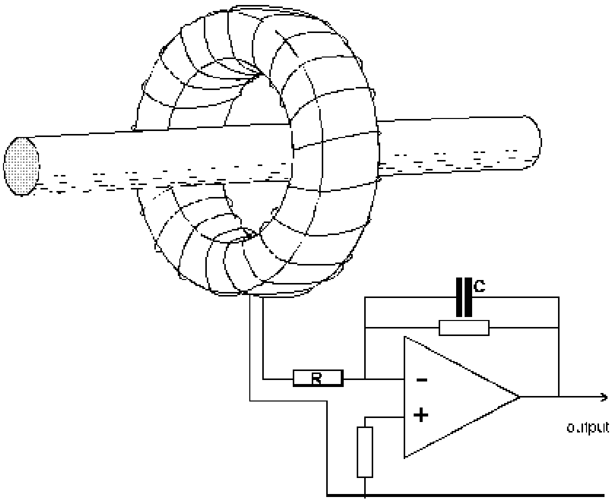
ROGOWSKI COILS

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

$$\frac{V_{out}}{I} = \frac{M}{CR} \qquad \text{(Volts/Ampere)}$$

Where 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 1mV/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.

References
1) 'On a magnetic potentiometer', A. P.Chattock, Philos. Mag., 1887, 24, (5), pp 94 - 96.
2) 'Die Messung der magnetischen Spannung', W. Rogowski und W. Steinhaus, Arch. Elektrotech., 1912, 1, Pt. 4, pp141 - 150.
3) 'Using Rogowski coils for transient current measurements', David .A. Ward and John La T. Exon, IEE Engineering and Science Journal, June 1993, pp105 - 113.

ROGOWSKI COIL CURRENT TRANSDUCER APPLICATIONS

Two forms of transducer coil have been developed. One is the Rigid Toroid design which can be used for high-precision measurements and some forms of permanent installation. This has an accuracy and stability comparable to a class AL current transformer but without the current-range limitations. A clip-on version of the rigid toroid can be produced with similar specifications. The alternative form of the transducer is the Flexible Coil. This is less sensitive and less accurate than the rigid form but is extremely compact and versatile. It consists of a flexible helical winding which is wrapped around the conductor being measured. It is useful with conductors of large size or awkward shape or in places where access to the conductor is restricted.

FEATURES

Rogowski Coil Transducers have many advantages over the conventional current transformer.
these include:

- Wide Dynamic Range - the same transducer coil can be used to measure currents from milliamps to hundreds of kilo amps.
- Wide Bandwidth - typically 0.1 Hz to over 100 kHz.
- Low Phase Error - less than 0.1° in the mid-frequency range.
- No danger from open-circuited secondaries.
- Cannot be damaged by large overloads.

The transducer does not measure direct currents but, unlike a current transformer, it can make accurate measurements even when a large dc component is present because there is no iron core to saturate. This is a useful feature for measuring ripple currents, for example, in battery charging systems. The transducer is also good for measuring transients and for protection applications because it can accurately measure asymmetrical currents without suffering saturation problems.

In addition to their good electrical performance Rogowski coils have several other attractive features. They are compact and can be installed in positions where access is limited. They are also light in weight and in many cases are light enough to be suspended on the conductor being measured. Transducers for large conductors or very large currents are also light and compact.

APPLICATIONS

Rogowski coil transducers have been used in the Power Supply Industry for many years in a wide range of applications associated with research and testing on electrical plant and are now finding applications in many other areas. The following lists some examples of where they have been used and illustrates the flexibility of the system and its ability to cope with different situations.

Measurement of Slip Currents on Wound Rotor Induction Motors: This is the application for which the transducers were originally developed. The currents, which flow at a very low frequency, are measured accurately and the transducer outputs fed to a comprehensive protection system. One of the protection functions is an earth fault monitor which works by summing the three phase currents and looking for a non-zero result. This requires a high degree of accuracy in the current measurement.

Currents in Generator Main Output Connections: The enclosures round these conductors are about 1.2m in diameter. Transducers have been used to check conductor and enclosure currents. This is believed to be the first time that accurate measurements on enclosures have been made. The transducers were also used during overload tests on some output connections where currents of more than 600kA were measured. The transducers can be fitted in a few minutes and are more convenient and safe to use than a CT.

Current Sharing in Flexible Braids: Transducers have been used to check the current distribution in a system of flexible braids connected in parallel. These measurements make use of the exceptionally low insertion impedance of Rogowski coils.

Generator Core Framework currents: Transducers have been installed in several generator stators to measure currents flowing around the stator support structure. These measurements were used to provide data for research into stator hot spots and core faults and to improve stator design. The transducers were useful in this application because they were compact and could be mounted in places where access was limited and because the current levels were unknown before installation.

***General-Purpose measurements**:* A 'split' solid transducer has been in use for several years to measure the current during stator flux tests. Because of its small phase error it is useful for power measurements in a low power factor system. Portable wrap-round transducers have been used for several one-off monitoring tasks. such as studying harmonics in power systems or energy management measurements. Each individual transducer can cope with a large range of currents and there is no danger from open-circuited secondaries.

Resistive Billet Heating: A rigid transducer was used to monitor currents of about 20 kA with a high harmonic content in an experimental rig used to heat metal billets by passing current through them.

Ripple Component of a Generator Rotor Current: A transducer was used to study the ripple in the excitation of a generator rotor as part of an investigation into the causes of a rotor failure. The fine details in the ripple could be examined without interference from the large dc component.

Spurious Currents in Transformer Pipework: Currents flowing in the cooling pipework of a large transformer have caused heating at bolts and flanges. A wrap-round transducer was used to trace the currents and monitor the effectiveness of a remedy because of its ability to measure large conductors.

Sudden Short-Circuit Testing of Generators: Rogowski coil transducers have been used on several occasions for sudden short circuit testing. Their ability to measure very large currents and to cope with asymmetrical currents makes them ideal for this application. The conventional method of measurement is to use a shunt which normally requires modification to the generator conductors before it can be installed. The Rogowski coil is accurate, more compact, easier to install, and is isolated from the generator conductors.

***Testing Uninterruptable Power Supplies**:* Rogowski coils were used to monitor the currents during tests on uninterruptable power supplies to determine their recovery times after faults had been applied. The coils were used because of their ability to measure transients accurately.

Pulsed Power Measurements: Pulsed power systems frequently require the measurement of hundreds of kilo amps with fast rise times. Rogowski coils are ideal for this purpose because of their exceptional high-current capability. The linearity of Rogowski coils means that they can be used reliably to measure currents much higher than those which can be generated for calibratioin purposes. A special low-output coil has been developed to cope with exceptionally fast rates of change of current and can be used at frequencies up to about 1 MHz.

Measuring Currents in Railway Lines: Railway signalling systems rely on special signalling currents flowing along the track to detect where the trains are. Rogowski coils are a good way of monitoring these currents for test and maintenance purposes.