High Frequency Improvements in Wide Bandwidth Rogowski Current Transducers

W.F. Ray & R.M. Davis
POWER ELECTRONIC MEASUREMENTS LTD.
143 Attenborough Lane, Attenborough, Nottingham
NG7 6AA, U.K.
Tel: +44 115 925 4212 Fax: +44 115 967 7685
Email: pemltd@proweb.co.uk
URL: http://www.proweb.co.uk/~pemltd

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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 outlines improvements to the integrator design which enables a bandwidth of 7MHz to be achieved.

Introduction

Two years ago the authors published [1] details of improvements to Rogowski current transducers, in particular the extension of the ranges of coil length, current and voltage ratings and the extension of low frequency bandwidth to enable current pulses of relatively long duration to be measured. The paper also provided details of accuracy and linearity. At the time the high frequency bandwidth was limited to approx. 1.5 MHz, not so much due to the coil and integrator dynamics but by the addition of an output filter to reduce the effect of high frequency oscillations and pre-shoot.

The main difficulty in achieving a wide bandwidth is the conflicting constraints on the coil for operation at very low or very high frequencies. The coil output voltage is proportional to the rate of change (dI/dt) of the current being measured and hence the voltage is very small (typically a few mV) at low frequencies. To achieve a high bandwidth the coil sensitivity (mV/A) needs to be relatively low so as to minimise the coil inductance. However, to measure low frequency currents of modest amplitude the coil sensitivity needs to be relatively high so as to minimise the low frequency gain required from the integrator and the related low frequency noise. The design of a suitable electronic integrator, which could operate from a relatively low sensitivity coil, whilst limiting the dc offset drift and low frequency noise to an acceptable level, was reported by the authors [2,3] in 1993. A conventional inverting integrator circuit was used with a low-noise op-amp IC and with a low pass filter in parallel with the feedback capacitor.

A fundamental disadvantage of the conventional inverting integrator circuit is that with an abrupt change of dI/dt, such as when a semiconducting device is turned on or off, the transducer output shows a transient pre-shoot which can be followed by oscillations or rings. This behaviour is further examined in section 3. In practice it was necessary to include a filter to reduce the magnitude of the pre-shoot and rings but this filter also had the effect of significantly reducing the high frequency bandwidth that could otherwise be achieved.

The main purpose of this paper is to investigate the use of a non-inverting integrator in place of the more typical inverting integrator. As a result the pre-shoot effect and the need for an output filter are eliminated and the high frequency performance is substantially improved, giving a bandwidth of 7MHz. Practical results showing this improvement are presented.

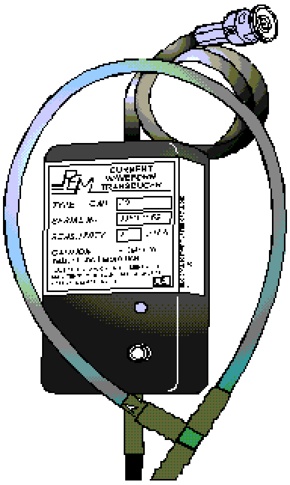

Figure 1: Rogowski current transducer

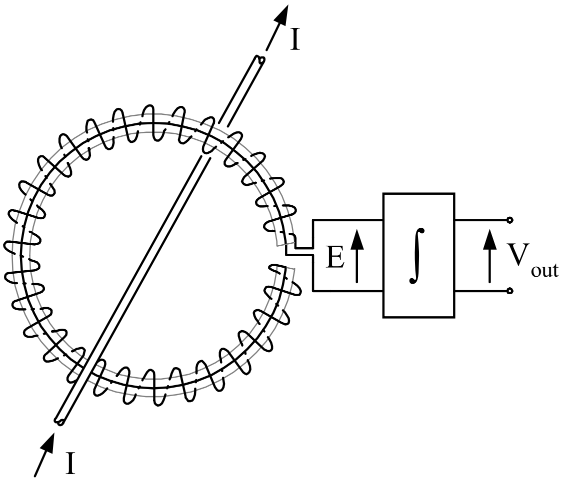

Figure 2: Schematic Rogowski current transducer

Basic Operation

A typical Rogowski transducer is shown in Figure 1 and its basic circuit in Figure 2. Its principle of operation has been well-publicised [1-3] and only a brief summary is provided. If a uniformly wound coil (N turns/m) on a non-magnetic former of constant cross-sectional area (A m²) is formed into a closed loop then the voltage e induced in the coil is given by the equation

$$E = \mu_0 N A \frac{dI}{dt} = H \frac{dI}{dt} \tag{1}$$

where H (Vs/A) is the coil sensitivity
I is the current to be measured passing through the loop.

To reproduce the current waveform as an analogue voltage signal, means for accurately integrating the coil voltage is required. Previously a conventional single-ended inverting operational amplifier has been used for the integration with an additional low pass filter network in parallel with the integration capacitor as shown in Figure 3 in which L and C represent the distributed coil inductance and capacitance respectively. The filter reduces the gain at frequencies below the transducer bandwidth (typically 0.5Hz) so as to limit the low frequency noise and direct voltage offset drift. The low frequency behaviour has been extensively reported [1,3] and is not further examined in this paper. The resistor R_d ($\approx\sqrt{(L/C)}$) provides appropriate damping for the coil.

For frequencies within the bandwidth of the transducer E=E' and the integrator behaviour is given by

$$V_{out} = -\frac{1}{C_1 R_0} \int E.dt = -R_{sh}.I \tag{2}$$

where $R_{sh}=H/(C_1R_0)$ is the transducer sensitivity.

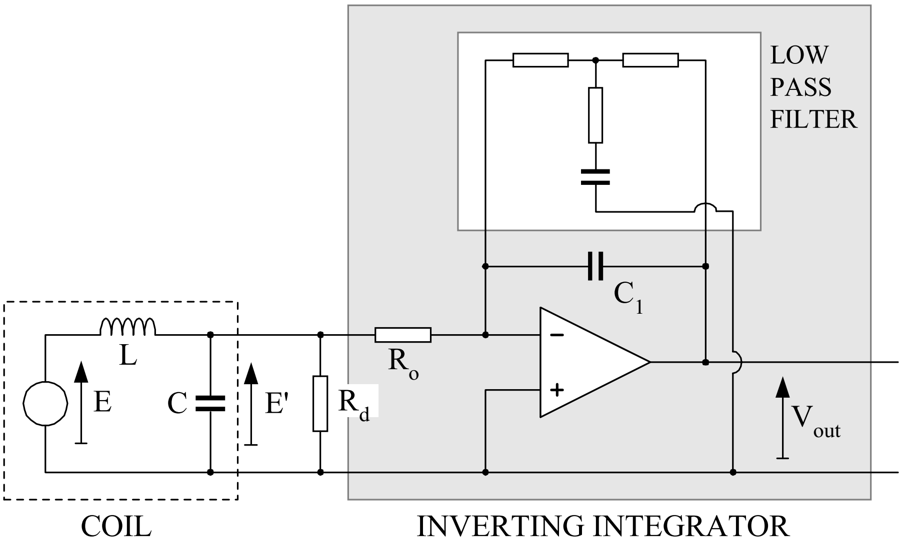

Figure 3: Transducer with inverting integrator

Pre-shoot and Rings

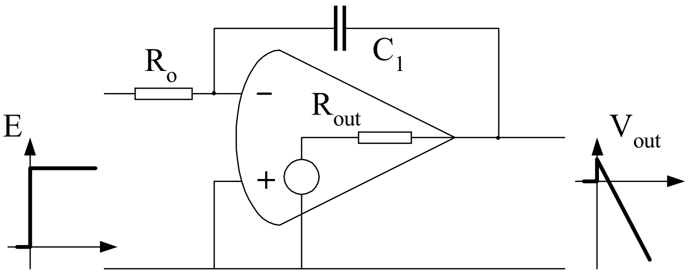

Figure 4: Pre-shoot effect using inverting integrator

A simplified explanation of the pre-shoot effect is illustrated in Figure 4. 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 to the integrator op-amp circuit and, due to the finite time of 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 approximately given by

$$V_{out} = \frac{R_{out} E}{R_0} \tag{3}$$

Once the op-amp responds the normal integration behaviour will follow eventually giving a negative output of $-H/(C_1 R_0).I$. The output therefore initially moves in the opposite direction to the subsequent output ramp as shown.

Figure 5 shows measurements of the rising edge of a 250A current pulse. The initial dI/dt is approximately 670 A/µs and the coil sensitivity 68 nVs/A giving an initial voltage step E of 45V. With an integrator resistor $R_0 = 20K\Omega$ and an output resistance $R_{out} \approx 50\Omega$, equation (2) predicts a pre-shoot of 112mV corresponding to 56A. Due to other system dynamics there is a slight filtering effect and the pre-shoot shown on the lower trace is approximately 95mV. The trace also shows 10MHz oscillations due to imperfect terminations of the coil and the cable connecting the coil to the integrator. It will also be seen that the measurement delay, relative to the co-axial shunt, is very small – of the order of 20ns.

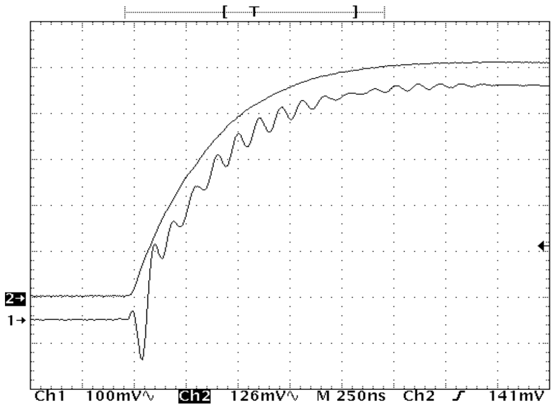

Figure 5: Current transient showing pre-shoot
Upper – co-axial shunt measurement (2.5mV/A)
Lower – CWT measurement (2mV/A) using inverting integrator with no output filter

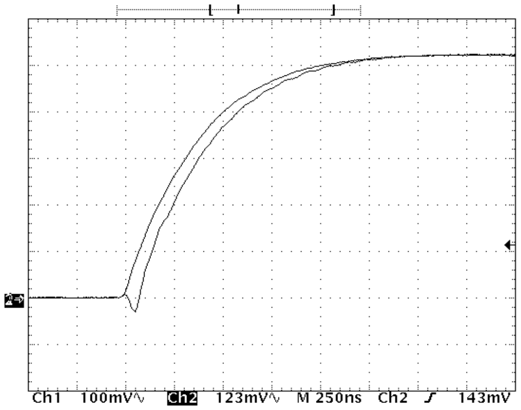

Figure 6: Measurement of current transient as Fig. 5. but including 75ns output filter

Figure 6 shows the effect of introducing an R-C output filter of approximately 75ns. The oscillations are largely eliminated and the pre-shoot is substantially reduced. In this case the zero levels for the two traces are co-incident so that the measurement delay is more readily seen. This has increased to nearly 100ns, as would be expected.

The inclusion of an output filter restricts the bandwidth to approx. 1.5MHZ, mainly due to the filter delay. Without the filter the bandwidth is only limited by the coil dynamics and the gain-bandwidth of the integrator IC and a significantly higher bandwidth can be achieved as shown in the next section.

Passive Integration

If the transducer is only required to measure small duration pulses (e.g. < 1 μs) or high frequency currents (e.g. > 100 kHz) a passive integration network can be used. Two alternatives are shown in Figure 7.

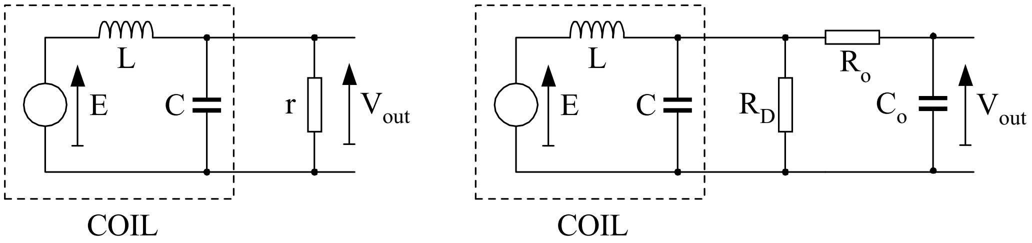

Figure 7: Passive integration networks

For Figure 7a the coil is terminated with a relatively low value resistor r. Superficial analysis indicates that, for frequencies $\omega > r/L$, $V_{out} = (r/N_t).\ I$, where N_t is the total number of coil turns. The upper frequency limit is $\omega < (1/(Cr))$, where C is the equivalent capacitance [2] for the coil, and since Cr is typically less than 1ns this apparently gives almost unlimited bandwidth.

The disadvantage of this method is that it is necessary for r to be significantly lower than the characteristic impedance of the coil ($\sqrt{(L/C)}$). Previous detailed analysis [4] of the distributed effect of the induced voltage for a circular coil loop in which the current is co-axially situated has shown that using a non-matched termination does not result in oscillations or rings. However it may be shown (and is not generally well known) that any asymmetry (which may be due to an adjacent current outside the coil) will provide a mechanism for significant oscillations at the coil resonant frequency. These oscillations will be triggered by any discontinuity in the current waveform such as a step or ramp,

The authors therefore conclude that, unless measuring substantially steady state sinusoidal currents, the L/r method of passive integration is does not yield satisfactory results for general purpose Rogowski transducers. Nevertheless this method has been used successfully for special applications for which symmetrical coil geometries have been carefully designed, and the measurement of currents with rise times of a few ns have been reported [5].

An alternative passive integration method, which avoids coil oscillations, is shown in Figure 7(b). A C_0R_0 integrating network is used, together with a parallel resistor R_D to provide the correct termination to the coil. Since at high frequency the impedance of C_0 is relatively low, the parallel combination of R_0 and R_D can be arranged to be equal to $\sqrt{(L/C)}$. The transducer gain is then $V_{out} = (H/(C_0R_0)).I$. The high frequency bandwidth ω_B is only limited by the natural frequency of the coil (i.e. $\omega_B < 1/\sqrt{(LC)}$) and the high-frequency capability of the coil can be fully utilised.

The main limitation of passive integration is that the low frequency bandwidth ω_A is limited by the integrator time constant – i.e. $\omega_A > 1/(C_0R_0)$. Typically this is only suitable for high frequencies such as 100 kHz and higher.

Using a Non-Inverting Integrator

Passive integration using a CR network and a correctly terminated Rogowski coil enables a high bandwidth to be achieved but is not suitable for low frequencies for which a high gain electronic integrator is necessary. Hence, in order to achieve a wide bandwidth it is advantageous to combine the use of active (op-amp based) integration for the lower range of frequencies and passive integration for higher frequencies.

To achieve this aim it is also advantageous to use the less-common non-inverting op-amp integrator circuit which avoids the preshoot effect of the inverting integrator described earlier in this paper. A relatively minor disadvantage is that the passive and active integrator time constants need to be accurately matched as discussed below.

A similar scheme was proposed by Pettinga [6] but the system described in his paper has several significant 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.

In comparison the system described below only utilises two stages of integration and ensures that both Rogowski coil and connecting cable are properly terminated.

Figure 8 shows the non-inverting integrator circuit. Assuming R_0 is >> R_d, R_d is selected to provide correct termination to the coil such that, for frequencies up to the bandwidth limit $\omega_B \approx \sqrt{(L/C)}$, the Rogowski coil output E' is substantially equal to the induced voltage E.

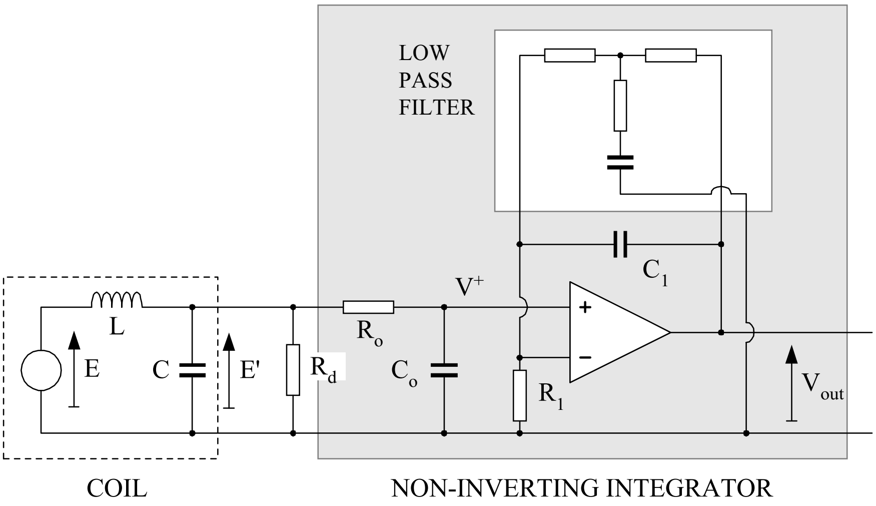

Figure 8: Transducer with non-inverting integrator

E’ is transmitted via a C_0R_0 passive-integration network to the op-amp non-inverting input. At low frequencies the C_0R_0 network has unity-gain and integration is provided by the op-amp. At high frequencies the impedance of C_1 is negligible compared with R_1 and the op-amp behaves as a unity follower.

The integrator transfer function is given by

$$\frac{V_{out}}{E'} = \frac{(1+T_i s)}{T_i s(1+T_0 s)} \tag{8}$$

where $T_i = C_1R_1$ and $T_0 = C_0R_0$. By arranging that the time constants match ($T_0 = T_i$) the desired relationship is obtained, i.e.

$$V_{out} = \frac{1}{T_i}\int E'\,dt \tag{9}$$

The non-inverting integrator has several advantages

(a) 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.

(b) the integrator capacitor does not load the output for transients of high dI/dt. (The inverting integrator requires an output current capability of C_1 (dV_{out} /dt) max which can impose a constraint in the size of C_1.)

(c) At high frequencies the op-amp behaves as a unity gain amplifier (which is a less demanding task then integrating) and the integration is performed by the passive C_0R_0 network.

The high frequency transfer function may be approximated by

$$\frac{V_{out}}{I} = \frac{R_{sh}.e^{-T_a s}}{(1+2\xi T_c s + T_c s^2)(1+T_b s)} \tag{10}$$

where

R_{sh} is the nominal sensitivity

T_a represents the transit delay for the co-axial cable

T_b represents the delay for the integrator, which can be calculated knowing the specified gain-bandwidth value for the integrator op-amp, and the output circuit

T_c represents the delay for the coil $(=\sqrt{(LC)})$. The coil termination is set to provide an equivalent damping ratio ξ of approx. 0.5.

Test Results and Conclusion

It has not been possible to directly measure the gain and phase displacement of the overall transducer at frequencies of 1MHz and higher since sufficiently high current sources at these frequencies were not available. Instead a high frequency sinusoidal source was injected into a 500mm Rogowski coil, to act in place of the induced voltage E=H.dI/dt, using the arrangement shown in Figure 9. This is equivalent to the voltage induced by a current within the coil loop but very close to the coil at one end. The input signal V_{in} and output signal V_{out} were compared using a 100MHz oscilloscope. The length of co-axial cable connecting V_{in} to the oscilloscope was matched to the length of the cable connecting the coil to the integrator so as to eliminate the transit delay T_a (see transfer function (10)) in the comparison.

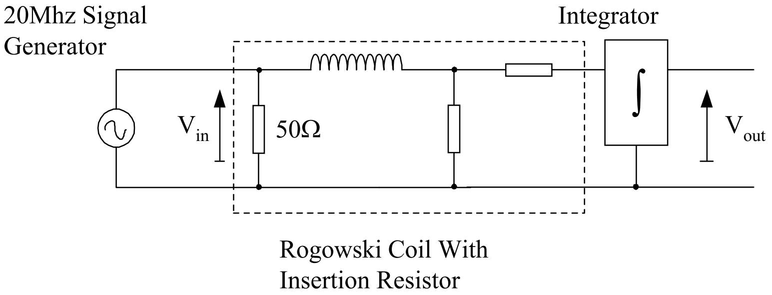

Figure 9: High frequency test circuit for Rogowski transducer

An injected voltage of 10 V pk-pk was used over a frequency range 0.5 to 10 MHz. In order to allow for the frequency-related equivalent measured current, the equivalent gain was taken to be frequency x V_{out}/V_{in} and normalised to give an equivalent gain of 1.0 (or 0dB) for frequencies less than 1MHz. The measured frequency response is shown in Figure 10.

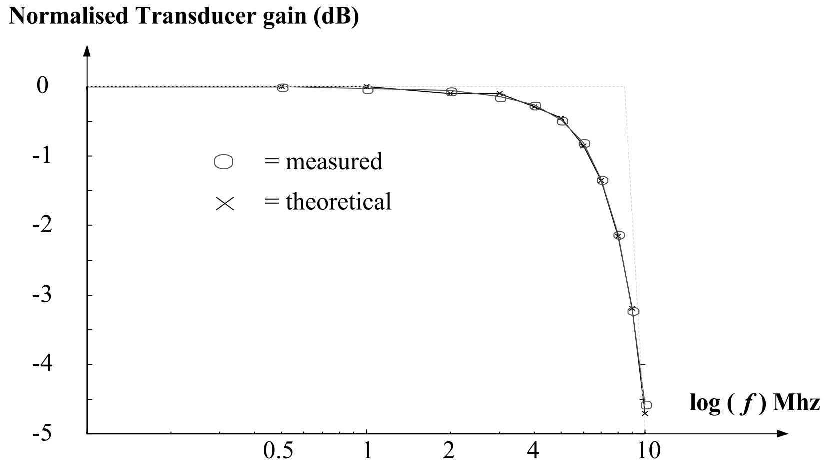

Figure 10: Frequency response for 2mV/A transducer with 500mm coil, showing 3dB bandwidth ≈ 8.5MHz

The approx. delay constant for the coil is 31ns/m giving, for a 500mm coil, the value T_c=16.5 ns with reference to the transfer function (10). The 16MHz gain-bandwidth op-amp has an equivalent delay of 10ns and with additionally approx. 5ns due to the effect of the output impedance the expected value of T_b=15ns. The values of the parameters giving the best fit were T_b=17.7ns, T_c=16.5ns and ξ=0.544 which compare favourably with expectations. The theoretical response using these values is also shown in Figure 10.

Figure 11a shows a comparison of current pulse measurements using a 500mm CWT15 transducer and a 20MHz current transformer. The current pulse of 2600A peak and 38 µs duration has a falling edge of 6700A/us. To eliminate co-axial cable delay from the comparison the same length (2.5m) cable was used for connecting the CT to the oscilloscope as for connecting the Rogowski coil to its integrator. Figure 11b shows the falling edges expanded to 100ns/div from which it will be seen the measurement delay for the Rogowski transducer is 30ns plus the delay for the CT which is relatively very small.

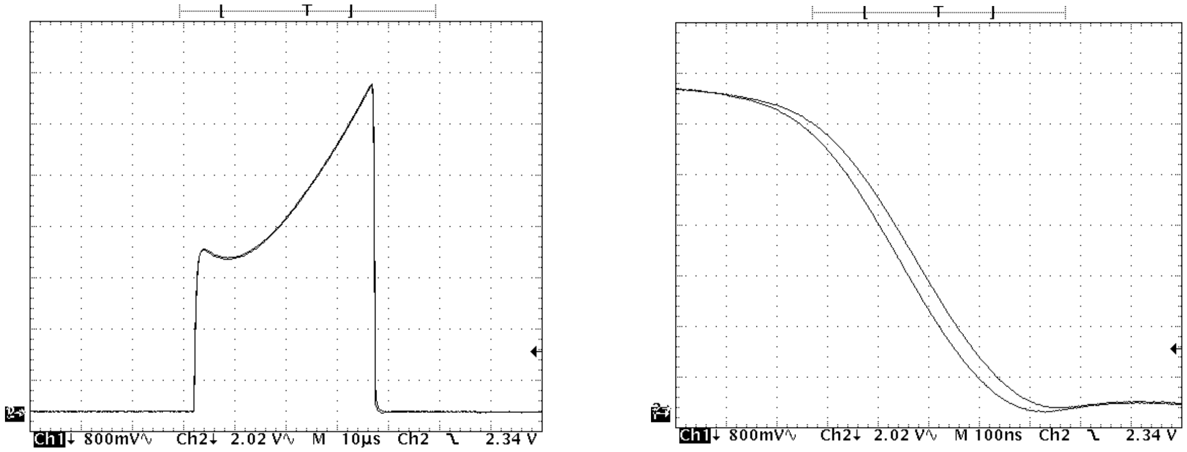

Figure 11: Measurement 400A/div of a 2600A pk current pulse
showing expanded 6700A/µs falling edge

CH1 – 2mV/A CWT15 Rogowski transducer, 500mm coil
CH2 - 5.05mV/A (20MHz current transformer)
Timebase - 100ns/div

It may be shown that, using the transfer function (10) given above, the theoretical measurement delay for a ramp change in current is $T_b+2\xi T_c$. Using the values predicted from the frequency response this indicates a total measurement delay of 35ns which agrees reasonably with Figure 11b.

The high frequency performance of Rogowski transducers is actually much more complex [2,4] than the simplified transfer function (10) indicates and performance evaluation at these frequencies is very difficult. More detailed testing is required to establish an accurate correlation between theoretical models and practical results. Nevertheless the relatively simplified tests outlined above give a satisfactory measure of agreement at this stage.

In conclusion, the use of a non-inverting integrator with a combination of passive and active integration eliminates the preshoot effect observed with the inverting integrator and enables the Rogowski coil and cable to be correctly terminated so that oscillations due to unmatched terminations are avoided. As a result it has not been necessary to include an output filter and the bandwidth of the transducer has been increased to at least 7MHz.

Acknowledgements

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