Using Rogowski coils for transient current measurements

by D. A. Ward and J. La T. Exon

In recent years the Rogowski-coil method of measuring electric current has developed from a 'laboratory curiosity to a versatile measuring system with many applications throughout industry and in research. The technique possesses many features which offer an advantage over iron-cored current measuring devices and these are well illustrated by considering how it can be used for measuring transient currents The paper describes the principle of operation of Rogowski coils and the practical aspects of using them and gives several examples of their use in making transient measurements. The Rogowski coil is a conceptually simple device. Its theory of operation illustrates some basic principles of electromagnetism applied in a practical device. The coil itself provides an elegant demonstration of Ampère's Law and, because of its inherent linearity, the response of a coil under extreme measuring situations is much easier to treat theoretically than iron-cored measuring instruments The educational aspects of studying Rogowski coils should not be overlooked.

Introduction

Rogowski coils have been used for the detection and measurement of electric currents for decades. They operate on a simple principle. An 'air-cored' coil is placed around the conductor in a toroidal fashion and the magnetic field produced by the current induces a voltage in the coil. The voltage output is proportional to the rate of change of current This voltage is integrated, thus producing an output proportional to the current. In most cases Rogowski coils have been made by placing the winding on a long, flexible former and then bending it round the conductor, but coils wound on rigid toroidal formers have also been used.

In 1887[1] Professor Chattock of Bristol University used a long, flexible coil of wire as a magnetic potentiometer and made magnetic reluctance measurements in iron circuits to investigate 'the more satisfactory designing of dynamos'. The coils were calibrated by bringing their ends together around an electric current. A recent use of the Chattock potentiometer is in the 'El Cid' technique which was developed by the CEGB (Central Electricity Generating Board) for testing the stator cores of generators and motors[2].

Rogowski and Steinhaus also described the technique in 1912[3]. They too were interested in measuring magnetic potentials. They describe a large number of ingenious experiments to test that their coil was providing reliable measurements.

Chattock and Rogowski used ballistic galvanometers for integration. The fields and currents they

Fig. 1 Selection of Rogowski coils

used were DC and measurements were made either by switching the current off and on or by quickly moving the coil-a transient measurement! With alternating currents and modern electronic integrators it is now possible to produce a far more convenient measuring system.

Many other authors have subsequently described applications of Rogowski coils for current measurement-.

In 1975 the CEGB in Harrogate investigated Rogowski coils to deal with measurement problems in the power industry where conventional methods were unsuitable. The technology was developed for producing high-accuracy, reliable and robust measuring systems. Rogowski coils soon became the preferred method of current measurement for a whole range of special measurements and investigations, both within and outside the power industry.

Coils and Integrators

Practical considerations with coil manufacture

Achieving ideal properties in a practical coil demands considerable care in its design and construction. For the coil to follow Ampère's Law well (see the panel on ‘Rogowski coils and Ampère's Law’)

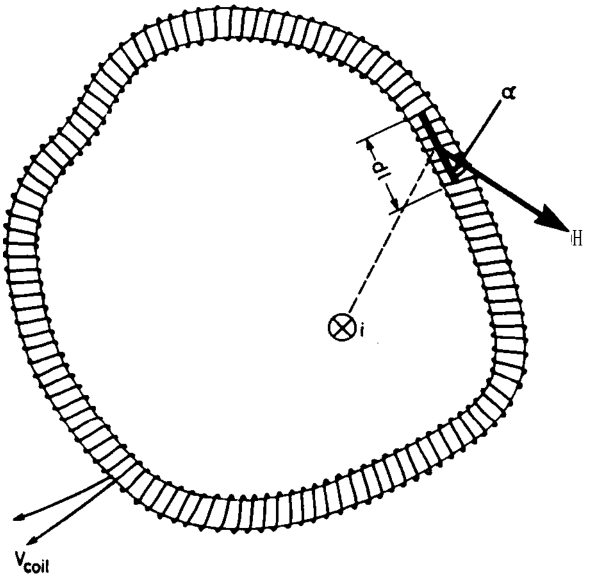
Rogowski coils and Ampère’s Law

The theory of a Rogowski coil illustrates very well how a coil can be considered as an embodiment of Ampere’s Law. A Rogowski coil works by sensing the magnetic field in the space around the conductor and Ampère's Law provides the relationship between the current flowing and the magnetic field around it.

If a line is drawn in a loop which totally encircles the current then, according to Ampère's Law, the line integral of the magnetic field around the loop is equal to the net current enclosed by it no matter what path the loop takes. If the loop encloses no net current the line integral is zero. Mathematically this is expressed as

$$\oint H cosa\, dl = i$$

where *dl* is a small element of length along the loop, *H* is the magnetic field and *a* is the angle between the direction of the field and the direction of the element.



The Figure shows a long, thin helical coil, with n turns per metre and cross-sectional area A which encircles a conductor carrying a current i. In a section of length *dl* the number of turns *is ndl* and the magnetic flux linking the section is

$$d\Phi = \mu_0 H A\ ndl\ cos\ a$$

Where H is the magnetic field and a is the angle between the direction of H and the axis of the coil section. The flux linking the entire coil is given by integrating along the coil:

$$\Phi = \int d\Phi = \mu_0 nA \int H\cos\alpha\, dl = \mu_0 nAi$$

Ampère's Law has been used to evaluate the integral. For an alternating current the voltage output from the coil is given by the rate of change of flux:

$$v_{coil} = -\frac{d\Phi}{dt} = -\mu_0 nA \frac{di}{dt}$$

A thin, flexible, Rogowski coil can be used to provide an elegant experimental demonstration of Ampère's Law because, according to this equation, the voltage output from the coil is independent of the way the coil is placed round the conductor provided only that the ends of the coil are brought together.

Ampère's Law makes a thin Rogowski coil ideal for use as a transducer for alternating currents since it responds only to currents which thread the loop and rejects currents and fields from external sources. Also the output of the transducer does not depend on the exact path taken by the loop. It can be shown that similar considerations apply to coils with a large cross-section, provided that they are circular.

For practical purposes the coupling between a coil and the conductors threading it is described in terms of a mutual inductance *M* where

$$M = \mu_0 nA$$

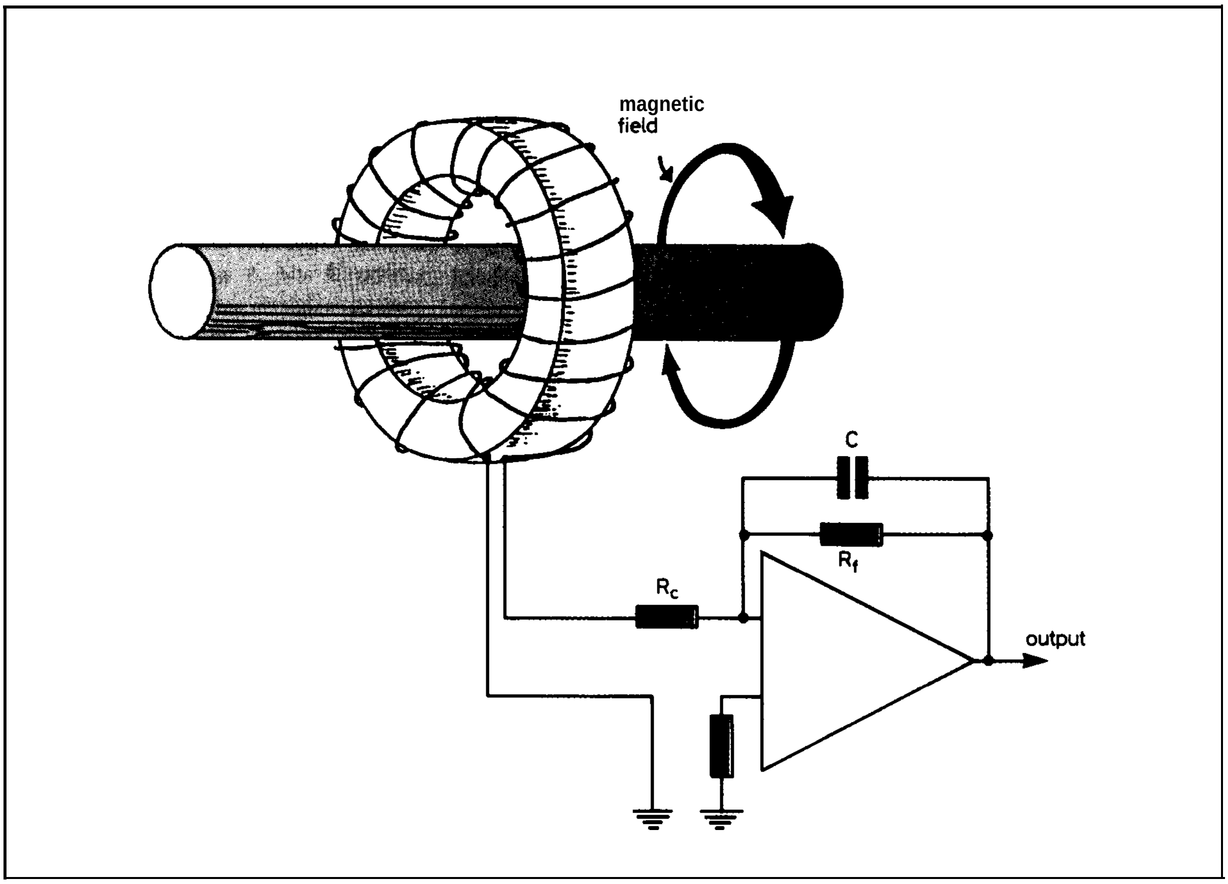


Fig. 2 Arrangement of coil' and integrator

it is essential that the cross-sectional area and the turns density remain constant along the length even when the coil is bent, if itis a flexible one. Both Chattock and Rogowski were well aware of the importance of good coil geometry and both remarked that their coils left room for improvement! The more accurately the coil is made, the better it will perform. The basic requirements for a good coil give scope for a wide range of designs and sizes. Fig. 1 shows a selection of modern coils.

The flexible coil design developed and patented by the CEGB/National Power uses modern materials and is very flexible. For example, a coil with a cross-sectional diameter of about 7 mm can be wrapped round a conductor less than 10 mm diameter with only a small change in sensitivity A good-quality solid coil requires a former with a very uniform cross-section and a highly uniform winding. A special toroidal coil winder was built by the CEGB with a control system designed specifically to provide uniform windings. These coils are used to build high-precision measuring systems which are accurate and stable to an uncertainty of less than 0.1%.

An alternative and easier method of making a solid coil is to wind it as a set of short, straight coils and arrange these in a regular polygon. This gives a good approximation to a circular coil. Clearly, the greater the number of sides in the polygon the better the approximation.

Measuring systems

The addition of an integrator to the coil completes the transducer to provide a voltage which reproduces the current waveform. Fig. 2 shows a typical active system using an inverting integrator. Other integrator designs, including passive integrators, can be used depending on the circumstances.

The characteristics of an integrator are described by an integration time constant, $\tau = CR_c$ and a 'degeneration' time constant, $T = CR_f$. Some form of low-frequency degeneration is essential or the integrator output will drift because of thermal EMFs and offsets in the operational amplifier. In designing complete systems other factors, particularly the limitations of the operational amplifiers used, must also be taken into account.

The sensitivity of a complete system is the ratio between the current being measured and the voltage output. If M is the mutual inductance between the Rogowski coil and the conductor, the output Iiom the coil is given by

$$v_{coil} = -M\frac{di}{dt}$$

The output of the integrator, within the designed working bandwidth, is

$$v_{out} = -\frac{1}{\tau}\int v_{coil}dt$$

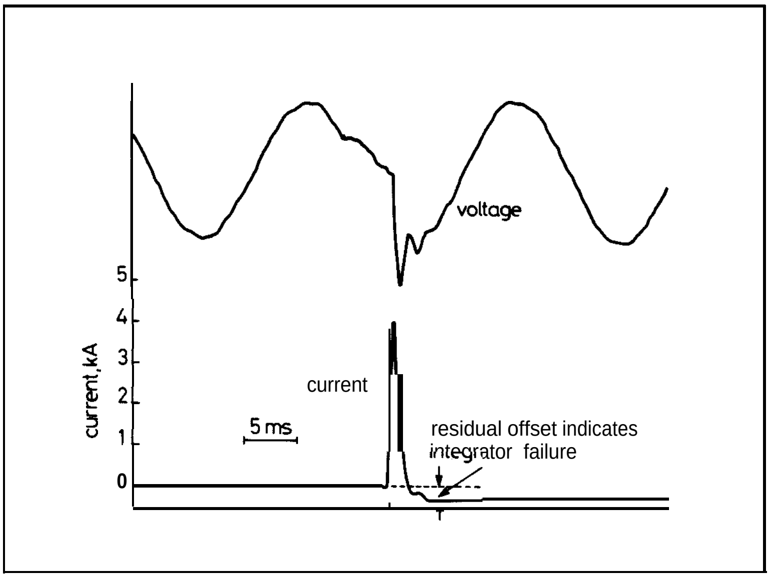


Fig. 3 Illustration of slew rate

and the sensitivity in volts per ampere is:

$$\frac{v_{out}}{i} = \frac{M}{\tau} \qquad (1)$$

For a given coil the sensitivity can be adjusted over an enormous range by adjusting 7. For example, the same flexible coil can be used to measure currents ranging from a few milliamperes to several megamperes. 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 current-measuring system.

The sensitivity in volts per ampere is equivalent to a resistance and can be thought of as an ‘equivalent shunt resistance’. Unlike a resistor, however, a Rogowski coil provides galvanic isolation and produces no heating.

Linearity

Unlike current transformers, and other ferro-magnetic-cored devices, Rogowski coils are linear. There are no effects from saturation and the mutual inductance is independent of the current being measured. The only factor limiting linearity would be an electrical breakdown in the winding caused by too high a voltage being developed across the ends of the coil. Many of the features of Rogowski coil systems that make them suitable for transient current measurements stem from this inherent linearity.

The integrator is also linear within certain predictable limitations. For reliable operation the designer must be aware of the limitations and design within them. Selection of components and circuit layout are also important in achieving high-integrity measurements.

The main limitations with integrators are saturation, when the output voltage becomes too large, and a slew-rate (rate of change of output for a step input) limit, which occurs when fast current edges are being measured. By examining the output waveform it is usually obvious when saturation has occurred and it is normally a simple matter to design the integrator to ensure that the output remains in the linear range. Fig. 3 shows an example of a waveform where the slew-rate limit has been exceeded. The effect shows up as a shift in the DC level between the start and finish of the transient. The problem is rectified by correct integrator design.

High frequencies

High-frequency behaviour is obviously very important with some transient measurements.

High frequencies-coils

At frequencies up to a few tens of kilohertz the coil behaves as a simple mutual inductor and measurement is straightforward. At higher frequencies the self-inductance and self-capacitance of the coil become significant. A simple equivalent circuit for studying high-frequency effects is shown in Fig. 4.

If the inductive impedance of the coil is comparable with the input resistance of the integrator there can be amplitude and phase errors which depend on the coil design. For most cases the effect is small at frequencies below a few tens of kilohertz. For critical applications compensation circuitry can be included in the integrator.

The self-capacitance and self-inductance of the coil cause a resonance. The resonant frequency is an important parameter of a Rogowski coil and is crucial to an understanding of its high-frequency behaviour. Using the equivalent circuit of Fig. 4 the transfer tinction of the coil/integrator combination can be calculated (Fig. 5). The integrator input resistor, R_c, has a damping effect and the resonance can be under damped, over-damped or critically-damped depending

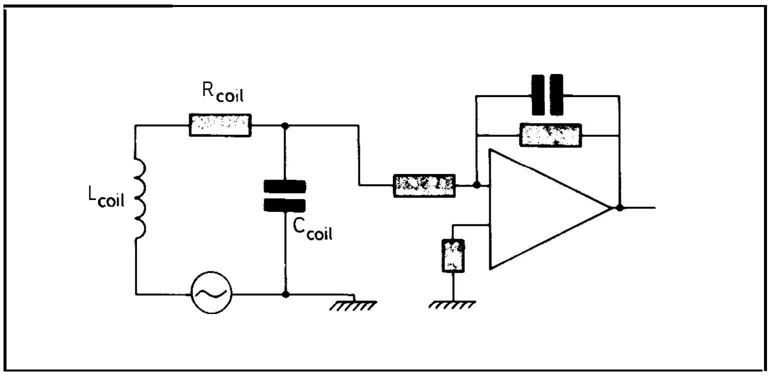


Fig. 4 Equivalent circuit including self-capacitance and inductance

on the value of R_c. If a coil is to be operated close to its resonant frequency the damping conditions must be carefully considered in the design.

The self-resonant frequency of a coil depends on its size, on the winding details and, in the case of flexible coils, on the length. Typical values are given in Table 1.

The resonant frequency is also affected by whether or not the coil is fitted with an electrostatic screen, and by the length of the output cable between the coil and the integrator, since both of these introduce additional capacitance.

At very high frequencies the coil behaves as a transmission line and correct termination of both ends of the coil is important. The induced voltage distribution along the length of the coil also becomes significant because of propagation time delays and this makes the output of the coil dependent on conductor position.

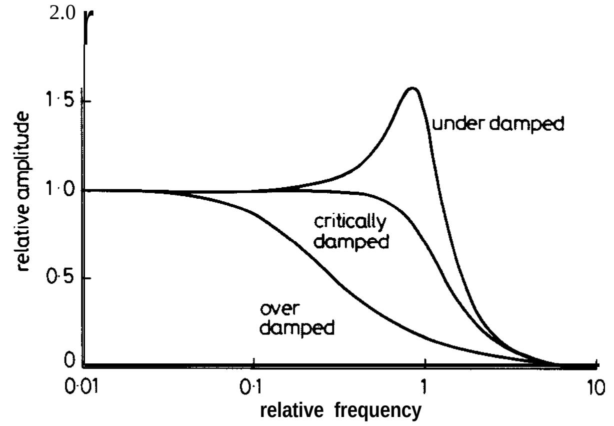


Fig. 5 Effect of self-resonance on high-frequency performance

Integration at high frequencies

The effect of slew-rate limitations on fast current edges has already been discussed. At frequencies approaching a few hundred kilohertz, bandwidth limitations of the operational amplifier used for integration become significant and active integration using a circuit such as the one shown in Fig. 2 can be difficult.

An alternative at higher frequencies is passive integration using a circuit as shown in Fig. 6. This is characterised by a time constant $\tau = CR$ and the output from the coil/integrator combination is given by eqn. 1. Using passive integration in conjunction with a 'low-output' coil it has been possible to measure current edges with a rise time of 0.5 μs.

Passive integrators should be used at frequencies much greater than $1/\tau$. If lower frequency components are present the waveform will be distorted, although a distorted waveform can sometimes be 'recovered' by operating on it mathematically Passive integrators are useful in applications where very large currents flowing for a few microseconds are measured.

Another approach to high-frequency integration is by operating the coil into a low impedance and using the inductance of the coil to perform a 'self integration'. The output signal is then a current rather than a voltage and the low-frequency limit is determined by the inductance and resistance of the coil, including any termination and sensing impedances. Coils operating on this principle have been used by the CEGB/National Power for monitoring discharge pulses in high-voltage insulation. They are capable of measuring currents in the frequency range 10 kHz-100 MHz.

Table 1: Resonant frequencies of some typical coil types

Coil type	Resonant frequency
Large cross-section solid coil	65 kHz
'Standard' flexible coil (600 mm long)	1 MHz
'Standard' flexible coil (300 mm long)	1.5 MHz
'Low output' flexible coil (730 mm long)	2.8 MHz

Pettinga and Siersema[7] have described integrator circuitry that combines all three methods described above to give a very wide bandwidth system.

Transient measurements

Rogowski coil transducers have several features that make them suitable for transient measurements.

Calibration

Most current transducers should be calibrated using a current level similar to the one being measured to avoid any problems with nonlinearities. With large transients calibration is difficult because the current levels may be much larger than any steady current that can be generated for calibration purposes. Rogowski coils don't suffer from this problem. Because they are linear they may be calibrated at any convenient current level and the calibration will be good for all currents including very large ones.

In some transient measurements the magnitude of the current is not known in advance. A Rogowski coil may be fitted with the confidence that it will be usable at any current level.

Physical characteristics

Rogowski coils are light-weight and compact compared with most other devices, particularly where high currents are involved. This has obvious advantages with transport and ease of installation but there are other, less obvious advantages.

Thin, flexible coils can be installed in awkward places and are far less likely than any other transducers to need any modifications to be made to the plant. They can usually be fitted at any convenient time prior to testing and left until required without affecting subsequent operation or maintenance. This contributes to increased flexibility in determining test schedules.

Another advantage was discovered during overload tests on the main output connections of a generator. The application of a sudden transient of 760 kA caused the test piece to leap into the air. The Rogowski coils jumped with it and were unharmed! A heavy current transformer or shunt would have caused considerable damage.

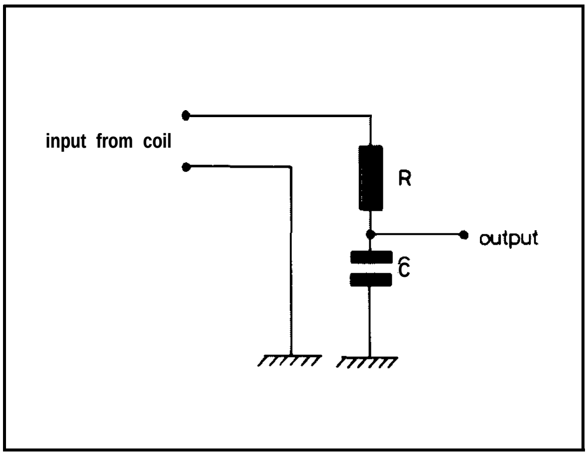


Fig. 6 Passive integrator

Preliminary testing

With some transient measurements, there is no opportunity to test the measuring equipment beforehand at full current and the ‘real thing’ may be too risky or too expensive to repeat. Because they are linear, Rogowski coils can be tested beforehand in the laboratory using a simulated waveform at a much lower current. If necessary, the sensitivity of the transducer can be temporarily increased. For example, the current waveform shown in Fig. 7 had a peak current of 200 kA with a rise time of a few microseconds. This was successfully simulated for preliminary test purposes using a current of less than an ampere from a pulse generator.

The two parts (coil and integrator) of the system can be tested separately if necessary. A voltage can be injected into the integrator to simulate the output of the transducer coil at full current to check for overloads and slew-rate limitations.

Offsets

Almost invariably, transients contain an asymmetrical component, or ‘DC offset. When measurements are made using current transformers, offsets cause temporary saturation and loss of information during the initial stages of the transient. This is well known with the use of current transformers (CTs) for protection(8) and, to minimise the effect, protection CT's are made extra large and sometimes a gap is introduced in the iron circuit. Rogowski coils do not suffer from saturation problems and, with the appropriate design of integrator, can reproduce asymmetrical transients accurately.

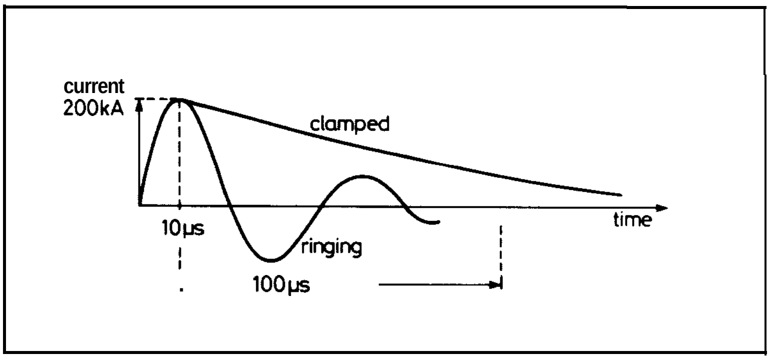


Fig. 7 Current waveform for lightning tests (courtesy of Lightning Test and Technology, Culham Laboratory)

Low-frequency performance

Any transient inherently contains frequency components lower than the fundamental frequency of the current being measured and where offsets are present they can decay with a long time constant. For example, the transient shown in Fig. 8 had an offset lasting for more than a second. Where necessary a Rogowski coil system can be designed to accommodate low frequencies; the integrators used for the measurements in Fig. 8 had a time constant of 100 s.

Comparison with other methods

Table 2 gives a summary of the characteristics of different measuring methods when used for large current transients such as a sudden short circuit test of a generator. The table is meant to give only a general indication as it is recognised that there are many variations for each transducer type which affect its performance.

Applications

Rogowski coils have found a large number of applications both inside and outside the power industry. This Section describes a number of these applications, concentrating on transient measurements.

Sudden short-circuit testing

This is a ‘type’ test applied to new generator designs. The generator is run open-circuit at about rated voltage and a three-phase short circuit is suddenly applied. Analysis of the resulting current transient provides essential information about the generator time constants and reactances.

Rogowski coils have been used to monitor these tests on ‘small’ 5 MW diesel generators and on a 300 MW pump-storage generator. The traditional method of monitoring short circuit tests is by using resistive shunts. These are extremely large; it is necessary to modify the generator copperwork to install them, and installation can take several days. The presence of the shunt can seriously restrict other construction work taking place at the same time. Instead Rogowski coils were fitted several weeks before the test was due. Installation time was short and there was no interference with other work being carried out on the generator. This gave substantial cost savings, provided greater flexibility in the timing of the test programme and provided high quality results. Fig. 8 shows one of the transients obtained.

Table 2: Comparison of different methods for measuring large transient currents

	Coaxial shunt	Current transformer	Hall effect device	Zero-flux Hall effect	Rogowski coil
isolation	🙁	🙂	🙂	🙂	🙂
Weight	🙁	😐	😐	😐	🙂
DC response	🙂	🙁	🙂	🙂	🙁
Low frequency resp.	🙂	😐	🙂	🙂	🙂
Fast current change	🙂	😐/🙂	😐	😐	🙂
Output	voltage	current	voltage	voltage	voltage
Ease of installation	🙁	😐	😐	😐	🙂
Cost	🙁	😐	😐	😐	🙂

Key: 🙁 = worst; 🙂 = best

Monitoring arc furnaces

The economy of an arc furnace is largely dependent upon exact adherence to the arc data. Rogowski coils have been used to measure the arc current as part of a system for determining arc resistance@. This enables the arc to be regulated so that it is always operating at its optimum and considerable economies are claimed resulting from the use of this system.

Rogowski coils were used in this application for many reasons, including their ability to measure very large currents at low cost, because they are compact and easy to install even on existing plant, and because they can cope with large current fluctuations.

Lightning test facility

The facility at Culham Laboratory uses lightning simulators to test the interaction of lightning with aerospace and ground structures. Simulated lightning is provided using a set of capacitor banks with a stored energy capability of 776 kJ which can be fired in sequence to provide a range of different waveforms. A typical waveform is given in Fig. 7, which shows a 200 kA oscillatory pulse having a risetime of 10 µs.

As part of the comprehensive monitoring associated with lightning tests it is necessary to measure the current flow along critical parts of the structure under test and Rogowski coils have been found very useful. A 'standard flexible coil with a mutual inductance of 200 nH could not be used in this application because of the large voltage that would be developed across the winding (more than 6 kV and the risk of insulation breakdown-Rogowski coils are normally thought of as safe, low-voltage devices! A special 'low output' coil has to be used.

Rogowski coils have been used in plasma physics applications for many years. An interesting variation in this context is the use of coils with a sine and cosine distribution of turns. This combination is used to find the position of the plasma current within the tube.

Monitoring weld quality

Precision welding systems are used in the production of devices such as barometric transducers, for sealing metal-package semiconductor devices and lithium batteries and in the production of relays. The welding current can be either a pulse from a capacitor or a short burst of alternating current. Seam welding uses a rapid sequence of single welds. In all cases precise control of the weld current is essential to ensure zero defects and to achieve high-quality, repeatable production.

Rogowski coils have been found to be ideal for this current-monitoring application on account of their superior transient capability and the ability of the flexible coils to adapt to the wide range of conductor sizes and shapes found in different welding systems. Fig. 9 shows a weld quality monitor which has recently been adapted to accept Rogowski-coil inputs. This monitors the current and voltage for each weld and computes a weld energy envelope. The envelope is compared with a standard energy envelope in real time and any weld which deviates significantly from the standard is logged and reported. In this way suspect welds can be eliminated and any gradual deviation of weld power can be detected and corrected.

Protection of slip-ring induction motors

Protecting and monitoring the rotor circuits of slip-ring induction motors was one of the first applications of Rogowski coils in the CEGB(9) Rogowski coils were

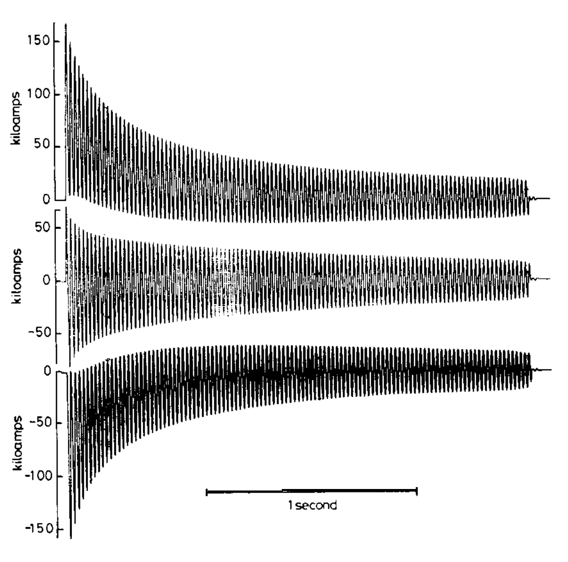


Fig. 8 Sudden short-circuit transients (courtesy of National Power)

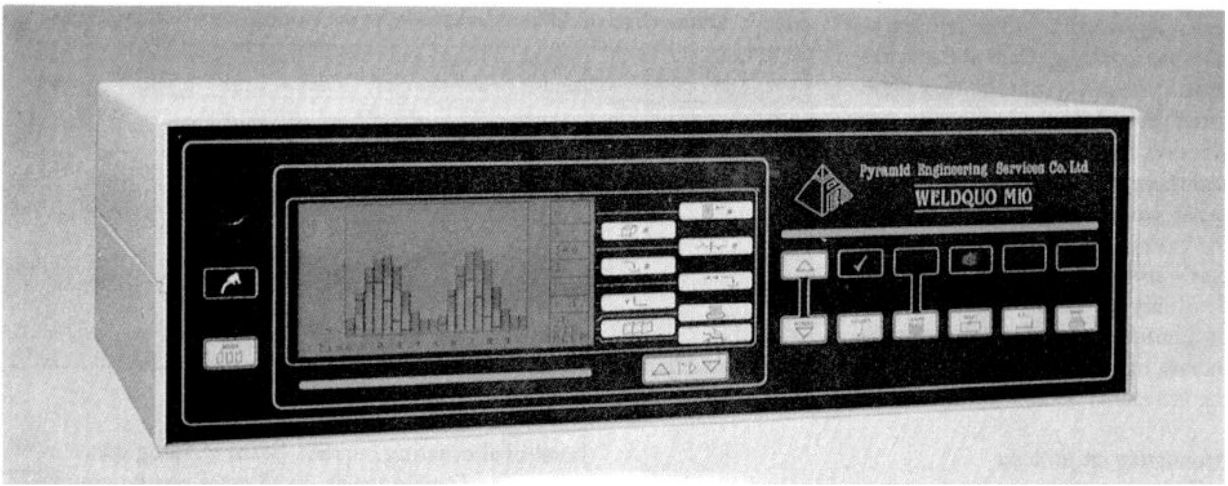


Fig. 9 Weld quality monitor (courtesy of Pyramid Engineering Ltd.)

used because of the requirement for a wide frequency range (<0.1 Hz to > 100 Hz) with transient DC offsets, and because coils could easily be made to have accurately matched outputs. Rogowski coils are useful in ‘high fidelity’ protection systems because a current transformer can be unreliable in the early stages of a transient.

High-precision solid coils were fitted on each of the three phases. These coils were matched to within less than 0.1% and by summing their outputs a sensitive earth fault protection was provided. The protection system was also capable of providing phase-unbalance protection, I^2t protection and overcurrent protection. Fig. 10 shows the coil installation on a power station boiler feed pump.

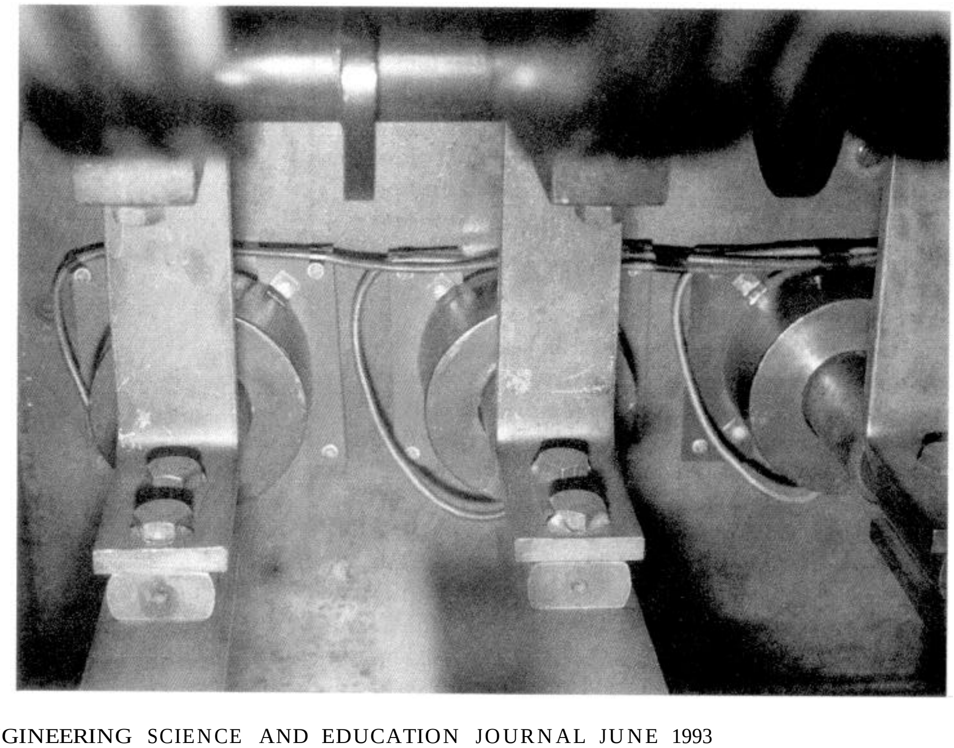
Electromagnetic launchers

Electromagnetic launchers are used for firing projectiles at very high velocities. They are being developed for use as weapons and for research into high-velocity impacts.

In the ‘rail gun’ configuration the projectile slides between two parallel rails (the barrel) and a very large current is passed along one rail through the projectile and down the other, thus providing a force to propel the projectile along the rail. The use of electrical propulsion means that a large amount of energy from an external store can be concentrated on the projectile and the force can be ‘profiled’ as the projectile travels along the barrel to achieve optimum launch conditions.

A description of the rail gun presently being installed at Kirkudbright is given in Reference 10. The current pulse is designed to peak at about 3.5 MA and will have a rice time of about 1 ms. Rogowski coils are a ‘natural’ component for measuring this type of current pulse on account of their good transient properties and their virtually unlimited high-current capability,

Fig. 10 Coils on a slipring induction motor (courtesy of National Power)



On-line insulation discharge monitoring

Discharge measurements are used as an on-line method of checking high-voltage insulation for incipient breakdown". The voltage stress across the insulation causes small electrical discharges in voids, delaminations and cracks. Analysis of the discharges gives a measure of the condition of the insulation.

Discharge currents take the form of pulses with a duration of a few tens of nanoseconds and an amplitude measured in milliamperes superimposed on several hundred amperes at 50 Hz. A Rogowski coil operating in the 'self integration' mode is a good transducer for this type of measurement and can be designed to totally reject the 50 Hz component. Rogowski-coils are frequently specified to be fitted on new motors and generators and commercial discharge monitoring systems are available (Fig. 11).

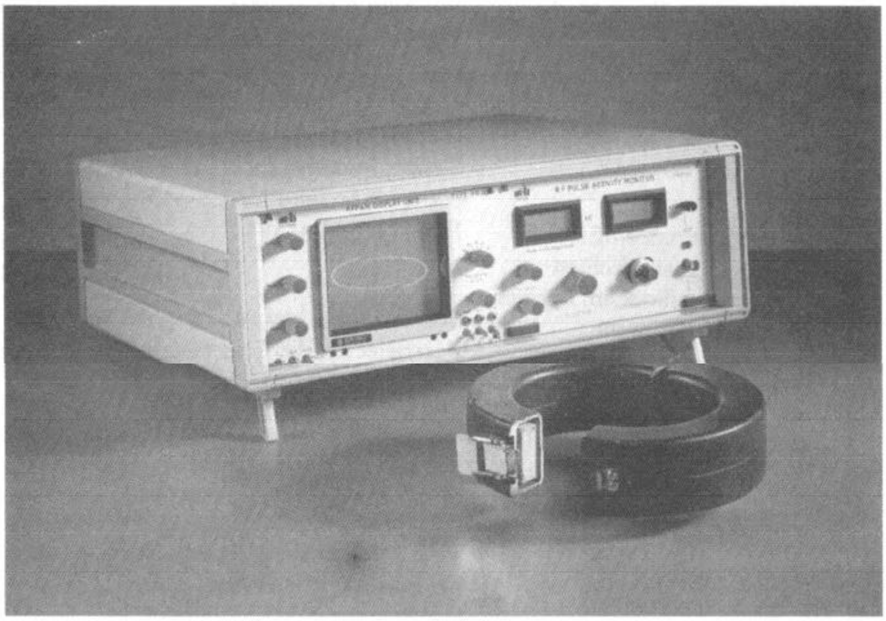


Fig. 11 Discharge monitor (courtesy of M&B Systems Ltd.)

Conclusion

Rogowski-coil current transducers can offer a very useful contribution to the art of measuring electric currents under difficult or unusual circumstances as well as for the more normal situations. A wider understanding of what they are and what they can do is obviously essential if their full potential is to be exploited and hopefully this article has made a contribution in that direction. The list of applications, which is not exhaustive, illustrates the large variety of measurement tasks that can be tackled with currents ranging from milliamperes to several million amperes. With wider knowledge of the technique the list is bound to grow!

Acknowledgments

Much of the development work on Rogowski coils was carried out by National Power plc. and the authors are grate&l to the Director of Engineering and Project Services for permission to include National Power material in this paper. Thanks are also due to Culham Laboratory, Pyramid Engineering Services Co. Ltd. and M+B Systems Ltd.

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