Verification of Rogowski Current Transducer's Ability to Measure Fast Switching Transients

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Abstract - **Rogowski current transducers combine a high bandwidth, an easy to use thin flexible coil, and low insertion impedance making them an ideal device for measuring pulsed currents in power electronic applications. Practical verification of a Rogowski transducer's ability to measure current transients due to the fastest MOSFET and IGBT switching requires a calibrated test facility capable of generating a pulse with a rise time of the order of a few 10's ns. A flexible 8-module system has been built which gives a 2000A peak current with a rise time of 40ns. The modular approach enables verification for a range of transducer coil sizes and ratings.**

I. INTRODUCTION

A Rogowski transducer usually comprises a thin, flexible, clip-around coil attached by a cable to an integrator as shown in Fig. 1. The coil induced voltage is proportional to the rate of change of current enclosed by the loop. The integrator voltage is therefore proportional to the instantaneous current. Improvements have been made to both the Rogowski coil and electronic integrator over the past ten years [1-3] such that transducers with a frequency response from less than 1Hz to greater than 20MHz are now commercially available.

Figure 1. A Rogowski current transducer and a Rogowski coil enclosing the leg of a T0-47 semiconductor package

Rogowski current transducers are an excellent tool for measuring currents in power electronic applications as they have

- a wide-bandwidth, enabling monitoring of fast (< 1µs) semiconductor switching transients or long (>1ms) capacitor discharge currents.
- virtually no insertion impedance, loading the circuit under test with only a few pH.
- ease of use. As Fig 1. shows the clip-around coils can be made thin and flexible enough to fit between the legs of small discrete semiconductor packages.
- an ability to measure 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 Rogowski coil is not damaged by overcurrent.
- isolation.
- very good linearity due to absence of magnetic materials.

Rogowski current transducers are often used to measure fast switching transients in the development of power electronic equipment. It is therefore important that the engineer testing the equipment has confidence in the ability of the transducer to replicate these waveforms accurately. Turn-on / turn-off times for MOSFET and IGBT devices are continually getting faster. This paper describes a flexible 8- module test system capable of generating a 2kA pulse with a 10 to 90% rise time, t_r, of 40ns. This rise time is comparable to the fastest switching transients encountered in power electronic development at this current level. The test rig is being used to investigate the practical limits of Rogowski measurement of rapid current transients.

II. REQUIREMENTS FOR THE TEST CIRCUIT

A. 2kA peak current

Rogowski current transducers are most commonly used to measure currents up to 10kA. Above 10kA switching times are longer.

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B. *Fast turn-on / turn off (less than 50 ns)*

Rogowski transducers with bandwidths of 20MHz will be shown to be capable of measuring current transients of the order of 100ns. To examine the limitations of such Rogowski transducers a rise / fall time of less than 50ns is required.

C. *Pulse shape - a flat pulse of the order of 0.5-10μs with non-oscillatory rise / fall transients*

The pulsed current should not contain high frequency oscillations (resulting from stray leakage inductance etc). Resolving the dynamics of the Rogowski transducer from those of the power circuit would be problematic.

D. *Modular construction*

Users of current measurement devices have developed high performance test rigs to verify transducer performance [4]. Usually such rigs are for a specific current rating, coil size or application. The modular design concept was chosen to permit verification of transducer performance for a variety of ratings and Rogowski coil dimensions. Arranging a number of modules around a Rogowski coil uniformly can be shown to be equivalent to symmetrical excitation of the Rogowski coil. Alternatively, a single module can be used to provide concentrated 'point source' excitation of a Rogowski coil (e.g. see Fig. 1).

E. *A reliable reference measurement*

To verify the Rogowski transducer's performance each test module needs to have a current measurement with a high frequency bandwidth significantly in excess of the Rogowski transducer.

III. THE MODULAR TEST RIG

The Power Circuit

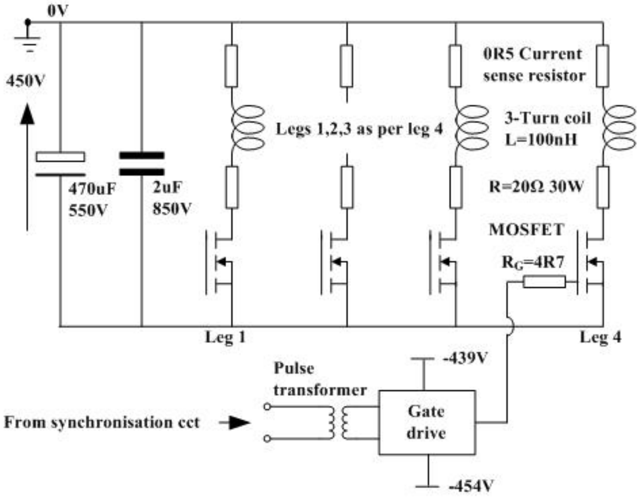
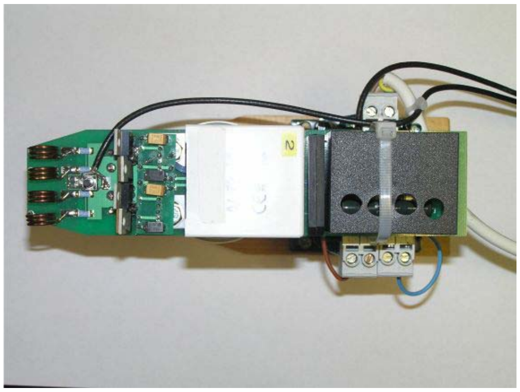


Figure 2. Schematic of a single module of the power circuit



a. Top View

b. Side View

Figure 3. A single module of the test circuit

Fig. 2. and Fig 3. show the chosen power circuit. In each leg there is a 3-turn coil, of inductance L=100nH, through which the Rogowski coil is threaded. A relatively large resistance R=20Ω (cf the switching device and current sense resistor) is used to minimise time constant τ=L/R=5ns to achieve a rise time of the order of 20ns. For this to be the case the switching element must have faster or at least comparable turn on / off times. Careful circuit layout must ensure that parasitic leakage inductance in the circuit is << 100nH.

With a nominal resistance of 20Ω per leg a DC link voltage of 450V is required so that each leg provides a nominal current of 20A. This current, multiplied by the 3-turn coil and multiplied again by the 4 legs means that each module can provide an effective output current of 240A. The modules must be arranged such that a Rogowski coil circumference of 300mm (11.8") can be threaded through 8 modules. In this way the Rogowski coil can measure 1920A.

The switching element of the circuit is chosen to be a COOLMOS N-Channel MOSFET with $V_{ds\ max}$=650V, $t_r \approx$ 5ns, $t_f \approx$ 4.5ns and a low $R_{DS\ on}$=0.19Ω. Using MOSFET's in parallel allows smaller package devices to be used which have faster switching times and a lower gate capacitance, thus reducing the power requirement on individual gate drive circuits. There is very little variation in switching characteristics between different packages of a given device and MOSFETs have an intrinsic ability to stably share currents. Very great care has been taken to achieve symmetrical layout of the gate drive and power circuitry to ensure equal current sharing in the legs of a module.

The DC voltage on each module is maintained by a 470uF / 550V low ESR electrolytic capacitor combined with a high frequency 2uF/ 850V polypropylene snubber capacitor. This is sufficient to maintain the current during the pulse of 10µs.

The 20Ω resistors are 30W film power resistors with a package inductance of <1nH. A 10µs pulse repetition frequency of 50Hz is used to keep the average power dissipation in the resistors to 8W per device. The resistors in a given module share a common 7°C/W heatsink keeping the operating temperature well below the T_{max} for the resistors such that the nominal impedance remains 20R.

The 0R5 current sense resistor is maintained at ground potential by the oscilloscope to which it is connected. Therefore the 3-turn coils through which the Rogowski coil is threaded are also approximately at ground potential. It is arranged that they are located as far as possible from any potentially high dV/dt transients across the MOSFET and 20R load resistor to minimise the potential for capacitive pick-up on the coil. The rest of the circuit is at negative potential with respect to the current sense resistor. Therefore the gate drive for the MOSFET provides a +11V pulse for turn on and -4V for turn off with respect to –450V. Isolation from the synchronisation circuit is maintained by an hf pulse transformer.

The Synchronisation Circuit

Each module is supplied with its own adjustable gate pulse generator and driver. The gate pulse for each module is synchronised to a single 50Hz source. The delay before the gate pulse turn-on can be adjusted over a range of 0 to 10ns which is sufficient to cover the variation between all 8 modules. Each module was slaved to one 'reference' module such that the rising edge of the 240A pulse, as measured by the 0R5 current sense resistors, were all synchronised to a tolerance of ±0.2ns. The pulse width is set to 1µs.

The Reference Measurement

Traditionally co-axial shunts are used as reference. These can have high frequency bandwidths in the 1GHz range. However they are bulky and constraints on circuit layout prevent their use. Also, the four currents to be measured per module must be summed to give a single signal representing the total module current.

The very low inductance of thick film surface mount resistors has proved (with careful layout) to satisfy both the measurement and summing requirements. 0R5 1% resistors with an inductance of less than 0.2nH are used to measure the 20A current, and four 300R surface mount resistors sum these signals into a 75ohm co-axial cable. This is terminated with a 63R and 12R resistive divider mounted inside a co-ax connector, also using surface-mount components for their low inductance. The connection from the current sense resistors to the oscilloscope is shown in Fig. 4.

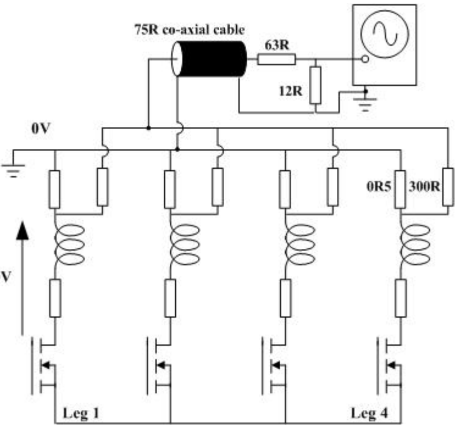
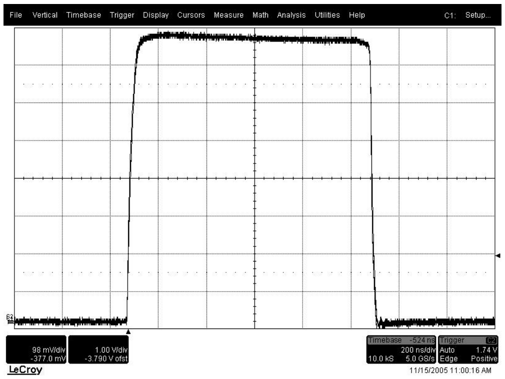


Fig 4. Connection to oscilloscope from 0R5 current sense resistors.

To verify the performance of the current measurement in-situ a co-axial shunt was placed in the 0V line between the 2uF capacitor and the 4 legs of the current measurement (see Fig. 2). The co-axial shunt has a resistance 0.1022Ω with an 800MHz high frequency (-3dB) bandwidth. The 3-turn coils were short circuit. Fig. 5 shows a comparison of the transient performance of the co-axial shunt and the module current measurement system.



98 mV/div
-377.0 mV
1.00 V/div
-3.790 V ofst
Timebase -524 ns
200 ns/div
10.0 kS 5.0 GS/s
Trigger C2
Auto 1.74 V
Edge Positive
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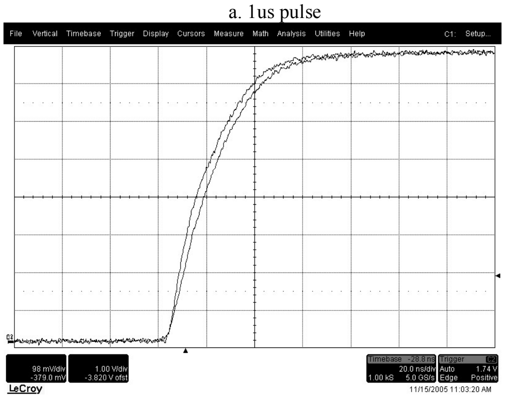
a. 1us pulse



98 mV/div
-379.0 mV
1.00 V/div
-3.820 V ofst
Timebase -28.8 ns
20.0 ns/div
1.00 kS 5.0 GS/s
Trigger C2
Auto 1.74 V
Edge Positive
11/15/2005 11:03:20 AM

b. t_r=40ns rising edge

Figure 5. Test pulse – coaxial shunt vs. SMT current sense resistors
Ch1. SMT current sense resistors 100mV/div overall sensitivity 10mV/A
Ch2. Shunt 1V/div sensitivity 0.1022V/A
Timebase: a. 200ns/div, b.20ns/div

The module current measurement system is leading the 800MHz shunt measurement by approximately 3ns which can be explained in part due to discrepancy in the length of connecting cables from the two devices. These results show that the current measurement system is capable of comparable transient performance to an 800MHz co-axial shunt.

IV. RESPONSE OF A ROGOWSKI TRANSDUCER WITH NON-INVERTING INTEGRATOR TO A FAST TRANSIENT CURRENT

Previous publications [1-3] by the authors describe a Rogowski coil and integrator utilising both passive and active integration capable of spanning a very wide frequency range, typically 7 decades. The method is summarised in Fig. 6.

At high frequencies $\omega > 1/T_o$ the integration time constant $T_o = R_o(C_o + C_a)$ where C_a is the cable capacitance, and the op-amp behaves as a unity gain amplifier. At frequencies $\omega < 1/T_1$ the integration time constant $T_1 = C_1R_1$ and the $R_oC_oC_a$ network has unity gain. To achieve the same sensitivity over the full frequency range T_1 and T_o are equalised.

The high frequency behaviour of the Rogowski transducer has been previously reported [1,2]. For frequencies up to $f = 1/(2\pi T_c')$ the linearised transfer function given below gives a good prediction for a symmetrically excited Rogowski coil [2].

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

where T_a = Cable delay
T_b = Integrator delay = $1/(2\pi \text{x gain bandwidth})$
T_c' = $2\sqrt{(LC)} / \pi$
L,C = Coil inductance and capacitance
R_{sh} = Transducer sensitivity
ξ' = $0.25\pi \sqrt{(L/C)} / (R_d^{-1} + R_o^{-1})$

At higher frequencies the coil behaviour is complex and can only be estimated using transmission line modelling. With non-symmetrical excitation there are resonant modes that can be excited if the frequency content is sufficiently high, even if the coil is damped by appropriate choice of R_d and R_o. Hence the behaviour with step current transients can become oscillatory if the rise-time is sufficiently fast.

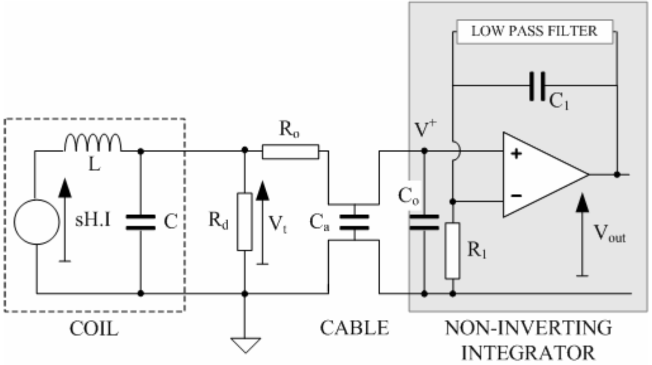


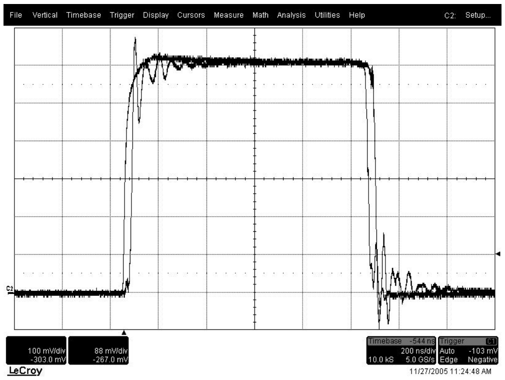
Figure 6. Rogowski transducer with non-inverting integrator.

Experimental Result, tr=40ns, I=540A

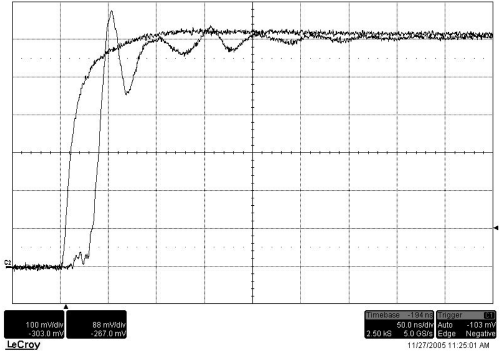
Three modules of the test rig were arranged symmetrically around the coil of a CWT30B Rogowski transducer with a 300mm coil having

Nominal sensitivity	R_{sh}	=	1.0	mV/A
1m cable between coil and integrator	T_a	=	5	ns
Integrator delay	T_b	=	10	ns
Integrator slew rate limit		=	40	kA/µs
Coil equivalent delay	T_c'	=	5.2	ns
	ξ'	=	0.76	
(-3dB) bandwidth from			0.6Hz to 16MHz	

The response is shown in Fig 7. Although the overall shape of the current pulse is replicated, clearly the fast transient edges are not. The 20MHz oscillations on the Rogowski measurement most likely originate from the electronic integrator. This is not entirely surprising. The transducer is designed to span 7 decades of frequency so as to be able to measure 60Hz power frequencies as well as micro-second pulsed currents. To achieve such a wide measurement bandwidth there is a compromise on the selection of op-amp used to perform the electronic integration. An op-amp with limited GBW product must be used which will satisfy noise and offset criteria to achieve the low frequency design. It is the electronic integrator in this instance which limits the 3dB high frequency bandwidth of the Rogowski transducer.



a. 1us pulse



b. t_r=40ns rising edge

Figure 7. Test pulse – CWT30B vs. SMT current sense resistors
Ch1. SMT current sense resistors 100mV/div overall sensitivity 3.33mV/A
Ch2. CWT30B (88mV/div) / sensitivity 0.975mV/A

Timebase: a. 200ns/div, b.50ns/div

Clearly these oscillations are not predicted by (1) and a better model of the high frequency behaviour is required. Before presenting improvements to the model, it is informative to see what the maximum rise time that the 'CWT30B with a 300mm coil' can measure without loss of integrity.

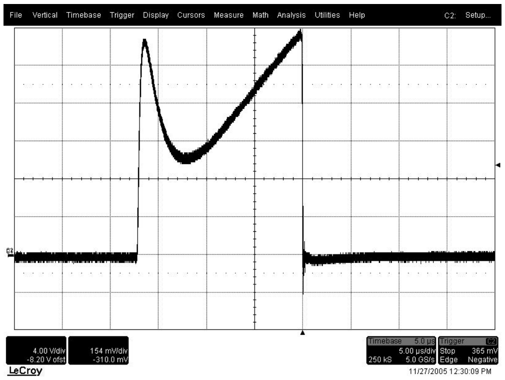
Experimental Result, tr=100ns, I=900A

The 'CWT30B with 300mm coil' is capable of measuring transients of ≥100ns as shown in Fig. 8.

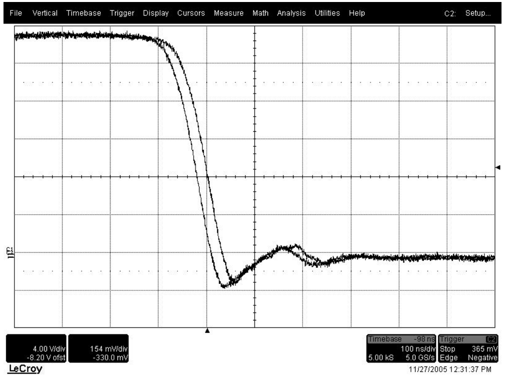
The current pulse is generated by a 'slower' test rig. In this case the Rogowski coil is excited by a small coil located half way along the Rogowski coil. The peak current is 900A and the 10-90% fall time of the pulse is 100ns. The comparative measuring device is a current transformer with a high frequency (-3dB) bandwidth of 70MHz and sensitivity of 0.1V/A.

From (1) the delay between the measured current and the response of the Rogowski transducer is predicted to be $T_b+T_a+2\xi' T_c' = 23.0$ns. From Fig. 8 the measured delay at 50% is 22ns. Making a correction of $T=1/2\pi(70\text{MHz})$ for the current transformer the measured delay is 24.3ns, in good agreement with the theoretical value.

The practical step response of a Rogowski transducer employing this method of integration is generally in good agreement with the linear model (1) for current steps where $t_r \geq 10T_c$ or $10T_b$ whichever is greater.



a. 17µs pulse



b. t_r=100ns falling edge

Figure 8. Test pulse – CWT30B vs. 70MHz 0.1V/A CT

Ch1. Current transformer (4.0V/div) / sensitivity 0.1V/A

Ch2. CWT30B (154mV/div) / sensitivity 0.975mV/A

Timebase: a. 5µs/div, b.100ns/div

V. Response of a Rogowski Transducer with Passive Integrator to a Fast Transient Current

The high frequency dynamics of the electronic integrator of the 'CWT30B with a 300mm coil' mean it is unsuitable for measuring current transients faster than 100ns. It seems sensible to eliminate the electronic integrator in Fig. 6. The high frequency bandwidth of the passive Rogowski transducer will then be determined solely by the distributed inductance and capacitance of the Rogowski coil and its termination impedance. The operation is summarised in Fig 9. and the transfer function between V_t and V_{out} is simply

$$\frac{V_{out}}{V_t} = \frac{1}{(1+T_i s)} \tag{2}$$

where the integration time constant $T_i=(C_o+C_a)R_o$. For frequencies such that $\omega T_i >> 1$, $V_{out}/V_t = 1/T_i s$, and

$$\frac{V_{out}}{I} = R_{sh}F(\omega T_c) \tag{3}$$

where and R_{sh} is the overall sensitivity of the transducer and $F(\omega T_c)$ represents the coil high frequency dynamics. The coil is effectively terminated by $R_o(>>1/\omega C_o)$.

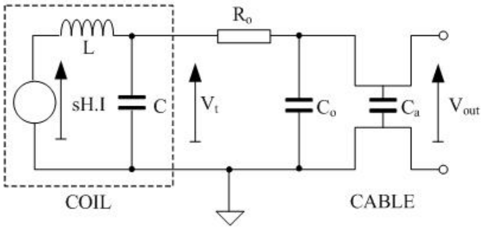


Figure 9. Rogowski transducer with passive integrator.

A better method of representing the high frequency behaviour of the Rogowski coil is to model it as a transmission line with a distributed inductance, L, and capacitance, C. The coil is best terminated by its nominal characteristic impedance $R_o=Z_o=\sqrt{L/C}$. This is found in practice to prevent unwanted reflections in the coil, seen as 'ringing' on the measurement. The variation of conductor position within the Rogowski loop, λ, is taken into account as is the relative size of the exciting coil, ±Δλ, relative to the Rogowski coil length as shown in Fig 10.

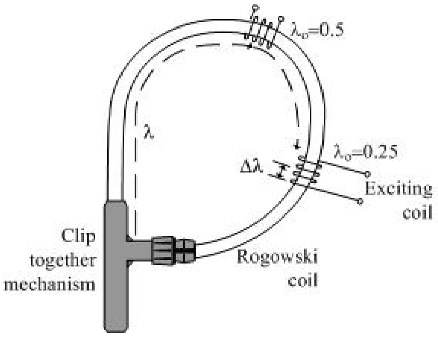


Figure 10. Use of a small exciting coil to test the Rogowski coil.

The relationship between measured current I inside the coil loop at position λ_0 and output across the terminating resistance of the Rogowski coil V_t is given by

$$\frac{\boldsymbol{V_t}}{j\omega T_i R_{sh}\boldsymbol{I}} = \frac{\cosh(\lambda_0\psi)\left\{\dfrac{\sinh(\Delta\lambda.\psi)}{\Delta\lambda.\psi}\right\}}{\cosh(\psi)+\dfrac{Z_o}{R_o}\sinh(\psi)} \qquad (4)$$

This can be represented in the s-domain and combined with (2), to give a transfer function relating the measured current I to V_{out}. This model is used to simulate the step response and provide comparison with the experimental results. It is assumed the resistance of the coil is negligible, thus $\psi=j\theta=j\omega\sqrt{(LC)}$.

$$\frac{\boldsymbol{V_{out}}}{\boldsymbol{I}} = R_{sh}\cdot\frac{\dfrac{z'+z'^{-1}}{2}\left\{\dfrac{z''-z''^{-1}}{2.\Delta\lambda.Ts}\right\}}{\dfrac{z+z^{-1}}{2}+\dfrac{Z_o}{R_o}\left\{\dfrac{z-z^{-1}}{2}\right\}}\cdot\frac{sT_i}{1+sT_i} \qquad (5)$$

where $z=e^{T_c s}$, $z'=e^{\lambda T_c s}$ and $z''=e^{\Delta\lambda T_c s}$.

One of the interesting outcomes of modelling the coil as a transmission line (TL) is that at high frequency the position of current relative to the Rogowski coil can affect the response of the transducer. The variation is relatively small if the coil propagation angle $\theta=\omega T_c<0.5$ rad. but becomes more pronounced as θ increases. This is of interest because the Rogowski coil is often excited by a point source of current for example threading the coil around the collector leg of a T0220 packaged device (see Fig. 1). The user of the Rogowski coil would quite rightly ask, what is the best position of the coil with respect to the point source conductor? The modular test rig has a sufficiently fast pulse and small exciting coil for this effect to be investigated.

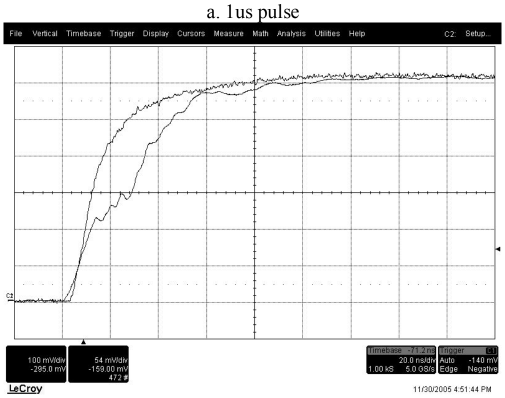
Although (4) gives a better approximation of the coil behaviour at high frequencies, when compared to simpler linear 'lumped parameter' models, even this approach has been shown to have limitations [5]. At frequencies above the resonant frequency of the coil $f_{res}=1/T_c$ the coil delay significantly increases. This effect is predicted by preliminary modelling of the coil as a waveguide. However this behaviour is complex and beyond the scope of this paper.

Experimental Result, tr=40ns, I=180A, λ_o=0.5

The Rogowski coil was threaded through the exciting coil of a single module of the test rig located at λ_0=0.5. The Rogowski coil is terminated by a passive RC integrator, with T_i=9.1µs where R_o=910Ω and C_o=10nF. The response is shown in Fig. 11.

Comparing Fig. 11. and Fig. 7. it is apparent that, given the same Rogowski coil, utilising passive RC integration provides a better reproduction of the current pulse. However Fig. 11.a. highlights the compromise with passive integration. The low frequency bandwidth of the transducer is now $f_{3dB}=1/2\pi T_i$. For T_i=9.1µs, f_{3dB}=17.5kHz compared with 0.6Hz using the op-amp integrator. The result of losing low frequency bandwidth is increased droop. For a rectangular current pulse of duration τ the percentage droop is given by $100(\tau/T_i)$ %. For a τ=1µs the expected droop is 11% - clearly seen in Fig.11.a.

a. 1us pulse



b. t_r=40ns rising edge

Figure 11. Test pulse λ=0.5 Passive transducer vs. SMT current sense resistors
Ch1. SMT current sense resistors 100mV/div overall sensitivity 10.0mV/A
Ch2. Passive RC (54mV/div) / sensitivity 1.8mV/A
Timebase: a. 200ns/div, b.20ns/div

In order to compare the theoretical prediction for the coil response to this 40ns current step it is necessary to increase the values for the coil delay T_c and the characteristic impedance Z_o [5]. For the frequency content corresponding to this step it was found that a factor of 1.59 was appropriate. Hence the coil and passive integrator parameters become

T_c=13.0 ns, T_c'=8.30 ns; Z_o=1.40 KΩ, Z_o'=2.20 KΩ .

With R_o=910Ω and C_o=10nF the damping ratio for the linearised model (1) ζ'=1.205. The integration time constant T_i=9.1µs remains unchanged.

Since the exciting coil is approximately 35mm a value of Δ=0.05 was used in the TL model (5). Z_o/R_o =1.54.

Fig. 12. shows the predicted measurements for the linearised model and the TL model for λ_0=0.5. The simulated current step is a close approximation to that measured by the SMT current sense resistors.

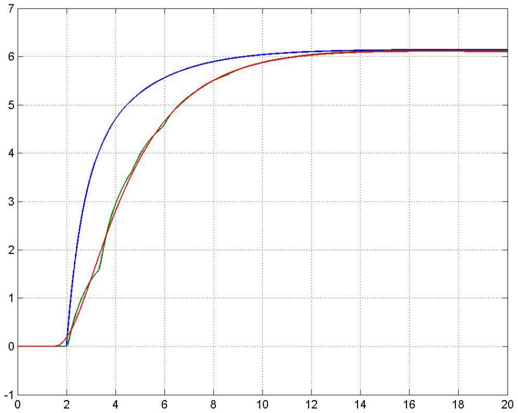


Figure 12. Simulated test pulse – red line (linearised) – green line (TL) at λ_o=0.5 – **Timebase** 1unit = 10ns

At these frequencies the two models are in close agreement in predicting the general shape of the Rogowski transducer response. However only the TL model shows the perturbation on the response due to the reflections in the coil, although not to the extent seen in the actual response of Fig 11b. The reason for the difference is not known. It could be interference pickup by the coil or inherent dynamic effects in the coil that have not yet been identified. It should be remembered that the TL model is an approximation at very high frequencies.

Experimental Result, tr=40ns, I=180A, λ_o=0.75

The same Rogowski coil and passive integrator as used in the previous section was threaded through the exciting coil of a single module of the test rig located at λ_o=0.75.

Fig. 13 shows the measured current and Fig. 14 shows the theoretically predicted measurements for λ_0=0.75. Whereas the linearised prediction is unchanged, it will be seen that the measurement is slightly affected by the position of the exciting coil as predicted by the TL model. This is also true for λ_0=0.25.

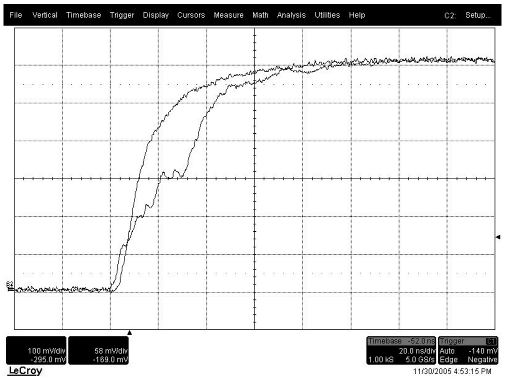


Figure 13. Test pulse λ=0.75 Passive transducer vs SMT current sense resistors
Ch1. SMT current sense resistors 100mV/div overall sensitivity 10.0mV/A
Ch2. Passive RC (54mV/div) / sensitivity 1.8mV/A
Timebase:. 20ns/div

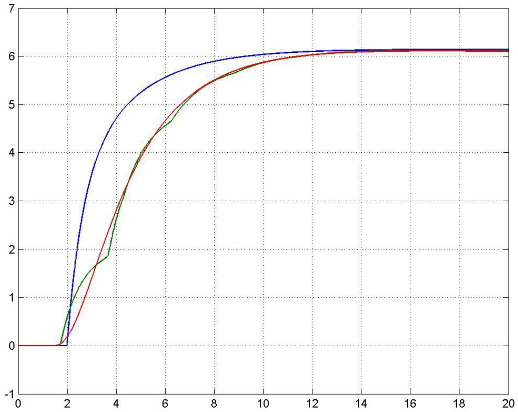


Figure 14. Simulated test pulse – red line (linearised) – green line (TL) at λ_o=0.75 – **Timebase** 1unit = 10ns

CONCLUSIONS

The paper has described the design and construction of a modular high-current fast rise time pulse rig and presented measurements of this pulse by a Rogowski transducer. The pulse rise time of 40ns is higher than the transducer is capable of accurately reproducing, particularly due to the limited gain bandwidth of the integrator op amp (16MHz). A purely passive integrator gives a better measurement although still not exact. With a rise-time of 100ns the transducer response was shown to be satisfactory.

Nevertheless it has been shown that the measurement varies with the position of the current within the coil loop, as predicted by the theoretical model.

It is the authors intention to develop an improved Rogowski transducer using a coil with a shorter delay time and an integrator op-amp with a higher bandwidth. The test rig will provide great assistance in achieving this aim.

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