The effect of temperature on the output of a Rogowski coil measuring system

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Abstract

This paper describes the effect of temperature on measurements made using both rigid and flexible Rogowski coils. Temperature changes affect both types of coil by causing the coil former material to expand and by changing the resistance of the winding. With rigid coils it is possible to design a measuring system so that these two effects cancel each other out. With flexible coils, which are wound on a rubber-like former, the softness of the former makes a self-cancelling system more difficult to implement.

We describe a theoretical model which attempts to explain the consequences of increasing the temperature of a flexible coil. The effect of temperature on the output of the coil is shown to depend on the relationship between the cross-section of the wire used for the winding and the cross-section of the 'return conductor' along the centre of the coil. The theory has been compared with actual measurements on a range of different coil designs and shows broad agreement. Whilst the theoretical model suggests how a coil could be designed to minimise temperature effects there are other practical constraints which have to be taken into consideration and the paper also considers these.

Keywords Rogowski coil, mutual inductance, measurement, temperature.

List of symbols

A	cross-sectional area of a coil former.
A_0	initial cross-sectional area before a temperature change.
A_{cen}	cross-sectional area of the centre conductor of a flexible coil.
α	linear temperature coefficient of expansion of the coil former material.
β	temperature coefficient of resistance of the coil winding material.
C	integrating capacitance.
d	diameter of the winding wire conductor.
F	force on the winding wire.
γ	coefficient of volume expansion for the core material (flexible coil).
λ	insulation factor: wire diameter including insulation = λd.
I	current being measured by the coil.
L	length of a section of flexible coil.
M	mutual inductance of coil.
M_0	initial mutual inductance before a temperature change (Eq. 5).
μ_0	permittivity of free space.
n	turns density (turns/m).
n_0	initial turns density before a temperature change.
P	hydrostatic pressure in a flexible coil former.
R	input resistance of the integrator.
R_{coil}	resistance of the (copper) coil winding.
t	time.
T	temperature.
V_{coil}	voltage output from a coil.
w	radius of a flexible coil former.

1. Introduction

Rogowski coils are now widely used for electric current measurements in many applications ranging from power quality monitoring of buildings to the measurement of lightning strikes, very large currents in arc furnaces and switchgear testing. They have several advantages over conventional current transformers. For a conventional current transformer, however, the output depends only on the number of turns which is not a temperature-dependent quantity. With a Rogowski-coil measuring system, although more flexible in its use, the design makes the output sensitive to temperature changes which cause thermal expansion of the coil former and alter the resistance of the winding.

2. Coil Construction

The Rogowski coil is an ‘air cored’ toroidal winding placed round the conductor in such a way that the alternating magnetic field produced by the current induces a voltage in the coil [1]. Despite its name this technique was first described by Chattock in 1887 [2].

Rogowski coils are generally classed as either rigid or flexible. For a rigid coil the coil former is in the shape of a toroid made of a hard material such as plastic. There is a secondary winding over the main winding which acts as a 'reverse turn'. The main purpose of the reverse turn winding is to counteract the effect of interference from external magnetic fields. Rigid coils are frequently used for precision measurements.

With flexible coils the winding is placed on a flexible former, such as rubber, which is then bent round to form a toroid. The reverse turn takes the form of a central conductor along the axis of the coil. This also ensures that the external connections to the coil are at one end only. The central conductor performs a mechanical function in that it prevents the coil from stretching [7] and the properties of the central conductor are an important factor determining the thermal behaviour of the coil.

2.1 Measurement principle

The coil is effectively a mutual inductor coupled to the conductor being measured and the voltage output direct from the coil is proportional to the rate of change of current. The coil is designed to ensure that its output is not influenced significantly if the conductor is positioned ‘off-centre’. This design also ensures that the influence from currents and magnetic fields external to the coil is minimal.

The coil 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, has an accurate phase response and can measure complex current waveforms and transients. By varying the integration parameters (C and R) the sensitivity of the complete measuring system, measured in Amperes per Volt, can be varied over several orders of magnitude. 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.

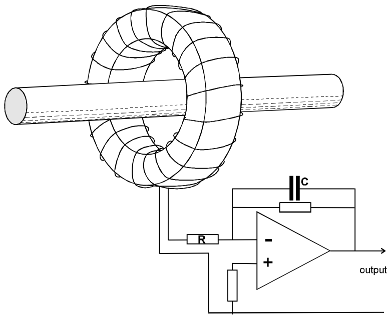

Figure 1. Schematic Arrangement of a Rogowski Coil and Integrator

The output of the coil is characterised by its mutual inductance (M) such that:

$$V_{coil} = M\frac{dI}{dt}. \qquad (1)$$

where I is the current in the conductor. The output of the integrator is given by:

$$\text{Output} = \frac{1}{C(R+R_{coil})}\int V_{coil}dt = \frac{M}{C(R+R_{coil})}I \qquad (2)$$

where R_{coil} is the resistance of the coil, R is the input resistance of the integrator and C is the integrating capacitance. The product $C(R+R_{coil})$ is the Time Constant of the integrator.

Equation 2 shows that the output of the integrator is proportional to the current but that the constant of proportionality contains four temperature-dependent components, M, R_{coil},R and C.

R and C are electronic components inside the integrator. They can be selected to have low temperature coefficients and their temperature-dependent properties are not the principal concern here. However the value of R has a profound effect on the temperature-dependent performance of the coil (section 3).

The mutual inductance of a coil (M) depends on its cross-sectional area and the turns density (turns per metre of coil). This is given by:

$$M = \mu_0 nA \qquad (3)$$

where n is the turns density, A is the cross-sectional area, μ_0 is the permittivity of free space. Both the turns density and the cross-sectional area are affected by thermal expansion.

The coil resistance (R_{coil}) is also temperature-dependent because coils are normally wound with copper wire and copper has a large temperature coefficient of resistance of about 0.39%/°C (3900ppm/°C) [3].

3. Resistance changes in the coil

This Section applies to both rigid and flexible coils which have copper windings. Coils with high-resistance windings which may have a lower temperature coefficient are not considered.

3.1 Theory

From equation 2 the output of the integrator is inversely proportional to the input resistance, $R + R_{coil}$. Compared with copper, R has a very low temperature coefficient of resistance, typically ±50ppm/°C, and for purposes of this analysis the value of R is considered to be constant.

If the temperature coefficient of R_{coil} is β the input resistance after a temperature change δT is:

$$R + R_{coil}(1 + \beta\delta T) = (R + R_{coil})(1 + \beta\frac{R_{coil}}{R+R_{coil}}\delta T) \qquad (4)$$

Equation 4 shows that the input resistance has an effective temperature coefficient of $\beta\frac{R_{coil}}{R+R_{coil}}$. The change in resistance of the coil is 'diluted' by the resistance, R, in series with it. In principle, by making R as large as possible the effective temperature coefficient can be made very small but, unfortunately, there are other constraints on the value of R which have to be taken into account. It is also possible to reduce the resistance of the coil by winding it on a smaller cross-section former with thicker wire but this gives a low mutual inductance (M) and is not always an option especially when low-current measurements are being considered.

The following Sections give some examples of situations where it is not possible to use a large input impedance to reduce the effective temperature coefficient of the coil because of other design constraints.

3.2 Low-current measurements

An integrator designed to measure low currents requires a low value for the time constant $C(R + R_{coil})$ (eq. 2). The value of C can be reduced but this will affect the performance of the integrator at low frequencies with respect to amplitude and phase response. Whether or not this is acceptable depends on the application but in many cases it becomes necessary to reduce the input resistance of the integrator with the consequent penalty of an increased temperature coefficient.

3.3 Coil resonance

Every Rogowski coil is subject to a self-resonance effect due to the self-inductance of the winding, the self-capacitance of the winding and the capacitance of the cable between the coil and the integrator. The resonant frequency depends on the type of coil and the length of the output lead and can vary from a few tens of kHz to several MHz depending on the coil design. At the resonant frequency the output of the coil can increase by a large factor and represents a serious source of inaccuracy.

For many applications the self-resonance of the coil is at a sufficiently high frequency to be of no consequence. For example this is usually the case with measurements at 50/60Hz and a few harmonics. In cases where the resonance is likely to be a problem it can be damped out by connecting a resistor across the coil output. With a correctly specified damping resistance the coil output as a function of frequency can be made flat up to near the resonant frequency. From experience damping resistors can be in the range from less than 100Ω to several kΩ and these are sufficiently low to have an appreciable effect on the temperature coefficient of the coil.

3.4 Interchangeable coil systems

The outputs of individual Rogowski Coils, even those made to the same specification, can vary by a few percent. To avoid having to re-calibrate the integrator if a coil needs to be replaced an 'interchangeable system' can be used. This requires the integrator to have a well-defined input impedance. Typical values are in the range 270Ω to 2500Ω.

It is not the intention here to give detailed numbers for the actual temperature coefficients of coil/integrator systems because these can vary over a very wide range depending on several design constraints. As a rough guide most coil resistances lie between 20Ω and 200Ω and input impedances are between about 270Ω and 2500Ω. The best and worst case temperature coefficients calculated from these numbers are -0.003%/℃ and -0.17%/℃.

4. Thermal expansion effects with rigid coils

4.1 Theory

Rigid coils are wound on a rigid, non-magnetic, toroidal former. The former material is usually a plastic such as Acrylic or a composite such as glass-reinforced epoxy. The winding rests on the surface and does not deform it as is the case with a flexible coil wound on a rubber former. The effect of temperature on rigid coils has been described previously [4 - 6] and is only reproduced here for completeness.

An increase in temperature causes the coil former to expand. This causes the cross sectional area (A in eq.3) to increase. If the coefficient of expansion of the former material is α the cross-sectional area for a temperature change δT is:

$$A = A_0(1 + \alpha\delta T)^2$$

Expansion of the former also affects the turns density because the circumference of the coil increases with temperature and the turns density (n in eq.3) will decrease in proportion to the length of the winding:

$$n = n_0/(1 + \alpha\delta T)$$

From Eq. 3 the mutual inductance, which is proportional to n x A, will have a coefficient:

$$M = M_0(1 + \alpha\delta T) \qquad (5)$$

A_0, n_0, and M_0 are 'zero temperature change' values for A, n and M

Using Equation 2 and substituting the temperature-dependent versions for mutual inductance (Eq.5) and resistance (Eq. 4) gives:

$$\text{output} = \frac{M_0(1+\alpha\delta T)}{C(R+R_{coil})(1+\beta\frac{R_{coil}}{R+R_{coil}}\delta T)} I \qquad (6)$$

For the special case where $\alpha = \beta\frac{R_{coil}}{R+R_{coil}}$ the output is independent of temperature. For this condition the quantity which is easiest to control is R and the condition becomes:

$$R = R_{coil}(\beta/\alpha - 1) \qquad (7)$$

Equation 7 can be satisfied provided $\beta > \alpha$. β for copper is approximately 0.39%/°C and is much higher than the temperature coefficient of expansion for Acrylic (about 0.0059%/°C), or any other material likely to be used as a former.

4.2 *Practical considerations*

4.2.1 Temperature compensation of rigid coils based on the theory of the previous Section has been in routine use on commercial coils for many years. In practice, however, the coefficient of expansion of plastic materials such as Acrylic is not well defined. It could depend, for example on whether the former is machined from a sheet or a rod and in some cases may be anisotropic. The best procedure is to heat the coil and make accurate measurements of the mutual inductance as a function of temperature (see Equation 5).

4.2.2 The theory assumes that the coil winding always stays in contact with the surface of the former. The expansion coefficient for copper is lower than most plastic materials so this is a good assumption for the case when the coil is heated above the temperature at which it was wound. When the coil is cooled the winding can become loose on the former and this could lead to some unpredictable results. To prevent this happening it is important to bond the winding on to the surface of the former so that it stays in contact even when the former is cooled.

4.2.3 As described in Section 3.3, a Rogowski coil is subject to a resonance effect and a damping resistance is needed across the output to give a flat frequency response. Unfortunately the resistance needed to give a flat frequency response is not the same as that needed to give a low temperature coefficient . Temperature-compensated coils are usually under-damped and show a resonance effect. It is possible that the situation could be improved by incorporating temperature-dependent resistors in the coil but this technique has not been explored to date.

4.2.4 It is a common situation for the coil temperature to be different from the integrator temperature. Coils are mounted on current-carrying conductors which are likely to be warmer than the surroundings. This compensation method does not need the coil and integrator to be at the same temperature. The resistor, R, in Eq. 7 is inside the integrator and its value is not altered significantly by temperature.

5. Thermal expansion effects with flexible coils

With flexible coils the winding can sink into a deformable surface and a simple analysis, as in Section 4 is not possible.

To tackle this situation we use a model of a flexible coil wound on a cylindrical rubber former with diameter 2w. The coil is close wound (turns touching) with an insulated copper wire diameter d. The diameter of the wire including insulation is λd where λ is the insulation factor.

Along the axis of the coil is the return conductor which is part of the Rogowski coil circuit. This serves three purposes (1) as a return conductor from the 'free end' of the coil, (2) to compensate the coil from pick-up due to external magnetic fields, and (3) to prevent the rubber core from stretching. The latter function is important because if a coil can be stretched easily the turns density (n in eq. 3) will be variable and this will affect the accuracy of the coil. [7]

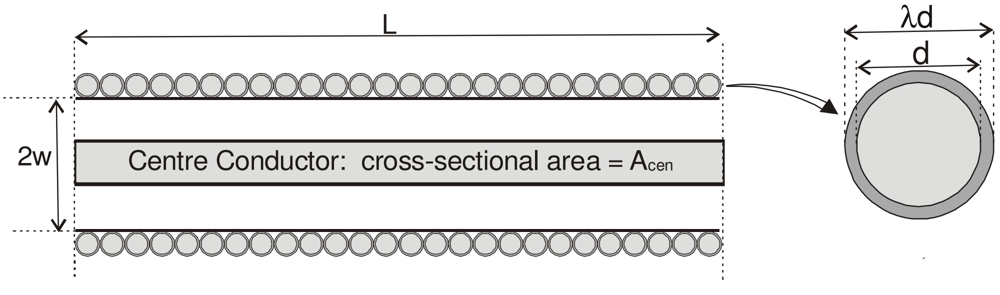

Figure 2. *Section of a flexible coil*

Figure 2 shows a section of coil of length L. The rubber former has a circular cross-section of diameter 2w. The coefficient of expansion of rubber is much higher than for copper. When the coil is heated and the former expands it will develop a hydrostatic pressure because it is restricted from expanding radially by the winding that surrounds it and it cannot expand axially because the return conductor prevents this. As the temperature increases the response of the coil follows a number of stages.

Stage 1 - Reversible

Initially the rubber can expand into the spaces between the windings. The extent to which this is possible depends on the diameter of the former (2w) and the diameter of the conductor (λd). If the conductor diameter is large there is more space between the conductors for the rubber to expand. If the diameter of the former is small there will be less rubber trying to expand into the space.

During this stage the mutual inductance of the coil does not change except for a negligible amount due to the thermal expansion of the copper. The ability of a coil to accommodate reversible expansion is proportional to the ratio (λd)/w (Appendix A). Coils with a high value for this ratio will keep a constant mutual inductance up to higher temperatures.

Stage 2 - Reversible

Once the possibility for expanding into the spaces has been exhausted there are two situations.

(a) The rubber can bulge out between the windings. This is more likely to happen when the coil is wound on a soft grade of rubber and when it is not covered by an outer layer of insulation. Figure 3 shows this happening. This effect, although it looks bad, may not actually affect the output of the coil seriously because the area of the turns and the average turns density has not been affected significantly. However, it will not be considered further.

Figure 3. *Coil former bulging out between the windings*

(b) With harder grades of rubber either the copper winding or centre conductor will stretch to accommodate the expanding rubber. Which copper component stretches will be determined later but the effect of stretching is to change the mutual inductance when the coil is hot. Provided the yield stress of the copper is not exceeded the coil will return to the original mutual inductance when it cools.

Stage 3 - Irreversible

Beyond the yield point of the copper the mutual inductance of the coil is permanently affected and does not return to its original value. Whether it is higher or lower than the original value depends on which copper component has stretched. If the centre conductor stretches the mutual inductance will be reduced because the turns density (n in eq. 3) is reduced. If the winding stretches the mutual inductance will increase because the area (A in eq. 3) is increased. Which one stretches depends on the relative strengths of the two components.

As the rubber temperature increases the expansion causes a hydrostatic pressure, P, which is resisted by the winding and the centre conductor. From Figure 2 for a length, L, of coil the total force on the winding wires is:

$$F = 2wLP \qquad (8)$$

The number of wires is $2L/\lambda d$ and the total area of copper is:

$$\text{copper area} = \frac{2L}{\lambda d} \times \frac{\pi d^2}{4} = \frac{\pi L d}{2\lambda}$$

The hoop stress on the copper (force /copper area) neglecting the insulation is:

$$\text{hoop stress} = \frac{4Pw\lambda}{\pi d} \qquad (9)$$

The axial force on the centre conductor is P x (cross-sectional area of rubber) = $P\pi w^2$.
If the centre conductor has a cross-sectional area A_{cen} the stress on the centre conductor is:

$$\text{centre conductor stress} = \frac{P\pi w^2}{A_{cen}} \qquad (10)$$

Assuming that both copper components have the same yield stress the condition for axial extension which will cause a reduction in mutual inductance is:

$$\frac{P\pi w^2}{A_{cen}} > 4\frac{Pw\lambda}{\pi d} \quad \text{or} \quad \frac{4\lambda A_{cen}}{\pi^2 wd} < 1 \qquad (11)$$

When this condition is not met the coil will expand radially and the mutual inductance will increase.

It is worth noting at this point that one way to prevent the expansion of the former material from stressing the copper components of the coil would be to use a former material which could absorb the pressure in some way. A practical difficulty with this approach is that the material would probably have a softer surface and it would become much more difficult to maintain a constant cross-section during the winding process. Although this technique is well worth pursuing it will not be considered any further here.

6. Experimental checks

6.1 Procedure

Measurements were made on a set of flexible coils wound using different former sizes and wire diameters to test the effect of heating them. Table 1 lists the coil characteristics.

Table 1. Characteristics of sample coils

sample number	former radius (w)	wire diameter (d)	central cond. area (A_{cen})	$\frac{\lambda d}{w}$	$\frac{4\lambda A_{cen}}{\pi^2 wd}$
1	1.65mm	0.224mm	0.75mm^2	0.1493	0.90
2	1.65mm	0.10mm	0.75mm^2	0.0667	2.03
3	3.5mm	0.224mm	1.0mm^2	0.0704	0.57
4	3.5mm	0.14mm	1.0mm^2	0.0440	0.91
5	3.5mm	0.10mm	1.0mm^2	0.0314	1.27

The quantity $(\lambda d)/w$ predicts the ability of the coil to recover reversibly after a temperature excursion. The larger the value the higher the temperature before the mutual inductance of the coil is permanently altered (see Stage 1 - Reversible).

The quantity $\frac{4\lambda A_{cen}}{\pi^2 wd}$ predicts whether the mutual inductance increases with increasing temperature (value > 1) or reduces with increasing temperature (value < 1) (See Stage 3 - Irreversible).

All the coils were close wound, i.e. with adjacent turns touching. Each coil was made to a length of 500mm. At the ends of each coil a small washer was soldered to the centre conductor to ensure that as the core expanded the rubber would not simply slide over the end (Figure 4).

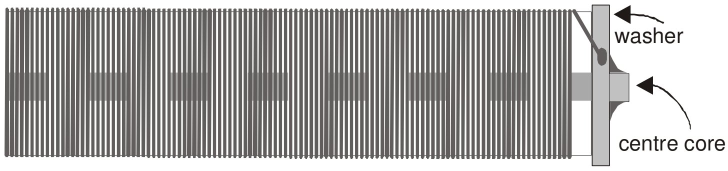

Figure 4. *Using a washer at the end of the winding to ensure that the coil former does not slide over the centre conductor.*

Mutual inductances were measured using a precision bridge developed by Rocoil Ltd. for their own use. This is capable of measuring mutual inductances to an uncertainty less than 0.1%.

The measurement procedure was as follows.

1) The coils were heat-treated for at least 1 hour at the specified temperature.
2) The coils were allowed to cool completely before being measured.
3) An accurate determination was made of the mutual inductance of each coil.
4) The length of each coil was measured with a steel ruler.
5) The resistance of each coil was measured with a digital multimeter.

The coils were then heated to successively higher temperatures and the process was repeated for each temperature. The highest temperature was 200°C.

For accurate mutual inductance measurements it is important that the ends of the winding are aligned correctly. The position of each end was marked with a piece of tape. As the heating sequence progressed the coils became increasingly 'distressed' and it became more difficult to determine exactly where the ends were! There is scope for improvement in this aspect of the experiment.

To measure their length the coils had to be straightened out. The coils were heated in a loosely coiled condition.

6.2 Mutual inductance measurements

The graphs in Figure 5 show mutual inductances measured after the coils had cooled back to ambient temperature. For each sample coil the mutual inductance was normalised to its initial value. The results are broadly in agreement with the predictions in Table 1.

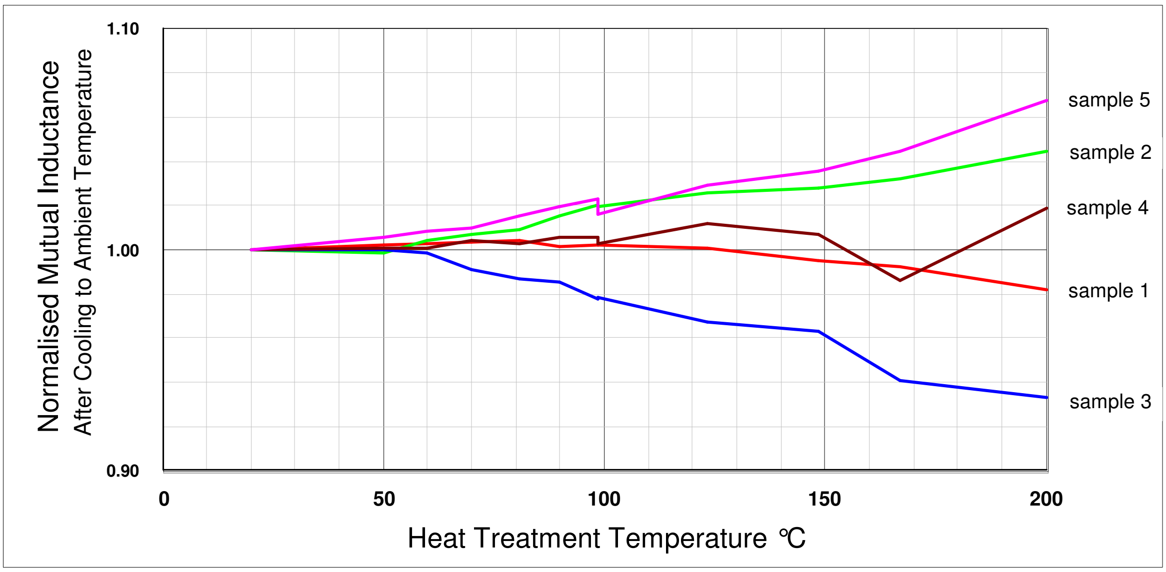

Figure 5. *Normalised mutual inductance measured at ambient temperature after the coil had been subjected to a series of increasing temperature heat treatments.*

Does the mutual inductance increase or decrease?
Column 6 in Table 1 lists the factor that determines whether the mutual inductance increases or is reduced as the heat-treatment temperature is increased.

Samples 2 and 5 showed a distinct increase in mutual inductance consistent with the factor being greater than unity.

Sample 3 showed a distinct reduction in mutual inductance consistent with the factor being less than unity.

Sample 1 showed a small reduction in mutual inductance consistent with the factor being only slightly less than unity.

Sample 4 had a factor slightly less than unity but its behaviour was indeterminate.

Up to what temperature does the mutual inductance remain constant?
Column 5 in Table 1 lists the factor that determines the heat treatment temperature up to which the mutual inductance is not permanently altered.

Sample 1 had the highest value for this factor and the mutual inductance was fairly constant for temperatures up to about 130℃.

Sample 5 had the lowest value for this factor and there was no discernable constant region for this coil.

6.3 Length and resistance measurements.

These measurements were made to support the conclusions for the mutual inductance measurements. If a coil shows a lengthwise extension (reducing mutual inductance) it was hoped that this length could be measured. For coils where the winding has stretched (increased mutual inductance) this should show as an increase in winding resistance. The results are tabulated below and give the final changes in resistance and length measured after the 200℃ heat treatment compared with the mutual inductance changes.

Table 2. Changes in Length, Resistance and Mutual Inductance after the final heat treatment.

sample number	resistance change	length change	mutual inductance change
1	-2.0%*	2.6%	-1.8%
2	4.5%	1.1%	4.5%
3	0.0%	7.2%	-6.7%
4	5.1%	3.3%	1.9%
5	8.3%	1.1%	6.8%

** NOTE: The negative resistance change in sample 1 needs an explanation! This sample had a low resistance (10Ω) which could not be measured accurately with the equipment available. It is a safe assumption that the resistance change was actually zero.*

The resistance and length changes agree, at least qualitatively, with the mutual inductance changes.

Samples 2 and 5 which showed a distinct increase in mutual inductance showed a large resistance change, indicating an increase in the diameter of the former, but only a small change in length.

Sample 3 which showed a distinct reduction in mutual inductance had a large increase in length consistent with this but no change in resistance.

Sample 1 had a small reduction in mutual inductance and a correspondingly small increase in length. The resistance change was probably zero. (see the note above).

Sample 4 had significant length changes and resistance changes. This indicated that it was showing signs of both increasing and decreasing mutual inductance at different times. This would explain the erratic mutual inductance graph.

7. Conclusions

1) Temperature changes can affect the output of a Rogowski coil measuring system. Thermal expansion of the former on which the winding is placed can alter the mutual inductance of the coil and changes in the resistance of the winding can influence the output when the coil is used with an integrator.

2) In the case of coils wound on a rigid former the temperature effects are reasonably straightforward to predict and it is possible to design a current-measuring system so that the expansion and resistance change balance each other giving a very low temperature coefficient for the measuring system.

3) For flexible coils, which are wound on a rubber-like former, the influence of temperature on the mutual inductance is more complex. It depends on the cross-sectional diameter of the winding wire as well as the cross section of the wire used along the centre of the coil to provide a return conductor.

4) For small temperature excursions the mutual inductance can change when the coil is hot but will return to its original value when the coil cools.

5) For larger temperature excursions the expansion of the former material causes either the winding or the centre conductor to stretch depending on which is the weaker. If the winding stretches the mutual inductance increases with increasing temperature. If the centre conductor stretches the mutual inductance reduces with increasing temperature.

6) Flexible coils which have small diameter winding wire and a large former cross-section are the most susceptible to temperature effects.

7) Measurements which have been made on the behaviour of flexible coils when they are heated are in broad agreement with the theoretical analysis.

8) In designing Rogowski coil measuring systems there is often a conflict between designing to achieve a low temperature coefficient and designing for a flat frequency response.

APPENDIX A. Reversible expansion.

This refers to Stage 1-Reversible (Section 5) where the rubber former of a flexible coil can expand into the spaces between the windings without actually stretching the copper winding or the central conductor.

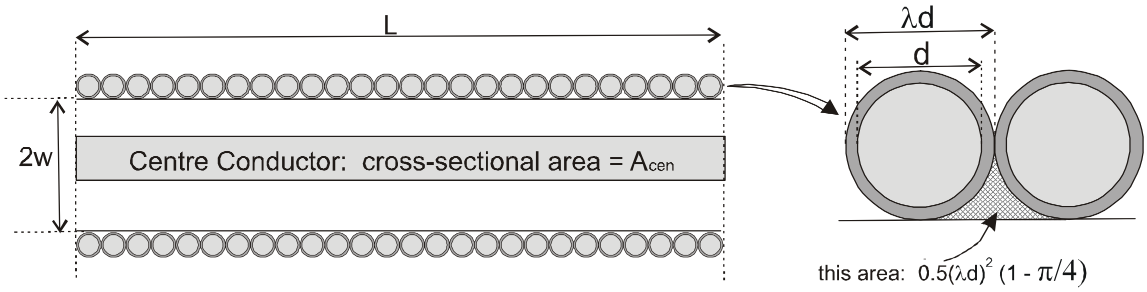

Figure 6. *Expansion of the rubber core between the windings*

Figure 6 shows that in a length of one turn pitch (λd) there is, potentially, an area between adjacent turns where the rubber core can expand.

(expansion area) = $0.5\text{x}(\lambda \text{d})^2(1-\pi/4)$ (A1.1)

The volume available for expansion = (expansion area) x (circumference of the former)

$$= 0.5\text{x}(\lambda \text{d})^2(1-\pi/4) \text{ x } 2\pi \text{w} \qquad \text{(A1.2)}$$

The volume of rubber core in the same pitch length is: $\pi w^2 \lambda d$ (A1.3).

For a temperature change, δT, the increase in volume of the core is

$$\pi w^2 \lambda d \gamma \delta T \qquad \text{(A1.4)}$$

where γ is the coefficient of volume expansion for the core material. The copper winding or the copper core will start to stretch for a temperature rise where the value of A1.4 exceeds the value of A1.2, or:

$$\delta T > \frac{\lambda d}{w\gamma}(1 - \pi/4) \qquad \text{(A1.5)}$$

This equation will not be very accurate because it is unlikely that the rubber will expand into all the corners of the volume available for expansion before the stresses on the copper winding and the central conductor become too large. Also the copper wire will have ‘bedded in’ to the rubber former, to some extent, due to winding tension. However, for a set of coils made with the same core material (γ is constant) the value of the factor $(\lambda d)/w$ is a useful figure of merit for determining the ability of a coil to recover reversibly after a temperature excursion. The larger the value the higher the temperature before the mutual inductance of the coil is altered permanently. This factor is given in Table 1 for the different coil samples. Samples 1 and 2, which had a smaller former radius, were wound on a different grade of silicone rubber so the comparison may not be exact.

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