The Basics of Rogowski Coil Current Probe

1. Principle

A Rogowski Coil Current Probe comprises a Rogowski coil and an integrator. The Rogowski coil consists of a homogeneously wound induction coil of constant section, which is closed upon itself around the current conductor and senses the magnetic field around a closed path.
The Rogowski Coil Current Probe is shown in Fig.1.
The voltage induced in a Rogowski Coil is proportional to the rate of change of current enclosed by the coil loop. The Integrator integrate the induce voltage from a Rogowski coil and produce a voltage proportional to the current and reproduce the current waveform on an oscilloscope.
Ampère's circuital law relates the integrated magnetic field around a closed loop to the current passing through the loop.
The Rogowski Coil Current Probe determines the current by Ampère's circuital law.

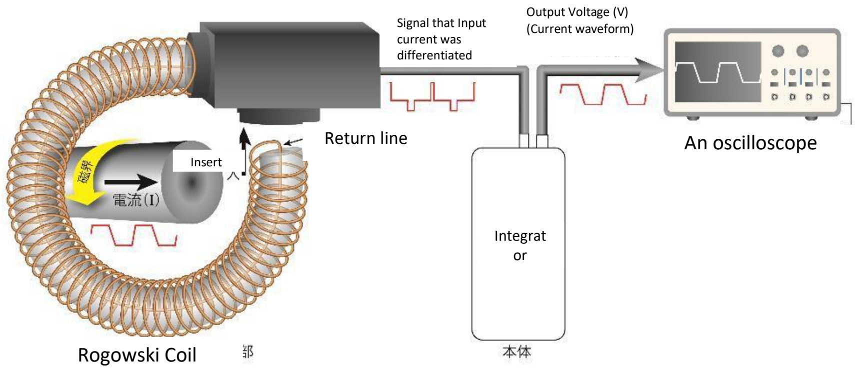


Fig.1 A Rogowski Coil Current Probe

A Rogowski coil in Fig.1 is an electrically conductive coil having a substantially uniform turns density of N(turns/m) wound on a structure referred to herein as a former. The former comprises a non-magnetic material, typically plastic, of cross sectional area A (m^2), and the coil is arranged to form a closed loop. In order to measure the value of a current in an electrical conductor, the Rogowski coil is placed around the conductor.
Ampère's law determines the current associated with a given magnetic field.
Now, if Rogowski Coil consists of N pieces of coil per unit and the distance between coils is δl, N = 1 / δl. And the measured current is to flow to the vertical and central direction toward Rogowski Coil. Magnetic field H is conditional on uniformity inside the coils.

$$I=\oint H\,\mathrm{dl}=\frac{1}{N}\sum_{i=1}^{N} Hi \quad \cdot\cdot\cdot (1)$$

$\oint H\,\mathrm{dl}$ is the closed line integral around the Rogowski Coil,

The **B** and **H** fields are related by the constitutive equation where μ_0 is the magnetic constant.

Coil Area: A, Magnetic field: B, The sum of Induced Voltage : V

$V=\frac{\partial}{\partial t}\int BdA=\mu_0 A\frac{\partial}{\partial t}\sum_{i=0}^{N} Hi$, Input (1) to this formula,

$=\mu_0 AN\frac{\partial I}{\partial t}$ ・・・ (2)

The current being measured is calculated by the integral of the sum of Induced Voltage (V). Like this, we can get the waveform of the current being measured by the integral of output voltage from Rogowski coil.

2. The differences from other current sensors

2.1. Shunt Resistor Device

As a method to measure current easily, there is a method to convert current to voltage using Shunt Resistor Device. It has an advantage of being able to measure current up to high frequency with great linearity. On the other hand, however, this method cannot measure under the isolated condition and it will be a problem to produce heat by the Shunt Resistor Device when high current is measured. Since the Shunt Resistor Device is implemented to the circuit being measured, this makes some influence to the circuit operation.

2.2. Current Transformer

As a method to measure current that is isolated from the circuits, there is Current Transformer (CT). CT consist of magnet core. The magnet core is made of magnetic materials, the following problems happen.

- Heat generation by magnetic loss in high frequency range, magnetic saturation and hysteresis problem
- CT size becomes larger for preventing magnetic saturation in high current range
- When the input signal is non-sine wave such as a pulse, the output maybe distorted by the limitation of frequency characteristics of magnetic materials.

2.3. Rogowski Coil Current Probe

Since Rogowski Coil Current Probe has no magnetic materials, there is no problem of magnetic saturation in principle which Current Transformer has. In addition, we know this method makes a very little influences (insertion impedance) on the circuit being measured because inductance is small.

As the Inductance of Rogowski Coil Current Probe is small, there is a little influence on the circuit being measured.

As the measurement in the small current range is difficult and easily affected by external magnetic field, it is required to make a care and an attention.

2.4. Comparison of Various Current Sensing Technorogies

Table 1

Current sensing Technorogy	Advantage	Disadvantage
Shunt Resistor Device	Low cost No magnetic saturation Best linearity Measurement from DC to high frequency	Isolation measurement is difficult. High current type is big in form. Current on PC board is implemented after disconnecting the circuit.
Hall element+ CT(Flux-gate)	Measurement from DC to high frequency Isolation measurement is available.	Saturation of Magnetic materials/hysteresis Affected a little by external magnetic field Current on PC board is implemented after disconnecting the
Current Transformer (CT)	High current measurement is supported. Measurement up to high frequency Isolation measurement is supported.	Measurement from DC is not available. Saturation of Magnetic materials/hysteresis Affected a little by external magnetic field Current on PC board is implemented after disconnecting the
Rogowski Coil	High current measurement is supported. Easy to fit by clump method	Measurement from DC is not available. Affected by external magnetic field

	No magnetic saturation The wide range in temperature Sensing for narrow space is supported. Insulation measurement is supported.	Low current measurement is difficult.

3. Selection of models (Measurement range・Low-frequency cutoff・Low-frequency noise)

It is required to consider Measurement range, Low-frequency cutoff and Low-frequency noise in order to select proper Rogowski Coil Probes.

3.1. Measurement range

Measurement range of Rogowski Coil Probes is defined by peak current. For example, SS-285A (600A) can measure upto±600Apeak and the output voltage is ±6V at that time. When alternating current is used, root mean square value is displayed many times. In this case, please require attention to convert √2 times.

Rogowski Coil Probe will not be damaged even if current of about twice as high as the specification of measurement range flows. However, since the integrator will be saturated, please note that the current waveform (measured value) maybe distorted just after exceeding the range.

3.1. Low-frequency cutoff

There are relationships of the value of low-frequency cutoff, low-frequency noise and sensitivity (mV/A).

Induced voltage : V

$$V = C\frac{\partial I}{\partial t} \cdot \cdot \cdot (3)$$

where is C: Constant of Rogowski Coil

I: Current being measured

If Current being measured I = $I \quad \sin(2\pi * f)t$.

$$V = C * I \quad * 2\pi * f * \cos(2\pi * f)t \cdot \cdot \cdot (4)$$

The Induced voltage V is proportional to the frequency f and I.
If the frequency of the current being measured becomes 1/10 times, the Induced voltage will be 1/10.

The integrator gain increases as frequency is reduced. Low-frequency noise increases. low-frequency cutoff must be limited low-frequency noise. Similarly, **the integrator gain increases as** Sensitivity (mV/A) **is increased. low-frequency noise increases,** low-frequency cutoff must be limited Sensitivity (mV/A),too.

3.2. Low-frequency noise

Noise consists of random signals containing many low-frequency components and is virtually in gauss distribution, so p-p voltage value will be about 6 times of rms value. If we multiply this voltage value by the sensitivity, we can calculate how large noise current is contained at the actual measurement.

Show it as above,low-frequency noise is limited the low frequency bandwidth and Measurement range.

If we measure very small current with the measurement range of Rogowski Coil Probe, it is needed to examine SN ratio affected by this noise current.

4. Precaution

4.1. Precaution concerning Environmental Temperature

The operating temperature of the Rogwski coil SS-28xA is -40℃ to 125℃. Polytetrafluoroethylene (PTFE) tube is used for the air-core and a layer outside the coil for insulation materials. The polymers is hard and gets broken easily at low temperature comparing to ordinary temperature. At high temperature, it has the property that it turns soft and the strength drops to a lower value. Please avoid tightly bending and pulling at low/high temperature.

4.2. Withstanding voltage

As the targeted withstanding voltage of SS-28xA series is 1.2kVpeak, the test was performed at 3.0kVrms for 60 seconds. Though insulation of Rogowski coil is tested in the withstanding test, the special attention is required because the insulation may deteriorate depending on usage environment and its usage.

· Please note that corona discharge may happen when high voltage is given for a long time to Rogowski coil.

· Even if Rogowski coil's voltage is less than the withstanding, corona discharge may happen and the insulation of outer coat may deteriorate due to frequency of bias voltage and the setting condition of sensor portion, which causes shock, fire, and malfunction.

· As corona discharge happens easily by concentration keep distance Rogowski coil and High voltage part as long as possible and take safety measures such as inserting insulation materials.

5. To ensure higher accuracies

5.1. Waveform measurement containing DC element

Rogowski Coil Current Probe is AC current probe and it cannot measure DC.
Like the measurement by oscilloscopes with AC coupling, DC information disappeared and the ground level of oscilloscope is the mean value of the measured waveform. If you know the ground level (Current zero) point on the actual waveform, we can adjust it to the actual measuring waveform current by offsetting the mean value.
For example, if the current is ON/OFF switching current waveform, when switch is OFF, the level is ground level (Current zero). So, by adjusting this line to the ground level, we can convert to the actual waveform current.

When the duty of a pulse waveform changes, the mean value of the waveform changes. The ground level of measuring waveform also changes. When PWM waveform is measured, take this effect into consideration. On an oscilloscope, Even if the current of the actual PWM waveform does not change, the mean value of the waveform changes because the duty of PWM waveform changes, and the ground level of measuring waveform may change.

5.2. Effect of Droop

When low frequency signal is measured even if the circuit contains no DC, pay attention to Low-frequency Cutoff of Rogowski Coil Probe. Rogowski Coil Current Probe has, in principle, a characteristic of decreasing the sensitivity (mV/A) in low frequency. In low frequency, the point that reduces the probe's sensitivity by 3dB is defined as Low-frequency Cutoff.

For this low frequency characteristics, when we measure a signal including low frequency components, pay attention to the fact that there may be differences between actual current and the result of measurement by Rogowski Coil Current Probe. This effect is shown as drooping after pulse rising, if it is a pulse waveform.

If it is a sine wave, as the amplitude decrease following its lowering frequency, the phase shifts, if you observe the phase relation to other signals, you need to use a model which has a function to filter sufficiently low frequency against the measurement signal.

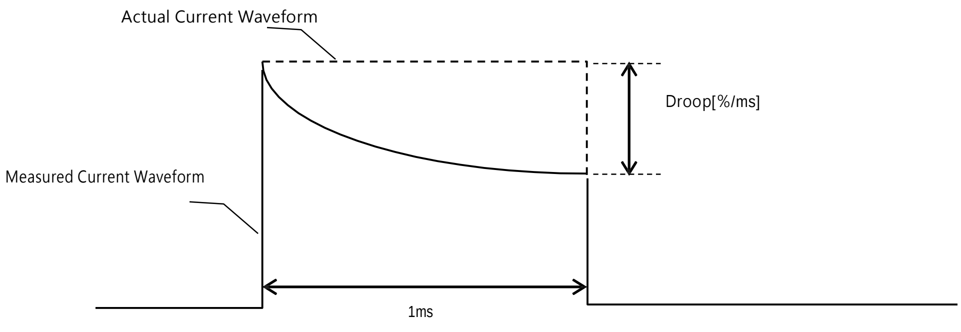


図.1 Droop characteristics

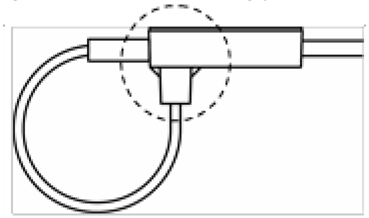
※For details please refer to Application Note ROG15021"Rogowski Coil Current Probe Low-frequency Characteristics and Droop".

5.3. Sensitivity Accuracy

Rogowski Coil Current Probe measures current by placing a coil around the current.

This coil ideally should be a closed circuit, however, actually there is a part causing an error due to the discontinuity of the coil at the joint (Coil conjunction part) for making Rogowsli coil ring-like.

This part is not suitable for the current measurement because the error becomes large if current being measured exists near there. In addition, if there is external current near there, the magnetic field cannot be cancelled sufficiently (Ampère's circuital law said). This product is calibrated to the current flow that is in the center part of Rogowski coil. In the accurate measurement is required, we recommend the measurement is performed in the center of Rogowski coil avoiding joint area as less as possible.



If it is difficult to measure the current in the center of Rogowski coil because of shape of device being measured, measure it at the area distant from the conjunction part as far as possible. If this is also difficult, we can improve the reproducibility of the measurement at least by fixing the places between the device and Rogowski coil.

5.4. Coil Damage and Sensitivity change

In measurement principle, the sensitivity of Rogowski Coil Probe is proportional to cross-section area of the coil. Accordingly, once a part of the coil changes, the sensitivity changes. For example, a part of coil gets crushed, cross-section area of coil becomes small and the sensitivity around such area comes to be reduced dramatically. Please avoid actions such as straining Rogowski coil and handle it carefully.

Even with a great care, we cannot avoid deteriorating the coil due to repeated measurement. So we recommend the periodical calibration. When the coil deteriorated, we accept the replacement of coil for a charge.

5.5. Effect of Voltage fluctuation

If there is a part with changing voltage close to Rogowski coil, it may cause the influence on output by electrostatic coupling with Rogowski coil.

Electrostatic coupling noise will be improved if Rogowski Coil sensor part is kept from the part with changing voltage.

For example, the electrostatic coupling noise will be better reduced if the current should be measured near the emitter terminal connected to the constant voltage on IGBT rather than collector terminal where the voltage changes drastically.

※For details please refer to Application Note ROG15022 "Rogowski Coil Current Probe High-speed SW Current Measurement".

6. Absolute maximum rating

6.1. Absolute maximum rating

Maximum allowable current at measuring Rogowski Coil Probe is determined by the time rate of change of current (di/dt). This means allowable current changes by frequency of current and rising time..

Table1
Absolute maximum the time rate of change of current

Model Name	Peak [kA/μs]	RMS [kA/μs]
SS-281A,282A	80	1
SS-283A,284A,285A	80	1.5
SS-286A	80	2

※Ｐｅａｋ: Number of Single Pulse Signal. Do not exceed this number even one time.
※RMS: Number of Continuous Signal. Do not exceed this number even one time.

6.2. Sinusoidal waveform

The time rate of change of current (dI/dt) is calculated taking differential of Sinusoidal waveform and the maximum dIrms/dt is 2×π× frequency× Irms

6.3. Pulse waveform

The time rate of change of current (di/dt) of Single shot pulse = Max. current value ÷ Rising time (or falling time)
In continuous pulse signal, calculate di/dt of current pulse rising time/falling time and calculate the effective value from the cycle T. This value must not exceed the absolute max rating RMS value.

$$\frac{d}{dt}Is(t)=\sqrt{\left(\frac{Is}{Tr}\right)^2\times\frac{Tr}{T}+\left(\frac{Is}{Tf}\right)^2\times\frac{Tf}{T}}$$

※For details please refer to Application Note ROG14069"Rogowski Coil Current Probe Maximum Allowed Current

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