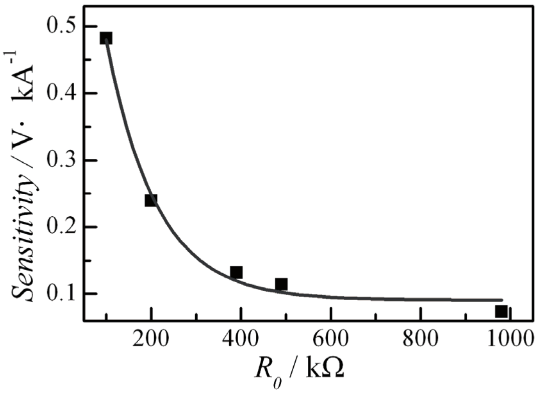
From Fig. 5, it can be seen that the sensitivity of the coil rises linearly with the increase in the sectional area, but approximately decrease exponentially with the increase in the effective magnetic path. This is because, when the sectional area of the core increases or the diameter of the core decreases, the mutual induction (M) caused by the magnetic flux through the helix of the coil increases.

From Fig. 5(b), it can be seen that there is a threshold value of l. When l exceeds 425mm, it has no significant effect on the sensitivity of the coil.

The external integral circuit of the Rogowski coil consists of three components: integral resistance (R_0), integral capacitance (C_0) and equivalent resistance (R_t), as shown in Fig. 3. Since R_t is determined by L_s and C_s [13, 15, 18], the response characteristics will be influenced by R_0 and C_0. Relationships between the sensitivities of the coil and the R_0 and C_0 are shown in Fig. 6, in which the number of turns and the core dimension of the coil are fixed as N=600, S=300mm^2 and l=458mm.



(a) Integral capacitance (R_0=490kΩ)



(b) Integral Resistance (C_0=10nF)

Fig. 6 Relationships between sensitivity and integral parameter

From Fig. 6, it can be seen that the sensitivity of the coil goes down approximately exponentially with the increase of R_0 and C_0, which indicates that the threshold values for R_0 and C_0 are 500kΩ and 30nF respectively. Further experimental results show that the threshold values change with the parameters of the coil.

The number of turns of the coil is another major influential factor on the characteristic of the Rogowski coil. When the coil dimension and the circuit parameters of the coil are fixed as R_0=490kΩ, C_0=10nF, S=300mm2 and l=458mm, the relationship between the sensitivity and the number of turns is shown in Fig. 7.

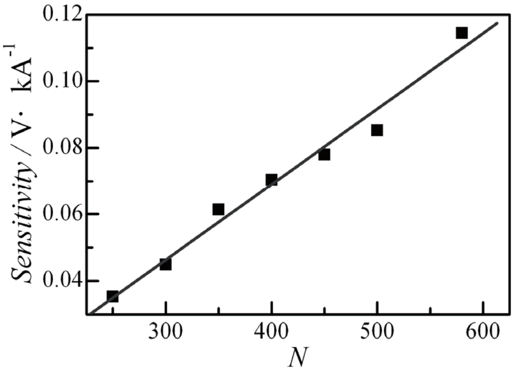


Fig. 7 Relationship between sensitivity and number of turns

Fig. 7 shows that the sensitivity of the coil increases linearly with the increase of the winding-number. It is because the output voltage is an accumulation of deduced voltage of each winding. When the number of turns of the coil increases, more induced voltage is obtained, leading to the increase of the output voltage of the coil.

Rogowski coil design and calibration

The experimental and calculated results of the response characteristics reported above have three main implications for the improvement of the coil characteristics. Firstly, high values of C_0, R_0 and l, or low values of N and S should be used when a low sensitivity of the coil is needed. Secondly, threshold values of C_0 and R_0 should be satisfied. Thirdly, the suitable dimension, including inner and outer diameters and height of the core, should be considered for measurement convenience.

A suitable coil dimension and circuit parameters of the Rogowski coil for the high amplitude lightning current measurement are developed based on the experimental results, which are as follows: d_1=130mm, d_2=160mm, h=20mm, N=580, R_0=490kΩ and C_0=10nF, where, d_1 and d_2 are the inner and outer diameters of the core, respectively, h is the height of the core. Parameters of the coil are measured by the electric bridge and R_t is calculated by Eq. 3 [15] and the parameters of the coil are shown in Table 1.

$$R_t = \sqrt{L_s / C_s} \tag{3}$$

Table 1 parameters of the coil

parameters	specification
C_s	247pF
L_s	0.4939μH
R_t	45Ω
R_s	2.6Ω

In our previous studies, the amplitude-frequency response characteristics were measured by the arbitrary waveform generator (AWG2021) [19-20], which can generate a sine wave from 1 Hz to 125 MHz with the amplitude of 0–5V, a calibrating square wave and an impulse wave from 1 Hz to 2.5 MHz with the amplitude of 0–5V. But with the coil for the measurement of lightning current up to 400kA, the output voltage of the coil is lower than 10^{-5}V when the calibrating current is generated from AWG2021, it is too small to be measured and recorded by the oscilloscope. Therefore, the amplitude-frequency response characteristics of the coil are investigated by the Pspice simulation based on the lumped parameter model as shown in Fig.3. The results of simulation with coil parameters in Tab. 1 are shown in Fig. 8.

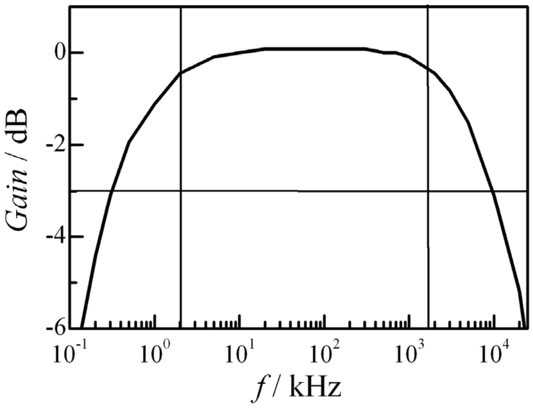
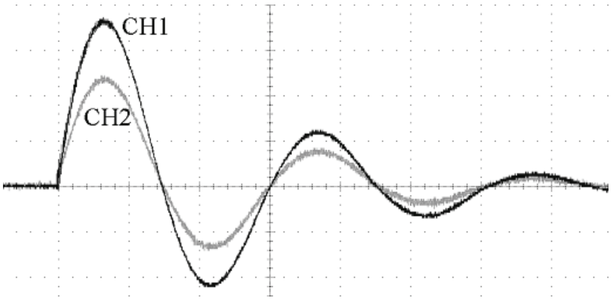


Fig. 8 Simulation results using measured parameters of the coil

Fig. 8 shows that the bandwidth of the coil is about 200Hz-10MHz (-3dB). The response characteristic of amplitude-frequency is good in the range of 2kHz-2MHz, and the typical frequency of the lightning current is also corresponds to this range. It is clear that the characteristics of the designed coil meet the requirement of the lightning current measurement.

Fig. 9 shows the output waveforms of the calibration of the sensitivity. The output waveforms of CH1 and CH2 are measuring result of the Rogowski coil designed in this paper and the current shunt, respectively. It can be seen that the waveforms are almost the same, which indicates that the designed Rogowski coil can be used to measure lightning current up to 300kA accurately.



CH1: 2V/DIV; CH2: 20V/DIV; T: 20μs/DIV

Fig. 9 The output signals by the coil and the current shunt

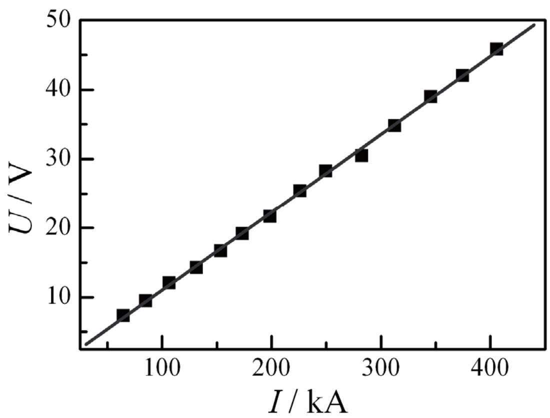


Fig. 10 the sensitivity of the coil

The relationship between the output voltage and the measured lightning current is shown in Fig. 10, which indicates a good linear relationship between the output voltages of the coil and the measured currents. The average sensitivity of the designed coil is 0.1144V/kA based on fitting of the results in Fig. 10.

When the current is measured by the Rogowski coil in the calibration experiment, it is found that the positional sensitivity of the Rogowski coil is another influence factor on the characteristics of the coil. The average sensitivities with various eccentricities are listed in Table 2. It can be seen that the higher the eccentricity is, the larger the measurement uncertainty of the Rogowski coil is. The maximum measurement uncertainty is up to 5% when the eccentricity is 100%.

Table 2 the influence by the eccentricity ratio

eccentricity (%)	sensitivity (V/kA)	uncertainty (%)
0	0.114447	0
20	0.113823	0.545231
40	0.112025	2.116263
60	0.110074	3.820983
80	0.109867	4.00159
100	0.108762	4.967365

It can thus be concluded that the positional sensitivity of the Rogowski coil of the current flowing through the coil will cause measurement uncertainty. The mechanism of the occurrence of the uncertainty is rather simple. Because the measured transmission line need through the core of the coil, the inner diameter of the core must large enough. When the measured current is not flowing along the center of the coil, induced magnetic flux will not distribute symmetrically around the coil. Accordingly, the magnetic flux through each winding of the coil will be unequal and then the induced voltage is different. As a result, the measurement uncertainty occurs. It follows that, to improve the accuracy of Rogowski coil, the measured current should be confined to flow through the center of the core as much as possible.

Application of current transducer on power grid

The designed Rogowski coil is a part of the lightning current transducer which is installed on the power grid for lightning current measurement. The transducer is combined by the designed coil, afflicted circuit and transmit antenna, where, the afflicted circuit which is connected to the output of the coil is consisted by analog-digital converter, digital data acquisition system, like Digital Signal Processing (DSP), wireless transmission module, filter converter, amplifying circuit, protection circuit and other auxiliary circuits. Sometimes all the circuits are installed in an extra shielding box for preventing signal interference from the corona on the transmission line.

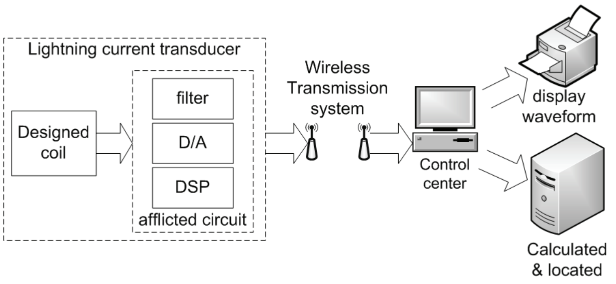


Fig. 11 Schematic diagram of the principle of the current transducer

Several current transducers are installed along the transmission lines while the distances between optional adjacent two transducers are equivalent. When a random position on the transmission line is stroked by the lightning, the lightning current is delivered to two terminations of the transmission line and flow through the center of the Rogowski coil along the line. The analog signals which are output from the coil are transferred to the digital signals by analog-digital converter. The processed digital signals, which are include the lightning parameters, induced time and transducer number, are sending to the control center by the wireless transmission system, for example, GPRS, 3G, WCDMA and other transmission channels. The principle of the transducer is shown in Fig. 11.

It is easy to display the waveforms of the lightning current by the received digital signals in the control center, and the time difference from adjacent current transducer is easy to known, too. Combined with the distance between adjacent transducer, the value and deliver speed along the line of lightning current can be calculated, and the position of the lightning stroke is located.

Conclusion

According to the comprehensive theoretical analysis and the experimental results of the Rogowski coil response characteristics, the present study probes into the influential factors of the coil. The bandwidth and the sensitivity of the coil are determined by the coil dimension, integral parameters and the winding-number.

The results of the experiment and the theory analysis show that when the parameters of the coil meet the integral conditions, the sensitivity of the coil linearly increases with the increase of the number of turnss and sectional area. The sensitivity of the coil decreases exponentially with the increases of the effective magnetic path, integral resistance or capacitance.

A Rogowski coil with external integrator is designed for the measurement of lightning current up to 400kA on the power grid, and the sensitivity is 0.1144V/kA for output voltage below 50V. Results of the calibration experiment demonstrate that the Rogowski coil can correctly reproduce the waveform of the lightning current up to 400kA with excellent linearity. The maximum measurement uncertainty (about 5%) is always caused by the off-centre position of the current flowing through the coil. At last, the lightning current transducer based on the designed coil used in power grid is introduced.

Acknowledgments: This work was supported by the National High Technology Research and Development Program of China (863 Program) under Grants 2008AA04Z408.

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