ROGOWSKI COILS

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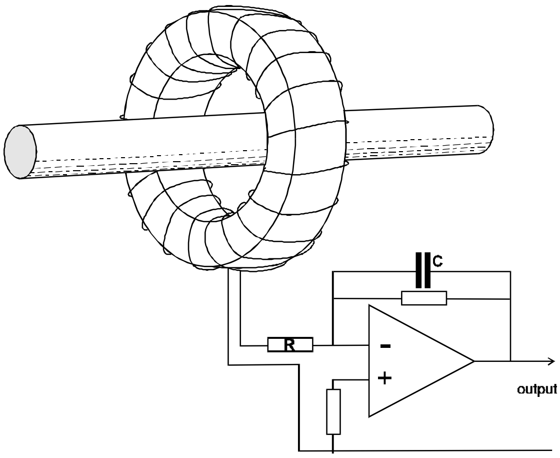
General Description

Rogowski coils are used for measuring alternating current. They work by sensing the magnetic field caused by the current without the need to make an electrical contact with the conductor. These coils have been used in various forms for detecting and measuring electric currents for decades but it is only in recent years that their potential is being realised on a commercial scale.

They operate on a simple principle. An 'air cored' coil is placed round the conductor in a toroidal fashion so that the alternating magnetic field produced by the current induces a voltage in the coil. The coil is effectively a mutual inductance coupled to the conductor being measured and the voltage output is proportional to the rate of change of current. To complete the transducer this voltage is integrated electronically (figure 1)

to provide an output that reproduces the current



waveform. This combination of coil and integrator provides a system where the output is independent of frequency, which has an accurate phase response, and which can measure complex current waveforms. The output from the integrator can be used with any form of electronic indicating device such as a voltmeter, oscilloscope, protection system or metering equipment.

The coils are wound either on a flexible former that is subsequently wrapped round the conductor to be measured or on a rigid toroidal former.

Features

Other devices exist that measure electric current without making electrical contact with the conductor. Many of these, including the conventional current transformer, use a ferro-magnetic core and are subject to magnetic saturation effects that limit the range of currents that they can measure. A Rogowski coil, on the other hand, is 'linear'; it does not saturate and the mutual inductance between the coil and the conductor is independent of the current.

Many of the useful features of Rogowski coil systems result from their linearity.

(i) They have a wide dynamic range in that the same coil can be used to measure currents ranging from a few milliamperes to several million amperes.

(ii) Calibration is easier because the coil may be calibrated at any convenient current level and the calibration will be accurate for all currents including very large ones.

(iii) They respond accurately to transient currents which makes them an excellent choice for use in protection systems and for measuring current pulses.

(iv) They are useful in situations where the approximate value of the current to be measured is not known beforehand.

Coils wound on flexible formers have the additional unique feature that they can be wrapped round the conductor being measured. A long coil can be used as a compact portable device to measure the current in large conductors. Flexible coils can be manufactured with a cross-section only a few millimetres (fraction of an inch) across and can be used where there is limited space round the conductor.

Development

In 1887 Professor Chattock of Bristol University described the use of a long, flexible coil of wire wound on a length of india-rubber as a magnetic potentiometer. The output of such a coil is proportional to the line integral of the magnetic field along its length ie. proportional to the 'magnetomotive force' or the 'magnetic scalar potential' between its ends. Chattock used his coil for measuring the magnetic reluctance in iron circuits but he calibrated his coil by bringing the ends together to encircle an electric current. This calibration method depended on Ampère's Law, which states that the value of the line integral of magnetic field along a loop which completely encircles a current is equal to the current.

Rogowski and Steinhaus described the technique in 1912. They were also interested in measuring magnetic potentials. Their paper describes several ingenious experiments to test that their

coil was providing reliable measurements including using it to measure electric currents.

For accurate measurements using a Rogowski coil it is essential that the winding is extremely uniform. From Ampère's Law, with a perfectly uniform coil encircling a current, the output does not depend on the path the coil takes round the current or on the position of the conductor within the loop. It is only necessary that the ends of the coil are brought together accurately. Also, if the coil does not encircle a current the output is zero even if the coil is positioned near a current-carrying conductor. These features are obviously highly desirable in an effective current-measuring transducer.

To achieve these ideal properties the coil must be wound with a constant number of turns per unit length on a former of uniform cross section. With a flexible coil the winding must remain uniform when the coil is bent. The more uniform the winding the better the coil will approximate to the ideal. Both Chattock and Rogowski were aware of the importance of good coil geometry and both remarked that their coils left room for improvement! Rogowski only managed to wind one coil and described how the wire broke three times in the process.

Practical Systems

By using the right technique it is now possible to wind both flexible and solid coils with sufficient uniformity for them to be used in a wide range of applications including those demanding precision measurements. The sensitivity of a complete system comprising a coil and integrator is the ratio between the voltage output and the current being measured. Referring to figure 1 the sensitivity is given by

$$\frac{V_{out}}{I} = \frac{M}{CR} \quad \textit{(volts per Ampere)}$$

Where I is the current and M is the mutual inductance between the coil and the conductor. For a given coil the sensitivity is adjustable over an enormous range by choosing suitable values of C and R. For example, with a typical flexible coil the sensitivity can be varied over a range greater than 1V/A to 1µV/A . With the coils themselves there is also plenty of scope for modifying their characteristics by altering the turns density and cross-sectional area. The full range of permutations of coils and integrators provides an exceptionally versatile measuring system.

Rogowski coils are not suitable for measuring direct currents but by careful design, systems can be built that measure at frequencies as low as 0.1Hz. The high-frequency limit is determined by the self-resonance of the coil and depends on the coil design. High-frequency limits in the range 20kHz to 1MHz are typical.

Very high frequency measurements can be made using a Rogowski coil by terminating the coil with a low impedance and using the self-inductance of the coil to perform the integration. The output signal is then a current rather than a voltage. Coils operating on this principle have been used to measure currents up to 100MHz.

Applications

An area of applications where Rogowski coils have been particularly valuable is in the measurement of current transients. Conventional current transformers can become 'confused' during the initial stages of a transient especially if the transient contains an asymmetric component (sometimes referred to as a DC offset).

Examples of transient measurements where Rogowski coils have been used are: (i) Monitoring the current in precision welding systems. (ii) Measuring the plasma current in a fusion experiment such as the JET experiment at Culham Laboratory. (iii) Current measurement in arc melting furnaces: Arc furnaces use very large fluctuating currents and they can be made more efficient by monitoring the current and appropriately regulating the arc. (iv) Monitoring electrical plant for protection purposes: Rogowski coils give a more accurate measurement particularly of the early stages of a fault current and are suitable for interfacing with modern, all-electronic protection relays. (v) Measuring the current pulse in an electromagnetic launcher (rail gun): The current can be several million amperes lasting a few milliseconds. (vi) Sudden short-circuit testing of generators.

Rogowski coils have also been used to advantage for the measurement of steady currents. Energy management systems that monitor the current consumption patterns of large buildings and industrial plant are becoming increasingly important. Some systems use Rogowski coils because of their versatility. They are useful for measurement of the harmonic components in electric currents because, being exceptionally linear, they faithfully reproduce the harmonic content. Rogowski coils are also used to measure currents with complex waveforms such as in thyristor circuits. They are used in the Railway Industry to monitor the signalling currents in railway lines. Flexible coils have been used to trace the currents induced in metal structures exposed to magnetic fields, for example near a large transformer. The flexible coil has an educational value as an excellent practical demonstration of Ampère's Law.

Reference

'Using Rogowski coils for transient current measurements', David A. Ward and John La T. Exon, IEE Engineering and Science Journal, June 1993, pp105 - 113.