

# High Performance Rogowski Current Transducers

W. F. Ray and C. R. Hewson  
Power Electronic Measurements Ltd.  
25 Barratt Lane, Attenborough, Nottingham  
NG9 6AD, U.K.

**Abstract** – A Rogowski current transducer is an invaluable tool for semiconductor and power electronic circuit development since it is non-intrusive and does not saturate at high currents. This paper reviews the operating principles, performance limitations and development of this measurement technology and outlines improvements to the integrator design that enables bandwidths of 10MHz to be achieved.

## I. INTRODUCTION

Compared with alternative transducers for current measurement such as CT's and Hall-effect, Rogowski transducers are relatively little known although interest in this method has grown substantially over the past decade.

Figure 1. shows a typical Rogowski transducer comprising a coil and an integrator unit with an inter-connecting co-axial cable. One end of the coil is inserted into a socket adjacent to the cable connection but can be unplugged for “clip around” use. The integrator is necessary since the coil provides a voltage proportional to the rate of change of measured current. The integrator output can be connected to an oscilloscope for monitoring the current waveform or to other equipment for control purposes.



Fig. 1. Rogowski transducer showing flexible coil, electronic integrator and interconnecting cable.

Rogowski transducers have the following features:

- Very high bandwidth enabling for example the measurement of switching transients in semiconductors
- Capability of measuring large currents. The same size coil can be used for measuring 100A or 100kA whereas other current transducers increase in size for increasing current magnitude.
- Non-saturation. The coil is not damaged by overcurrent.
- Isolation
- Ease of use. The coil can be relatively thin and flexible enabling it to be clipped around a conductor or current carrying device.
- Non-intrusive. There is no discernable loading of the circuit carrying the current to be measured and the injected impedance is typically a few p $\Omega$ .
- Very good linearity due to absence of magnetic materials.

The operating principle was formulated by Rogowski and Steinhaus [1] and is summarized by aid of Figure 2.

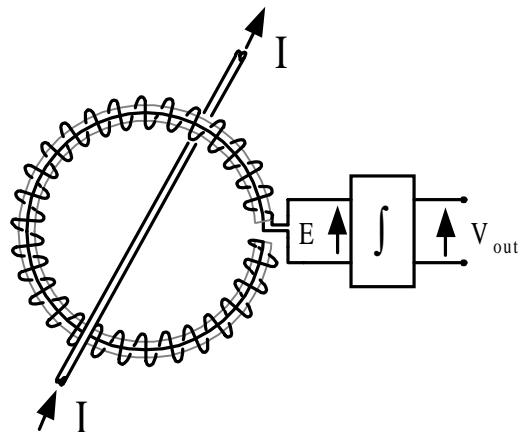


Fig. 2. Basic Rogowski Transducer

If a coil is evenly wound with  $N$  turns/m on a non-magnetic former of constant cross sectional area  $A$  m<sup>2</sup> then provided the coil constitutes a closed loop with no discontinuities it may be

shown that the induced voltage  $E$  is proportional to the rate of change of the encircled current  $I$ , i.e.

$$E = H \frac{dI}{dt} \quad (1)$$

where  $H = 4\pi \cdot 10^{-7}$  NA is the coil sensitivity (Vs/A). The coil loop does not need to be circular nor does the current need to be centrally situated. The coil is connected to an integrator, which may be passive or active or a combination of both. If the integrator has a time-constant  $T_i$  then the overall transducer gain is given by

$$V_{out} = R_{sh} I \quad (2)$$

where  $R_{sh} = H/T_i$  is the transducer sensitivity (V/A).

Due to the unavailability of suitable electronic integrators earlier publications [2 to 5] examined the behaviour of Rogowski coils with passive integration networks. This restricted the application of this measurement method to relatively short duration ( $<1\mu s$ ) current pulses. Electronic integration was first examined by Pettinga [6] in 1983 for currents up to 500kA with a 100kHz bandwidth. The first commercially available range of wide-bandwidth Rogowski transducers for general-purpose applications became available in 1992 from Power Electronic Measurements Ltd. and was reported in detail by Ray and Davis [8,9]. This range utilized the conventional inverting op-amp integrator circuit. Since then substantial improvements have been made [11] to the high frequency performance by using a non-inverting op-amp circuit and it is the purpose of this paper to report in more detail on these improvements.

A consequence of equation (1) is that Rogowski transducers cannot continuously reproduce the mean or dc component of the measured current. There is therefore a frequency  $f_A$  below which the transducer gain decreases. Furthermore there is an upper limit of frequency  $f_B$  above which gain decreases due to the inherent time delays in the coil and integrator as shown by Figure 3.

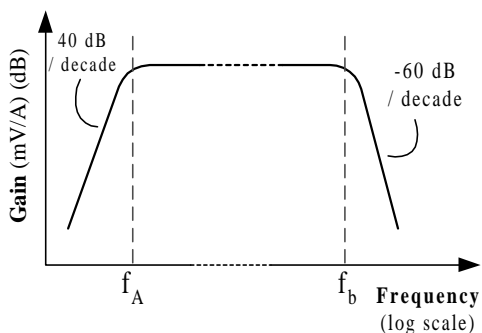


Fig. 3. Transducer sensitivity vs. frequency relationship

By “high performance”, as per the title of this paper, it is meant as high an upper limit  $f_B$  as possible in order to measure fast switching transients whilst retaining the capacity to accurately measure currents of 50/60Hz, which necessitates  $f_A$  around 1 Hz. A wide bandwidth of 7 decades of frequency is the aim. This imposes a significant difficulty for the integrator design since the integrator gain will change over this frequency range by the ratio  $10^7:1$ . Furthermore to achieve a high  $f_B$  it is necessary to utilize a low inductance coil whereas to limit low frequency noise a high inductance coil is preferable. The implications of these conflicting constraints are examined in the following section.

## II. ROGOWSKI COIL HIGH FREQUENCY BEHAVIOUR

The high frequency behaviour of the coil, in particular its bandwidth and susceptibility to high frequency oscillations, is significantly influenced by the termination impedance. It is also significantly influenced by whether or not the geometry is symmetrical. By symmetrical it is meant that the coil loop is circular and the current to be measured is centrally situated and perpendicular to the plane of the coil, and there are no other external currents close to the coil.

In simplified form the coil can be represented by the equivalent circuit shown in Figure 4, where  $L$  and  $C$  represent the distributed inductance and capacitance and  $R_d$  is the terminating resistance. (The series  $R_o$  is for integration purposes as discussed later). However the coil behaviour is considerably more complex than this model indicates.

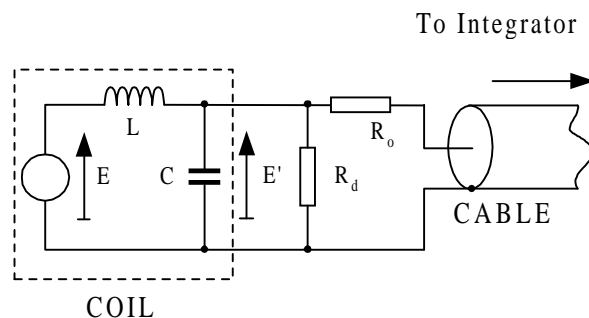


Fig. 4. Coil equivalent circuit with terminating resistance  $R_d$  and series resistor  $R_o$  ( $R_o \gg R_d$ )

Cooper [2] showed that for the symmetrical case the coil behaviour relating the coil terminal voltage  $E'$  to the measured current  $I$  at frequency  $\omega$  is equivalent to

$$\frac{E'}{I} = j\omega H F(\theta) \quad (3)$$

where

$$F(\theta) = \frac{1}{\theta \left( \cot \theta + j \frac{Z_0}{R_d} \right)} \quad (4)$$

and where

$$\theta = \omega \sqrt{LC}$$

$$Z_0 = \sqrt{L/C}$$

Ray [8] showed that for values of  $\theta \leq \pi/2$  (effectively the bandwidth of the coil unless  $R_d/Z_0 \ll 1$ ) the approximation  $\theta \cdot \cot \theta = 1 - (2\theta/\pi)^2$  enables  $F(\theta)$  to be simplified to

$$F(\theta) = \frac{1}{1 + \frac{j\omega L}{R_d} - \omega^2 LC'} \quad (5)$$

which is equivalent to Figure 3 with  $C$  replaced by  $C'$  where

$$C' = \left( \frac{2}{\pi} \right)^2 C \quad (6)$$

In order to provide the coil with appropriate damping, and taking a damping ratio of  $\xi = 0.5$  to be suitable, the corresponding termination resistance or damping resistance  $R_d$  is given [8] by

$$R_d = \sqrt{\frac{L}{C'}} = \frac{\pi}{2} \sqrt{\frac{L}{C}} \quad (7)$$

This value of  $R_d$  is higher than the characteristic impedance of the coil  $Z_0 = \sqrt{L/C}$  and, although it is arguable that the coil should ideally be terminated with  $Z_0$ , it has been found that (7) gives the better transient response for step changes in measured current.

However the analysis summarized above does not represent the majority of practical measurement situations using flexible Rogowski coils for which the coil is looped around a busbar or semiconducting device. In most cases the coil loop is not circular and the current is usually situated nearer to the part of the coil opposite to the cable termination.

Taking the extreme case of a concentrated current very close to a circular coil and at a relative position  $\lambda$  from the free end of the coil as shown in Figure 5, it may be shown that the corresponding  $F(\theta)$  is approximately given by

$$F(\theta) = \frac{F_n(\theta)}{\theta \left( \cot \theta + j \frac{Z_0}{R_d} \right)} \quad (8)$$

where

$$F_n(\theta) = \frac{1}{2} \left( 1 + \frac{\theta \cdot \cos(\lambda\theta)}{\sin \theta} \right) \quad (9)$$

which should be compared with (4).

This has important implications for the case  $R_d \ll Z_0$  as discussed in the next section.

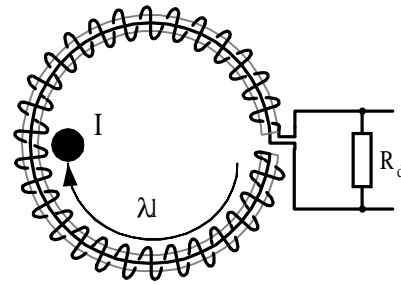


Fig. 5. Coil with closely adjacent source at position  $\lambda l$  from free end, where  $l$  = coil length

In most cases it is best to terminate the coil with a damping resistor  $R_d$  as given by (7). However consideration must be given to the effect of the co-axial cable connecting the coil to the integrator or monitoring equipment. The cable will have a characteristic impedance of typically 50 ohms which will be significantly different from the value of  $Z_0$  for the coil. It is not therefore possible to correctly terminate the coil with a damping resistor  $R_d$  at the integrator end of the cable and  $R_d$  must be fitted at the coil end. Furthermore the cable capacitance will substantially increase the effective coil capacitance and thereby substantially reduce the coil bandwidth. To avoid this effect a series resistance  $R_0$  (generally  $\gg R_d$ ) is connected at the coil end of the cable as shown in Figure 3. This resistor forms part of the integrator circuit as discussed later in this paper.

The bandwidth  $f_B$  of the coil may be represented by the natural frequency of the equivalent circuit of Figure 4, (i.e.  $\theta = \pi/2$ ), giving

$$f_B = \frac{1}{2\pi \sqrt{LC'}} = \frac{1}{4\sqrt{LC}} \quad (10)$$

To achieve a high bandwidth it is necessary to utilize a low inductance coil. Since the coil inductance  $L$  is related to the coil sensitivity  $H$  by

$$L = N_t H \quad (11)$$

where  $N_t$  is the total number of coil turns,  $H$  will be relatively small, necessitating a high gain integrator if low frequency currents are also to be measured.

To minimize the coil capacitance it is preferable to utilize a small diameter wire for the central return conductor in the coil as shown in Figure 2. Multi-layer coils will substantially increase coil capacitance in addition to coil inductance.

For a typical low inductance coil with  $H = 18 \text{ nVs/A}$ ,  $L = 18 \text{ } \mu\text{H/m}$ ,  $C = 50 \text{ pF/m}$ , the coil bandwidth is 8.3 MHz for a 1m coil or 16.6 MHz for a 500mm coil.

Figure 6 illustrates the theoretical high frequency behaviour of the coil (i.e.  $F(\theta)$ ) for the cases represented by

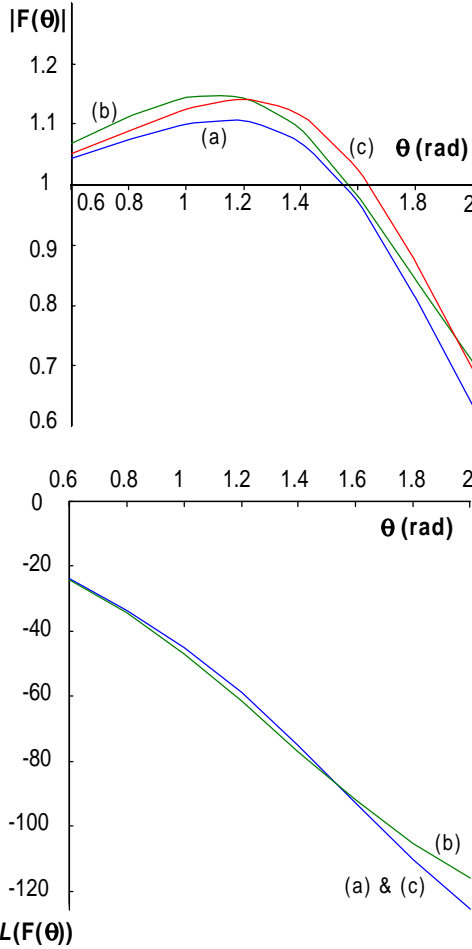


Fig. 6. Coil gain- frequency variation  $F(\theta)$  around upper frequency bandwidth limit for  
 (a) symmetric excitation  
 (b) linear model approximation for (a)  
 (c) concentrated excitation with  $\lambda = 0.5$  (see Fig. 5.)

equations (4), (5) and (8), with  $R_d = \pi \cdot Z_o / 2$ . Although inexact, the equivalent circuit of Figure 3 gives an adequate representation of high frequency performance.

### III. PASSIVE INTEGRATION

Figure 7. shows two alternative methods of passive integration.

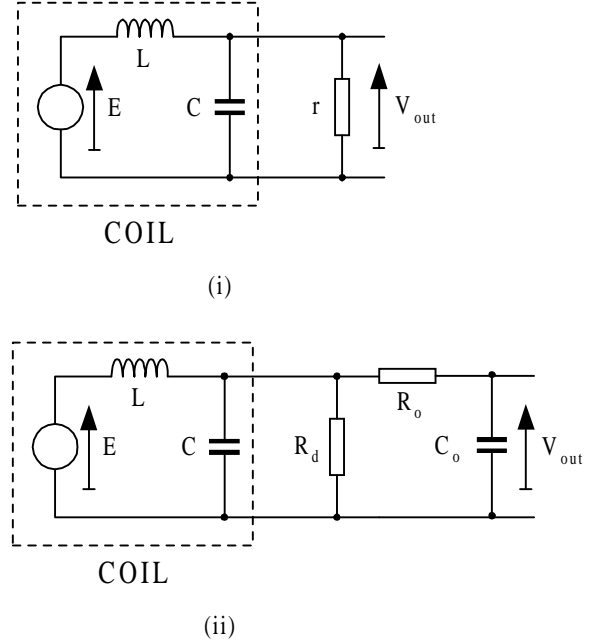


Fig. 7. Passive integration networks (i)  $L/r$  (ii)  $CR$

#### A. $L/r$ Integration

This is the method examined by many earlier publications such as [2, 4]. If the coil is terminated with a small non-inductive resistance  $r \ll Z_o$  as in Figure 7(i) then, at frequencies such that  $\omega L \gg r$ , the transducer gain is given by

$$\frac{V_{out}}{I} = j\omega H \frac{r}{j\omega L} = \frac{H}{T_i} = \frac{r}{N_t} \quad (12)$$

where the integration time constant  $T_i = L/r$ . The coil is then said to be self-integrating and effectively acts as a current transformer with turns ratio  $N_t$ . The low frequency bandwidth  $f_A$  is given by

$$f_A = \frac{1}{2\pi T_i} \left\{ 1 + \frac{r_c}{r} \right\} \quad (13)$$

where  $r_c$  = coil resistance. To obtain a reasonable sensitivity the low frequency bandwidth is usually at least several kHz so

passive integration is only applicable for relatively high frequencies (> 100kHz) or for short duration pulses (<5μs).

At high frequencies, for the symmetrical excitation case, equations (3) and (4) may be represented as

$$\frac{V_{out}}{I} = R_{sh} \frac{F_n(\theta)}{1 - j \frac{r+r_c}{Z_0} \cot \theta} \quad (14)$$

where  $R_{sh} = r/N_t$  and  $F_n(\theta) = 1$ .

For  $r+r_c \ll Z_0$ , except at frequencies for which  $\theta = \pi, 2\pi$  etc. when the gain drops sharply to zero, the transducer gain remains at  $r/N_t$  and extremely high bandwidths are feasible. Pellinen [4] reports a 0.3mV/A transducer for measuring mega-amp current pulses for which the coil has a rise-time of 2ns. This is only possible with a specially engineered symmetrical geometry and non-inductive termination resistor.

For the concentrated excitation case  $F_n(\theta)$  in equation (14) is  $\neq 1$  and is approx. given by (9). In this case the gain becomes theoretically infinite at  $\theta = \pi$  (or at  $\theta = 2\pi$  for  $\lambda = 0.5$ ). In practice this means the coil is susceptible to high frequency rings at frequency  $f = 1/(2\sqrt{LC})$  if the current to be measured, or any external current close to the coil loop, has transient changes.

For practical applications with a flexible coil  $L/r$  integration is not to be recommended unless the currents concerned are sinusoidal.

### B. CR Integration

The alternative method [2,3] of passive integration is shown in Figure 7(ii). Assuming that the coil is terminated with the appropriate damping resistance  $R_d$  and  $R_o \gg R_d$ , then

$$\frac{V_{out}}{I} = \frac{j\omega H \cdot F(\theta)}{1 + j\omega T_i} \quad (15)$$

where the integration time constant  $T_i = C_o R_o$ . For frequencies such that  $\omega T_i \gg 1$

$$\frac{V_{out}}{I} = R_{sh} \cdot F(\theta) \quad (16)$$

where  $R_{sh} = H/T_i$ . As for  $L/r$  integration, CR integration is only applicable for high frequency currents or short duration current pulses (the low frequency bandwidth is given by (13) with  $r_c = 0$ ). However CR integration does not inherently suffer from the high frequency rings described in section III.

## IV. ACTIVE INTEGRATION USING INVERTING OP-AMP

At low frequencies (50 or 60Hz) the coil voltage will be very small, typically several  $\mu V/A$ , unless a coil of exceptionally high sensitivity is used which will be large, cumbersome and expensive. Electronic integration is necessary.

Figure 8 shows the conventional inverting integrator used in conjunction with a Rogowski coil. The integrating resistor  $R_o$  is fitted at the coil end of the connecting cable to avoid cable capacitance reducing the coil bandwidth and the coil is appropriately terminated with  $R_d$  as discussed in section II.

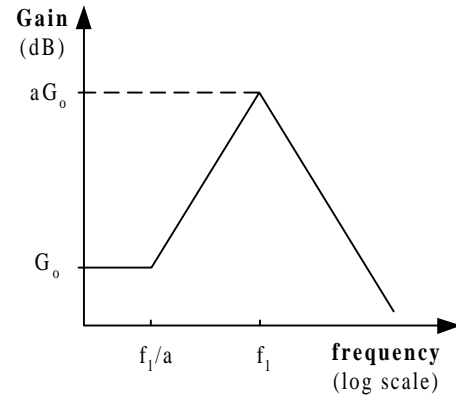
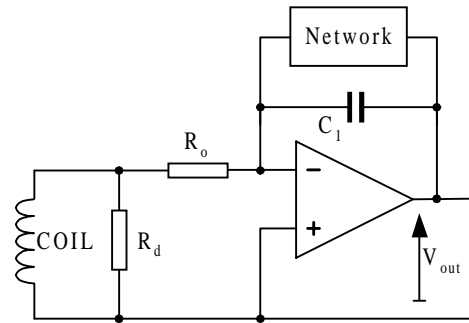


Fig. 8. Rogowski coil and integrator showing gain-frequency relationship for the integrator

The behavior of the non-inverting integrator has been examined in detail by Ray [9] so it will suffice to summarize the essential features, in particular the low frequency behaviour.

Since the integrator gain increases as frequency decreases, thereby amplifying the low frequency random noise and zero frequency offset drift, it is necessary to reduce the integrator gain for frequencies below which measurement accuracy is not affected. For measurement at 50Hz with phase displacement less than 1.5 degree a lower bandwidth  $f_\lambda$  of 1 Hz is appropriate.

Figure 8 also shows the integrator gain-frequency relationship. This is achieved by placing a low pass filter in parallel with the integrating capacitor  $C_1$ . For low frequencies the transducer gain is given by

$$\frac{V_{out}}{I} = \frac{R_{sh}}{(1 - jf_1 / f)^2} \quad (17)$$

The 3dB bandwidth  $f_A = 1.55f_1$ . Assuming the low frequency noise density ( $V / \sqrt{Hz}$ ) is inversely proportional to  $f$  (so called  $1/f$  noise) it has been shown [9] that the noise resulting from the gain-frequency relationship of figure 8, expressed as an equivalent measured current  $I_{n,rms}$ , is

$$I_{n,rms} = \frac{0.112k_n}{Hf_1} \quad (18)$$

where  $k_n$  (V) is equal to the noise density at 1Hz for the op-amp IC used. For a given coil  $H$  and op-amp  $k_n$ ,  $I_{n,rms}$  can only be reduced by increasing  $f_1$  which increases the phase lead at 50Hz.

For a high bandwidth coil of  $H=18nVs/A$ , a typical value  $k_n = 80nV / \sqrt{Hz}$  at 1Hz and  $f_1 = 0.5Hz$ ,  $I_n = 1.0$  A rms or approx. 6A pk-pk. This illustrates the limitations on Rogowski transducers for measuring small currents at 50 – 60 Hz whilst maintaining a high upper bandwidth. The noise can be reduced by utilizing a coil with a high sensitivity at the cost of reduction in high frequency bandwidth. As in all engineering systems, performance is a compromise.

The main disadvantages of utilising the inverting op-amp circuit of Figure 8 are high frequency rings and an opposite polarity pre-shoot which are superimposed on the output waveform following a transient change in measured current.

The oscillations are due to the interaction of cable dynamics and op-amp dynamics (including the open-loop output resistance of the op-amp) at frequencies above 1MHz.

For a simplified explanation of the pre-shoot effect consider a sudden change in measured current from zero to a high  $dI/dt$  ramp. The Rogowski coil output will provide a step voltage input  $E$  to the integrator op-amp circuit and, due to the finite time response of the op-amp, this step voltage will be passed via the integration capacitor  $C_1$  to the output. For a positive voltage step  $E=H (dI/dt)$  the integrator output will therefore initially take a positive value of  $V_{out}=(R_{out}/R_0).E$  where  $R_{out}$  is the op-amp output resistance. The normal integration behaviour will eventually follow giving a negative output of  $-H/(C_1R_0).I$ . The output therefore initially moves in the opposite direction to the subsequent output ramp.

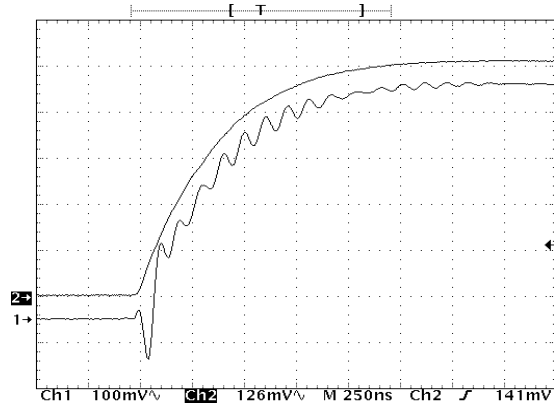


Fig. 9. Current transient showing pre-shoot for inverting integrator  
UPPER - Co-axial shunt measurement (2.5mV/A)  
LOWER - CWT measurement (2mV/A)

Figure 9 shows typical rings and pre-shoot for measurement of a 250A current pulse with an initial  $dI/dt$  of approximately 670A/ $\mu s$ . With  $H=68$  nVs/A,  $R_o = 20$  K $\Omega$  and  $R_{out} = 50\Omega$  the predicted pre-shoot is 112 mV.

In order to reduce the magnitude of the rings and pre-shoot a filter may be included at the transducer output but this significantly reduces the bandwidth which could otherwise be achieved. These disadvantages can be avoided by using a non-inverting integrator as shown below.

#### V. ACTIVE INTEGRATION USING NON-INVERTING OP-AMP

The transducer circuit utilising a non-inverting op-amp is shown in Figure 10. At high frequencies the integration is achieved by the passive  $R_0C_0$  network and since  $1/(\omega C_1) \ll R_1$  the op-amp behaves as a unity gain amplifier (which is a less demanding task than integrating). At low frequencies for which  $1/(\omega C_0) \gg R_0$  the passive  $R_0C_0$  network has unity gain and the integration is achieved by the op-amp with an integration time constant of  $R_1C_1$ .

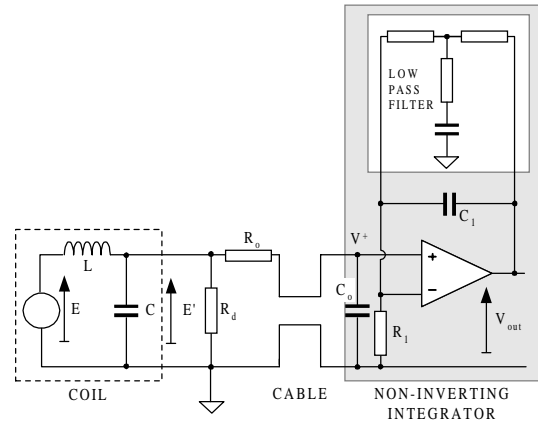


Fig. 10. Transducer with non-inverting integrator

The non-inverting integrator has the advantage that there is no capacitive coupling from the non-inverting input to the output and therefore the preshoot effect and the requirement for an output filter are eliminated. Furthermore the dynamics of the cable and  $R_oC_o$  network are de-coupled from the op-amp dynamics by the high input impedance of the op-amp and the mechanism for oscillations is thereby avoided provided care is taken to properly terminate the coil and the cable [12].

For a constant transducer sensitivity over the operating frequency range it is necessary to match the passive and active integrator time constants. The overall integrator transfer function is given by

$$\frac{V_{out}}{E'} = \frac{(1 + T_i s)}{T_i s(1 + T_o s)} \quad (19)$$

where  $T_i = C_i R_i$ ,  $T_o = (C_o + C_a).R_o$  and  $C_a$  is the cable capacitance. By arranging that the time constants match ( $T_o = T_i$ ) the desired relationship is obtained, i.e.

$$V_{out} = \frac{1}{T_i} \int E' dt \quad (20)$$

The use of a non-inverting integrator has previously been examined by Pettinga [6] but the system he describes has several significantly disadvantages:

- (i) It utilises three stages of integration (two passive, one active) which requires the accurate matching of two sets of time constants and is therefore difficult to set-up and calibrate.
- (ii) The top frequency range utilises L/r integration, which as explained above is prone to high frequency oscillations.
- (iii) As a result of using L/r integration the Rogowski coil is not correctly terminated.
- (iv) For the circuit used it is not possible to correctly terminate both the coil and the connecting cable (which have widely differing characteristic impedances).
- (v) It was only designed for a bandwidth of 100kHz.

At high frequencies approaching the transducer bandwidth the coil behaviour is influenced by the relative position of the measured current, which will vary with use, and therefore, since an exact representation is not possible, the equivalent linear  $F(\theta)$  is adequate. The op-amp acts as a unity gain amplifier with an equivalent simple time delay  $T_b$ . The high frequency transfer function may therefore be approximated by

$$\frac{V_{out}}{I} = \frac{R_{sh} \cdot e^{-T_a s}}{(1 + 2\xi T_c s + T_c^2 s^2)(1 + T_b s)} \quad (21)$$

where  $R_{sh}$  is the nominal sensitivity

$T_a$  represents the transit delay for the coaxial cable  
 $T_b = 1/(2\pi \times \text{gain-bandwidth})$ , e.g. 10ns for 16MHz.  
 $T_c$  is the equivalent coil delay =  $\sqrt{LC}$  (see (6)).

The coil termination is preferably set to provide an equivalent damping ratio of approx.  $\xi=0.5$ .

## VI. TEST RESULTS AND CONCLUSIONS

### A. L/r integration

To demonstrate the limitations of a self-integrating Rogowski coil a 730mm coil with 3000 turns was used for measuring a current rise  $I = I_1 \{1 - \exp(-t/\tau)\}$  where  $\tau = 0.45 \mu s$  in comparison with measurement by a high frequency Pearson CT as shown in Figure 11. The current position was close to the coil at the opposite end to the cable junction (ie  $\lambda=0.5$ ). The coil had a relatively high inductance  $L = 200 \mu H$  and low frequency bandwidth  $f_A = 60.7 \text{ kHz}$ , with a sensitivity  $R_{sh} = 17 \text{ mV/A}$  and  $\sqrt{LC} \approx 86 \text{ ns}$ . Oscillations occur at approx. the predicted value  $(1/(2\sqrt{LC}))$  of 5.8 MHz. The measurement droop is due to the relatively high value of  $f_A$ .

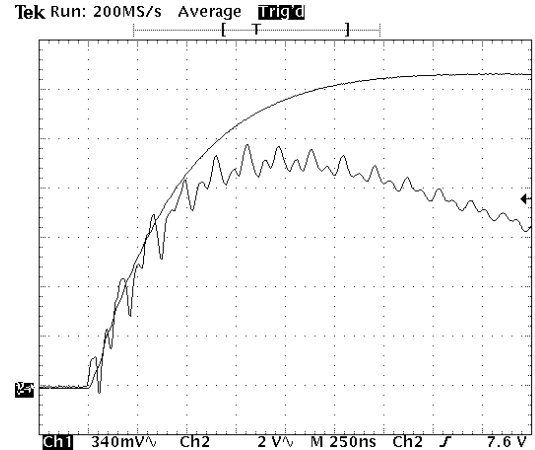


Fig. 11 Measurement of current step (20A/div) using Pearson CT (UPPER) and self-integrating Rogowski coil (LOWER)

### B. Combined Passive and Active Integration

Figure 12(a) shows comparative measurements of a  $17 \mu s$  1440A peak current pulse using a CWT30 Rogowski transducer and a 20MHz Pearson CT. The measured waveforms closely match. In Figure 12(b) the falling edge is expanded to 100ns/div showing the CWT30 measurement delayed by approx. 25ns compared with the CT. The CT was connected to the recording oscilloscope by the same length coaxial cable (2.5m) as that connecting the coil to the integrator .

The cable delay  $T_a$  (see transfer function (21)) is therefore cancelled in the comparison.

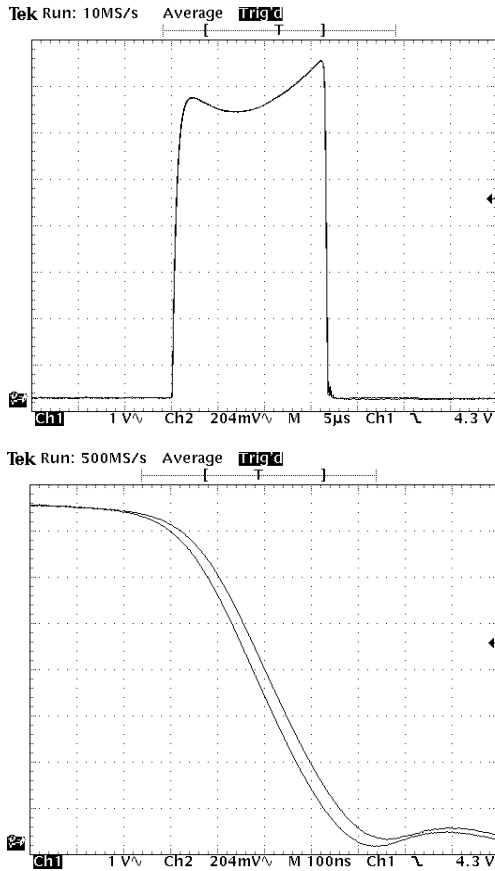


Fig 12. Measurement of current pulse (200A/div)  
**Ch1.** 20MHz C.T.      **Ch 2.** CWT30 (Rogowski)  
 (a) TOP : showing superimposed waveforms at 5µs/div  
 (b) BOTTOM: showing expanded falling edge 100ns/div

The CWT30 is of the type described in section V and figure 10, and has a 530mm coil with an equivalent delay  $T_c \approx 11$ ns estimated from known values of the coil inductance and capacitance. The integrator op-amp has a 16MHz gain-bandwidth corresponding to  $T_b = 10$ ns. For the equivalent transfer function (21) the delay for the current ramp is  $2\xi T_c + T_b$  which with  $\xi \approx 0.55$  gives an expected delay of approx. 22ns. There is an additional delay of 2.5ns for the cable connecting the integrator to the oscilloscope. The measured delay therefore approximately correlates with expectations assuming the delay for the CT is negligible.

The corresponding 3dB bandwidth for the transducer is 14MHz which is significantly higher than claimed. At present PEM does not have sinusoidal current sources of sufficiently high frequency to verify the bandwidth. Tests by injecting a voltage signal directly into the coil have been reported in [11].

Nevertheless it has been demonstrated that by correctly terminating the Rogowski coil very high frequency performance can be achieved without incurring oscillations inherent in the self-integration coil behaviour.

Figure 13 shows comparative measurements of the same current pulse using a LEM-flex Rogowski transducer. The LEM-flex utilises a much higher inductance lower bandwidth coil as seen by the oscillations on the waveform at 300kHz.



Fig. 13. Measurement of current pulse (200A/div)  
 UPPER: LEM-flex;      LOWER CWT30

In conclusion a very satisfactory performance has been achieved in practice. However modelling and testing the high frequency performance is very difficult. It is hoped to make further progress in these areas and to report further in due course.

#### REFERENCES

- [1] Rogowski, W and Steinhaus, W: Die messung der magnetische spannung, Arch Electrotech 1, pp.141-150, (1912)
- [2] Cooper, J: On the high frequency response of a Rogowski coil, Journal of Nuclear Energy, Part C, Vol 5, pp.285-289, (1963)
- [3] Thomas, R T: High impulse voltage and current measurement. IEEE Trans, Vol IM-19, No 2, pp.112-117, May 1970
- [4] Pellinen, D G and Spense, P W: A nano-second rise time megampere current monitor. Rev Sci Instrum, Vol 42, No 11, pp.1699-1701, May 1971
- [5] Stygar, W and Gerdin, G: High frequency Rogowski coil response characteristics, IEEE Trans, Vol PS-10, No 1, pp. 40-44, March 1982
- [6] Pettinga, J A J and Siersema, J: A polyphase 500 kA current measuring system with Rogowski coils, IEE Proc, Vol130, Pt B, No5, pp. 360-363, Sept 1983
- [7] Ray, W F and Davis R M: Improvements in current measurement, GB Patent 2259150 filed 28.8.91
- [8] Ray W F and Davis R M: "Wide bandwidth Rogowski current transducers: Part 1 – The Rogowski coil", EPE Journal, Vol 3, No 1, pp51-59, March 1993
- [9] Ray W F and Davis R M: "Wide bandwidth Rogowski current transducers: Part 2 – The Integrator", EPE Journal, Vol 3, No 2, pp116-122, June 1993
- [10] Ward D A and J La T Exon: "Using Rogowski coils for transient current measurements" IEE Science and Engineering Journal Vol 2 No 3 June 1993
- [11] Ray W F and Davis R M: "High frequency improvements in wide bandwidth Rogowski transducers", EPE 99 Conference Proc., Lausanne. Sept 1999.
- [12] Ray W F: "A current measuring device" International Patent Application WO99/54740 published 22.8.99.