Optimising the high frequency bandwidth and immuntity to interference of Rogowski coils in measurement applications with large local dV/dt.

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Abstract—**Electrostatic interference through capacitive coupling onto a Rogowski coil causes unwanted pick-up noise on the output of the integrator. An electrostatic screen fitted to a Rogowski coil reduces this interference. This paper discusses how to maximise the high frequency (hf) bandwidth of a Rogowski transducer with a screened coil.**

I. INTRODUCTION

Rogowski current transducers, comprising a Rogowski coil and electronic integrator, are often used for measuring pulsed and transient currents in power electronic circuits [1][2]. They can be thin, flexible, clip-around and thus easy to use. The Rogowski coil has a very low insertion impedance and the overall transducer can have a high frequency bandwidth of greater than 10MHz.

There are an increasing number of power electronic applications that require a high bandwidth current measurement with excellent immunity to large local dV/dt transients. Such applications still need a thin, flexible, Rogowski coil. For example in power converters faster IGBT switching speeds and higher blocking voltages in increasingly compact designs place the Rogowski coil near to 'noisy' environments. Another example is the increasing power capability of solid state rf transmitters and amplifiers where currents of 100A, voltages of up to 1kV, at frequencies of several MHz are common.

The problem of electrostatic interference through capacitive coupling on to the Rogowski coil is analysed in [3][4][5]. Fig 1. shows the coupling mechanism of a voltage source V_x via stray capacitance C_x on to a Rogowski coil having self-inductance L, and outer winding to inner return conductor capacitance C (where from [1] $C'=(2/\pi)^2C$). The worst case occurs if all the coupling capacitance is concentrated at the free end of the Rogowski coil. The injected current will go through the entire coil impedance generating a voltage, which once integrated, appears as pick-up noise on V_{out}. Typically the capacitance is distributed uniformly along the coil, (e.g. where the conductor is a cable or cable bunch with an outer diameter approaching the inner coil diameter). This is approximated by assuming the coupling capacitance is concentrated at the mid-point of the Rogowski winding.

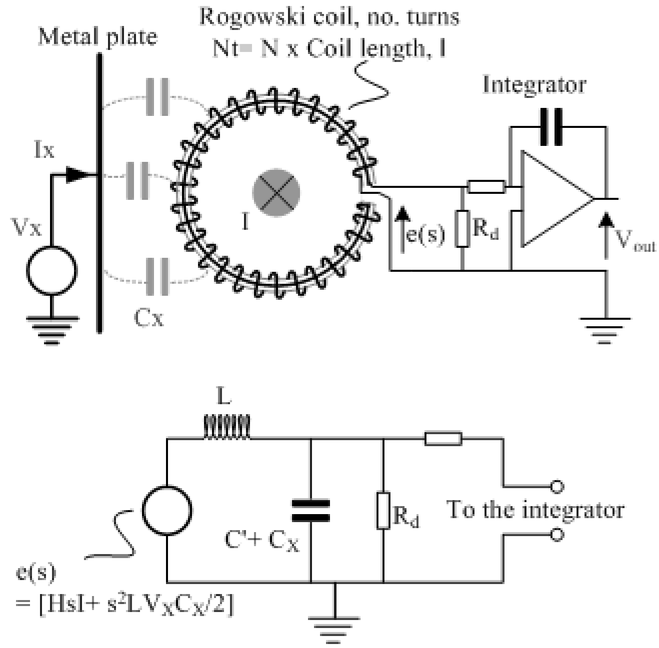


Fig. 1. Schematic and equivalent circuit showing capacitive coupling onto the Rogowski coil

From the schematic of Fig 1. a lumped parameter model is obtained. The voltage HsI is generated by the primary current I, where H is the coil sensitivity in (Vs/A). The coil winding is assumed to be close packed where $H=L/N_t$. In addition to the voltage HdI/dt induced by the primary current there is a voltage $(LC_x/2)(d^2V_x/dt^2)$ induced by the displacement current I_x due to the electrostatic field as shown in Fig. 1. Hence the equivalent error current is given by:

$$I_e = \frac{C_x N_t}{2}\frac{dV_x}{dt} \tag{1}$$

To reduce the interference from the electrostatic field it is necessary to either bypass I_x by fitting an electrostatic screen or to minimise I_x by inserting a common mode impedance. Fitting the coil with an electrostatic screen will reduce the high frequency performance of the Rogowski transducer [5]. This paper examines how to maximise the high frequency bandwidth of a Rogowski coil, reject interference from high dV/dt fields, and maintain a thin flexible coil.

II. FITTING AN ELECTROSTATIC SCREEN

Screening the coil provides a low impedance path to ground to enable I_x to by-pass the coil winding. The screen introduces capacitance C_s between the coil winding and ground, which is in parallel with C' and which replaces C_x in Fig 1. Thus including the dynamics of the electronic integrator from Fig 1. the high frequency response of the Rogowski transducer is [2]:

$$\frac{V_{out}}{R_{SH} I} = \frac{1}{1+2\xi T'_c s + T'^2_c s^2}\frac{1}{1+T_b s} \tag{2}$$

The integrator delay $T_b=1/2\pi GBW$, where GBW is the gain bandwidth product of the op-amp. The coil delay T'_c is increased by the additional screen capacitance i.e. $T'_c=\surd L(C+C_s)$' and $\xi=(\surd L/(C+C_s)')/2R_d$. To reduce any 'peaking' in the hf response of the Rogowski transducer due to C_s the terminating resistor R_d can be adjusted, but inevitably the addition of a screen for a given coil cross section and winding density results in a reduction of the hf bandwidth of the transducer.

A. Optimising the bandwidth of a screened coil

From (2) it is clear that to maximise Rogowski coil bandwidth it is necessary to reduce coil inductance and the total coil and screen capacitance, but how is this optimised for a given high frequency bandwidth and coil thickness and what are the resulting limitations on overall Rogowski transducer performance?

If we wish to maintain a thin coil with a specific voltage insulation capability the outer screen diameter d_s is fixed. Similarly the Rogowski coil winding wire diameter, d_{wire}, is fixed, being as thin as can practicably survive repeated opening and closing of a Rogowski coil. With reference to Fig 2. both the diameter of the plastic former onto which the Rogowski coil is wound, d_f, and the pitch of the winding, x, can be manipulated to alter the self inductance of the coil L and the capacitance $C+C_s$.

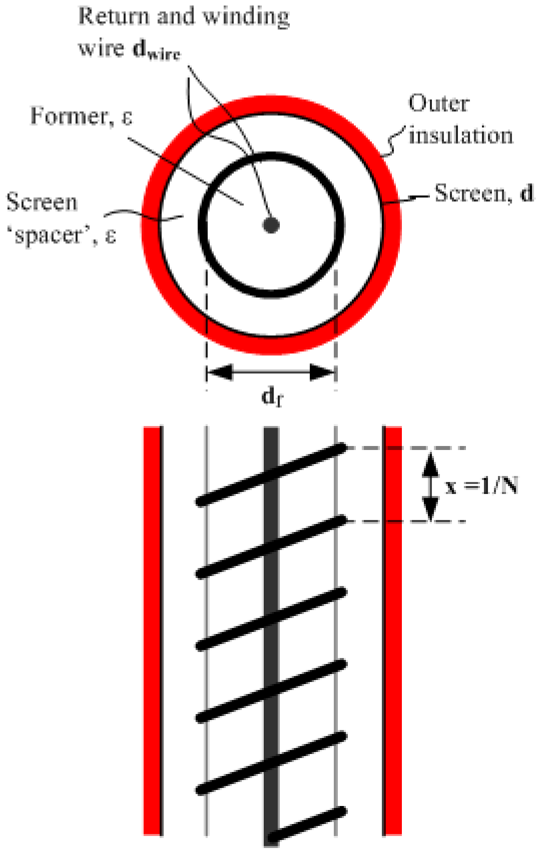


Fig 2. Construction of a Rogowski coil with screen

Assuming that the flux in each turn of the Rogowski coil is constant the coil sensitivity is

$$H = \mu_o NA \tag{3}$$

where A is the cross sectional turn area $A=(\pi/4)(d_f+d_{wire})^2$ and $N=N_t$/coil length. The flux per turn is constant provided the Rogowski coil is formed into a closed loop around the conductor, the pitch is uniform, and the turn area A is << than the conductor radius, or if the conductor is very thin, it is spaced a distance d away from the edge of the coil where $d^2 > (d_f+d_{wire})^2$. With Rogowski coil and conductor insulation taken into account we need to ensure this is the case for typical currents of >100A, conductor diameters >10mm. There are other practical considerations in the choice of A and x. For power electronic applications the thinner the Rogowski coil the better as converter designs become more compact, therefore an overall coil cross section including screen and insulation of < 7mm is chosen, this limits d_f to typically 5mm. Assuming a wire radius of 0.2mm this sets the minimum former diameter to 1.5mm to enable sufficient wire bending radius. It is difficult to wind an accurate pitch for a loose spaced winding. An accurate pitch is essential for rejecting interference from currents external to the Rogowski coil. Given a d_f of between 1.5 and 5mm, experience of winding coils limits the pitch to < 5mm.

Reducing the coil winding area A and the winding density N to reduce the time constant T'_c will also reduce H. A low frequency and broadband noise, V_{noise}, is generated in the electronic integrator of a Rogowski transducer where $f_l V_{noise} \alpha\ 1/H$ and f_l is the low frequency limit of the integrator [2]. Thus the effect of reducing T'_c is to either increase the transducer noise or limit the low frequency performance.

B. Optimising T_c for a given coil sensitivity H

The coil sensitivity H can be fixed to achieve a given low frequency Rogowski transducer performance. Additionally if the screen diameter d_s and winding wire diameter d_{wire} are fixed then, if the former diameter, d_f, is chosen, from (3) the turns density N must be chosen to achieve the specified H. The time delay of the Rogowski coil is given by

$$T_c = \sqrt{L(C+C_s)} \qquad (4)$$

As d_f and N are adjusted for a given H, so the inductance and capacitance of the Rogowski coil will vary. This section introduces approximate expressions for L and $C+C_s$ in terms of d_f and $N=1/x$. Ultimately these expressions are used to calculate the minimum T_c that can be achieved for a given H and thus optimise the bandwidth of the overall Rogowski transducer.

The inductance per m (H/m) of a long close packed Rogowski coil winding (effectively a solenoid) is well known and is given by

$$L = \mu_o N^2 A \qquad (5)$$

For a close packed winding, which we will define as a pitch of $x < 2.5d_{wire}$, all the flux within the coil cross section area A of the winding links all the turns, as the pitch of the winding is increased there is additional flux that links just the wire itself and not all the turns thus the measured inductance is larger than predicted by (5). As the pitch, x, is increased the inductance can be adequately predicted by

$$L = \mu_o N^2 A + 2x10^{-7} l_{wire} \ln\left[0.3667((2x/d_{wire})-2)\right] \qquad (6)$$

where $l_{wire}=(\pi hN+1)$ and $h=\sqrt{((d_f+d_{wire})^2+(1/\pi N)^2}$ for $x \geq 2.5d_{wire}$.

Table 1a. and 1b. show a comparison of measured inductance values against those predicted by (5) and (6). The measurements are taken using an LCR bridge, model LCR400, the frequency of the measurement is 10kHz. At 10kHz the skin depth of copper wire is δ=0.65mm, thus for d_{wire}=0.22mm there is a distribution of flux inside the wire adding an additional inductance to the measurement of $(\mu_o/8\pi)*l_{wire}$ which is added to (6) to give the total inductance 'Theory' in Table 1.

TABLE I. COMPARISON OF THEORETICAL AND MEASURED ROGOWSKI COIL SELF-INDUCTANCE

Pitch x=1/N (mm)	**L, Inductance (μH/m)** – for d_f = 3.74mm, d_{wire} = 0.22mm		
	Measured	**Theory**	**Error (%)**
0.22	315.20	322.65	-2.39
0.44	82.70	81.41	1.57
0.657	39.84	38.40	3.63
0.88	23.76	23.14	2.63
1.667	8.66	8.68	-0.22
4.545	3.22	3.03	6.3
5.857	2.46	2.58	-3.49
9.100	1.97	2.15	-9.17

1a.

Pitch x=1/N (mm)	**L, Inductance (μH/m)** – for d_f = 1.86mm, d_{wire} = 0.22mm		
	Measured	**Theory**	**Error (%)**
0.22	86.96	89.76	-3.22
0.44	23.19	22.85	1.47
0.88	7.11	7.28	-2.34
1.176	5.18	4.96	4.35
3.846	1.99	1.92	3.45
6.33	1.56	1.70	-8.65

1b.

For a pitch < 5mm the theoretical value is within 5% of the measured value and (5) and (6) provide a good estimation of inductance. At a pitch of > 5mm the winding is tending toward a configuration more akin to two parallel wire conductors and (6) is no longer valid, however as previously discussed x < 5mm also represents a reasonable practical limit in the construction of accurately wound Rogowski coils.

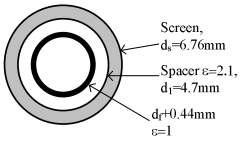
The capacitance of a screened close packed Rogowski coil winding is the parallel capacitance between the coil outer winding and the screen ,and the coil outer winding and the return conductor. For a coil with a pitch of d_{wire} this approximates to the co-axial case where

$$C_{total} = C_{s\_nom} + C = \frac{2\pi\varepsilon}{\ln\left(d_s/\left(2d_{wire}+d_f\right)\right)} + \frac{2\pi\varepsilon}{\ln\left(d_f/d_{wire}\right)} \qquad (7)$$

Table 2. shows the measurement of capacitance C_s for two different coil former diameters with a close packed winding $x=d_{wire}$ and a fixed d_{wire}=0.22mm and d_s=6.76mm where the screen is fitted on a PTFE former of inner diameter 4.7mm. The capacitance measurements were made on an LCR bridge,

model LCR400, at 10kHz. The measured results and those predicted by (7) are in excellent agreement.

TABLE II. CAPACIATNCE C_S FOR CLOSE PACKED CASE WHERE X=D_{WIRE}

	df (mm)	C_s Theory (pF/m)	C_s Measured (pF/m)
	3.74	191.6	192.7
	1.86	62.6	65.9

However for a given former diameter as the pitch is increased significantly it is no longer reasonable to assume an evenly distributed charge on the surface of the outer coil winding and (7) with its implication of two discrete capacitances is an approximation. In the limit the capacitance between the outer winding and the screen coil can be modelled as a single wire above an infinite plane to represent the screen, multiplied by the total length of the winding wire. Measurements verify this as a reasonably accurate estimation but only where the influence of screen to inner conductor capacitance is negligible, this makes the approximation of little practical use for our range of d_f=1 to 5mm and x<5mm.

In the absence of a reasonable theoretical model to determine the variation of C_{total} as x varies, measurements of the capacitance C_s for d_f=1.86mm and d_f=3.74mm as x varies from d_{wire} to 5mm were obtained. The capacitance measurements have been normalised to the close packed co-axial case where x=d_{wire}. The results are plotted in Fig. 3. The variation of C_s with x can be roughly estimated from the linear trend-line shown in Fig 3.

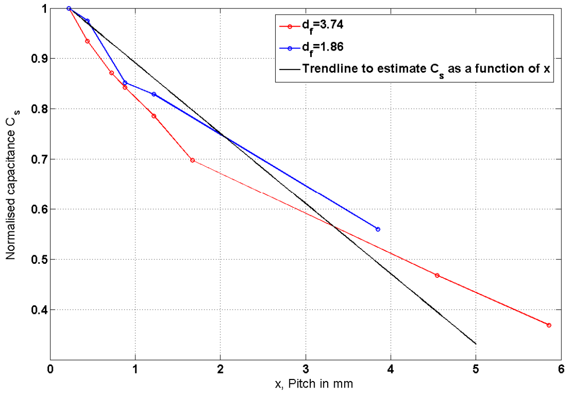


Fig 3. Variation in C_s with a variable pitch x and d_f

The empirical relationship (8) is used to obtain C_s for variations in x where $C_{s\ nom}$ is obtained for a given former diameter d_f from (7). The linear fit is quite poor but does provide a tolerable indication of the capacitance variation.

$$C_s = (1.031-0.14x)C_{s\_nom}$$
$$C_{total} = C_s + C \qquad (8)$$

There is a similar but smaller variation for C. However this value is typically very much smaller than C_s. Using (7) to calculate C is a reasonable approximation for the range of d_f and x investigated in this paper.

It should be noted that the measurement of L and C, and the approximate formulas derived for calculating L and C_{total} are based on measurements at 10kHz. In [6] these low frequency estimates of L and C_{total} are shown to be a reasonable indication of T_c up to $f=1/4\sqrt{(LC_{total})}$.

In (5),(6),(7) and (8) we have expressions for L and C_{total} in terms of d_f and x. From (3) it is possible to generate values of d_f and x for a given H and subsequently find $T_{c\ min}$. For example assume H=20nVs/A, with d_{wire}=0.22mm, d_s=6.76mm (the screen is fitted on a PTFE spacer of inner diameter 4.7mm and ε_r=2.1), d_f=1.5 to 5mm, x=0.22 to 5mm. We can plot the resultant (d_f, x) for H=20nVs/A and see how T_c varies. This is shown in Figure 4.

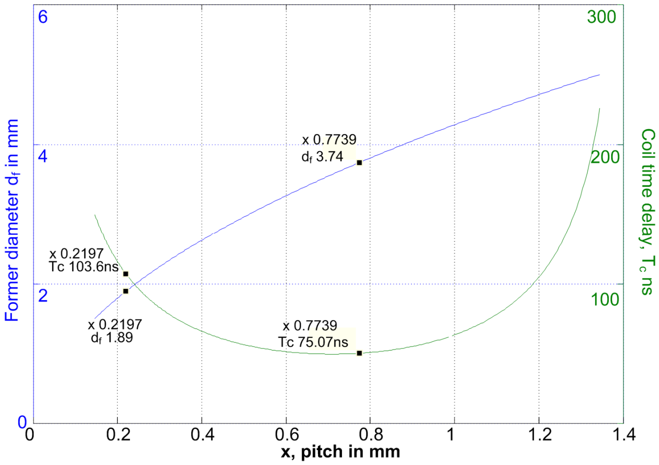


Fig 4. Variation in winding pitch x, former d_f, and coil delay T_c for H=20.0nVs/A, d_{wire}=0.22mm, d_f=6.76mm

C. *Comparison of overall transducer performance for a specified H with a different T_c*

From Fig. 4 it is informative to pick two points on the curve and compare the high and low frequency performance of two complete transducers with Rogowski coils of identical H but different T_c.

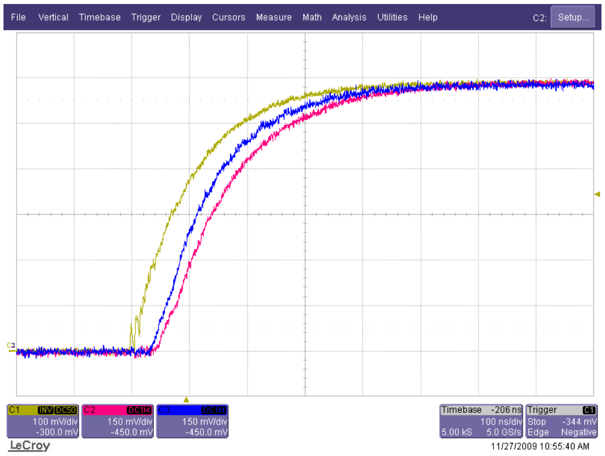
Both coils use the same integrator with T_b=10ns and a gain T_i = 2µs. This yields an overall transducer sensitivity of 10mV/A. The coil length is 445mm and the length of the cable between coil and integrator is 1m.

There is a small difference from the theoretical T_c and H predicted by Fig. 4 but not significant given our approximate formulas, the measured values for both coils are given in Table 3. where $Z_o=\sqrt{L/(C+C_s)}$:

TABLE III. MEASURED COIL VALUES

	Coil 1. **df=3.74mm, x=0.78mm**	**Coil 2.** **df=1.86mm, x=0.22mm**	
H	19.96	20.23	nVs/A
C_s	154	82.5	pF/m
C	30	39	pF/m
L	27	87	µH/m
R_d	388	836	Ω
T_c	70.5	102.8	ns/m
Z_o	383	846.2	Ω

In both cases $T_c > T_b$ so from (2) the high frequency performance is principally determined by the coil dynamics and not the integrator. Figure. 5 shows the response of the two transducers to a 10 to 90% step of approx 220ns with I_{peak} = 90A. The reference measurement is an 800MHz SDN-10 co-axial shunt with a nominal sensitivity of 100mV/A, this is in series with a 15T coil through which the Rogowski coil is threaded.



C1 INV DC50 100 mV/div -300.0 mV
C2 DC1M 150 mV/div -450.0 mV
C3 DC1M 150 mV/div -450.0 mV
Timebase -206 ns 100 ns/div 5.00 kS 5.0 GS/s
Trigger C1 Stop -344 mV Edge Negative
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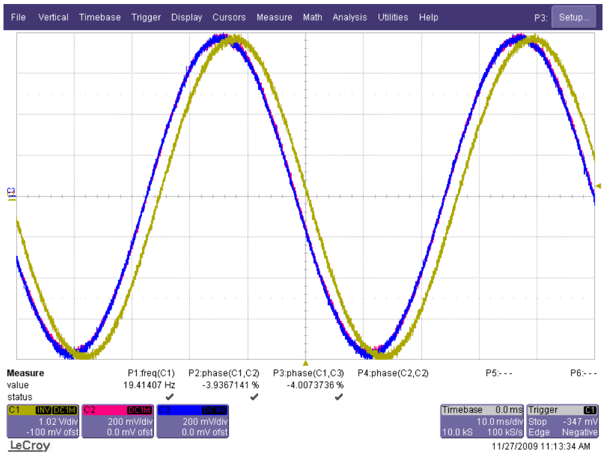
Figure 5.
C1 Yellow – SDN-100 800MHz co-ax shunt nominal 100mV/A, 100mV/div
C2 – Blue Transducer with coil 1 (15 x10mV/A), 150mV/div
C3 Red Transducer with coil 2 (15 x10mV/A), 150mV/div
Timebase: 100ns/div

The expected delay between the two traces is 14.5ns, which is evident at the start of the pulse, however the difference between the two traces increases as the current rises because T_c=46ns for the transducer with Coil 2. This is not sufficiently fast compared to the current rise time, thus some distortion of the measured waveform is evident due to the bandwidth limitation .

The low frequency limit of the two Rogowski transducers is set to be identical f_l=4.2Hz which yields a (3dB) bandwidth of 3.5Hz. Thus it is expected that the both the amplitude and phase shift should be identical measuring a 20Hz waveform, we would also expect the low frequency noise (centred around the low frequency bandwidth) to be identical. This is evidenced in Figures 6 and 7.



Measure P1:freq(C1) P2:phase(C1,C2) P3:phase(C1,C3) P4:phase(C2,C2) P5:- - - P6:- - -
value 19.41407 Hz -3.9367141 % -4.0073736 %
status ✓ ✓ ✓
C1 INV DC1M 1.02 V/div -100 mV ofst
C2 DC1M 200 mV/div 0.0 mV ofst
C3 DC1M 200 mV/div 0.0 mV ofst
Timebase 0.0 ms 10.0 ms/div 10.0 kS 100 kS/s
Trigger C1 Stop -347 mV Edge Negative
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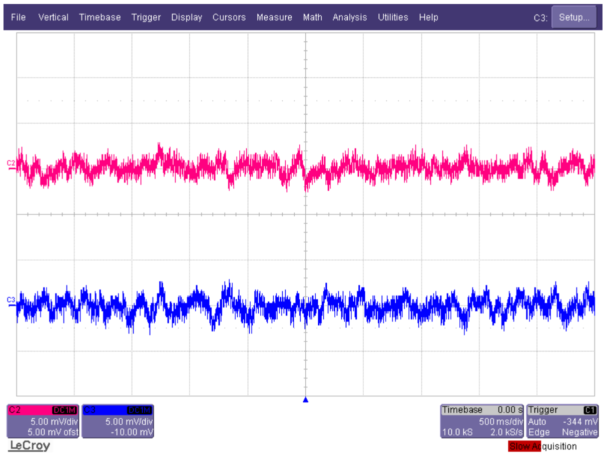
Figure 6. Measurement phase shift at 20Hz
C1 Yellow – SDN-10 400MHz co-ax shunt nominal 1.00V/A
C2 – Blue Transducer with coil 1 (through 20T x 10mV/A), 200mV/div
C3 Red Transducer with coil 2 (through 20T x 10mV/A), 200mV/div
Timebase: 10ms/div



C2 DC1M 5.00 mV/div 5.00 mV ofst
C3 DC1M 5.00 mV/div -10.00 mV
Timebase 0.00 s 500 ms/div 10.0 kS 2.0 kS/s
Trigger C1 Auto -344 mV Edge Negative

Figure 7. Low frequency noise measaurement
C2 – Blue Transducer with Coil 1 (10mV/A) 5.0mV/div
C3 Red Transducer with Coil 2 (10mnV/A) 5.0mV/div
Timebase: 500ms/div

D. A 30MHz transducer with a screened Rogowski coil

There is a degree of optimization of T_c for a given H that can be achieved, but ultimately for a specified H the additional capacitance of the screen will reduce the high frequency bandwidth. The following example shows how much the low frequency has to be 'sacrificed' to achieve a 30MHz (-3dB) bandwidth with a 445mm Rogowski coil. To quantify the effectiveness of the screen there are also results to show how the high frequency performance differs with the and without the screen.

A 30MHz (-3dB) can be achieved with T_c=6.6ns where the coil is terminated with a damping resistor R_d=152.5Ω and using an active integrator utilising an op-amp with T_b=0.8ns. Using the same coil length as the in sub-section C., and with a former diameter of d_f =3.74, and using the same d_{wire}=0.22mm and d_s=6.76mm, T_c=6.6ns can be achieved with x=5.88mm. The values for L, C and H are provided in Table 4 below.

TABLE IV MEASURED COIL VALUES

	Coil 1. df=3.74mm, x=5.875mm	**Coil 2. df=3.74mm, x=5.875mm**	
H	2.58	*as coil 1.*	nVs/A
Cs	72.4	No screen	pF/m
C	18.9	*as coil 1.*	pF/m
L	2.42	*as coil 1.*	µH/m
R_d	152.5	359	Ω
T_c	14.9	6.8	ns/m
Z_o	162.8	357.8	Ω

The same coil and integrator is used for both the screened and unscreened versions where an integrator gain of T_i = 0.26µs yields an overall transducer sensitivity of 10mV/A as per the previous sub-section. The length of the cable between coil and integrator is 1m.

The test circuit in this case is the modified high di/dt pulse rig described in [7] used to verify the hf performance of Rogowski coils. In the original design great care was taken to ensure the excitation coil through which the Rogowski coil is threaded was largely at gnd potential and away from any dV/dt interference. In this case the circuit has been modified as shown in the schematic and photograph of Figure 8a and 8b so that the excitation coil is right next to the high dV/dt and furthermore the excitation turn area has been increased to ensure a large degree of coupling to the coil. Additionally each leg of the pulse rig has been reduced to a single excitation turn (c.f. 3T on the original) so that the transducer has to resolve a smaller current in the presence of a much higher dV/dt.

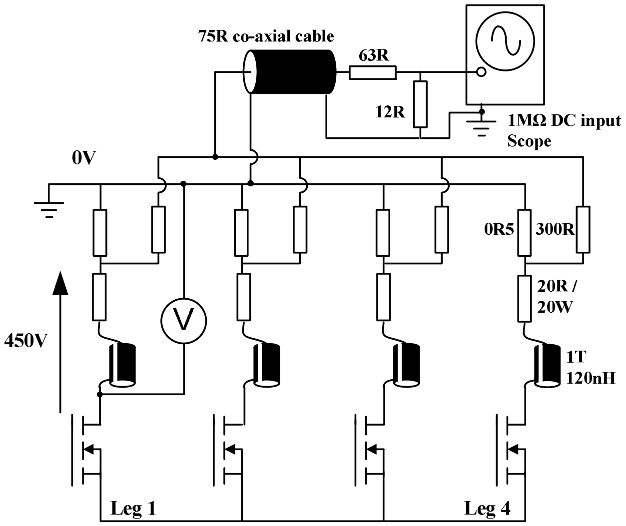


Figure 8a. Schematic of test circuit showing SMT resistor measurement and voltage measurement

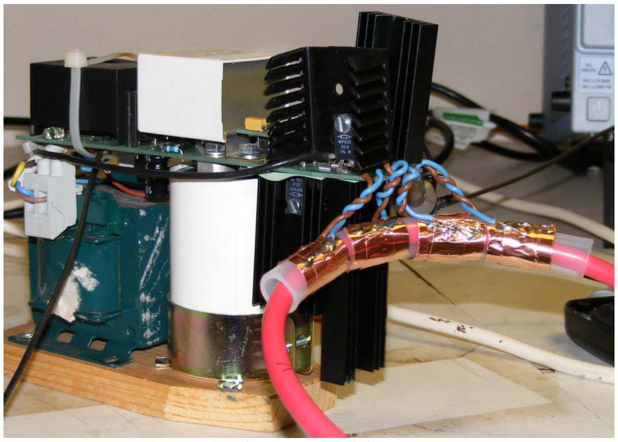


Figure 8b. Photograph of the test set-up

The results are shown in Fig 9. (Screened coil 1.) and Fig 10. (Unscreened coil 2.)

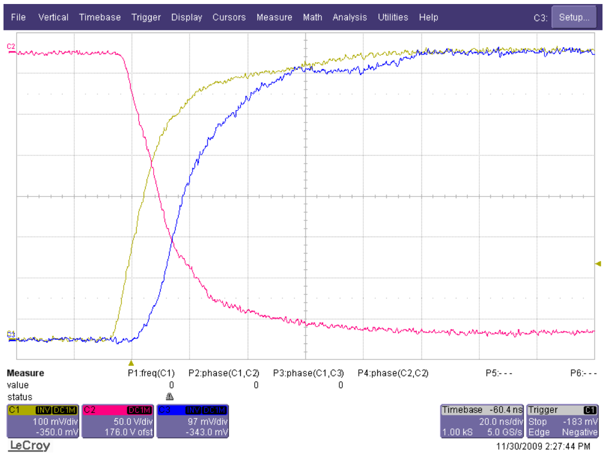


Figure 9.
C1 – Yellow – SMT resistor measurement, sensitivity 0.1V/A , 100mV/div
C2 Red –Voltage measurement 50V/div
C3- Blue – Rogowski measurement (4 x10mV/A), 97mV/div
Timebase: 20ns/div

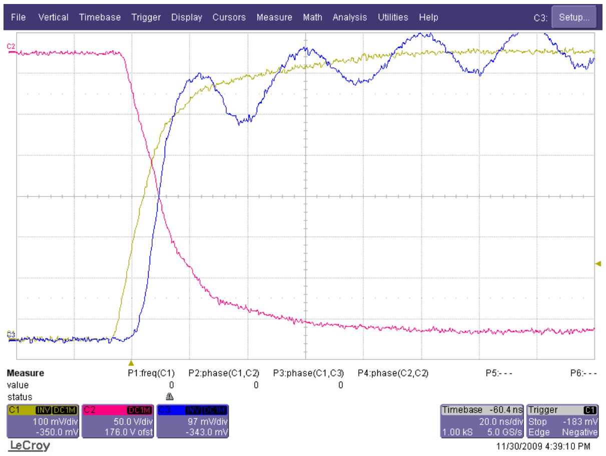


Figure 10.
C1 – Yellow – SMT resistor measurement, sensitivity 0.1V/A , 100mV/div
C2 Red –Voltage measurement 50V/div
C3- Blue – Rogowski measurement (4 x10mV/A), 97mV/div
Timebase: 20ns/div

The 10 to 90% rise time of the measurement in Fig 9. is 40ns and the measured delay of the Rogowski transducer is 13ns, in excellent agreement with the calculated delay. The waveform also shows very little distortion due to the close coupled dV/dt, which is a high as 25kV/µs at the steepest point. There is a slight ripple in the Rogowski measurement at the top of the waveform, this is larger than that exhibited by the shunt measurement. This is conceivably due to the mis-match in damping resistor R_d and Z_o but more likely to be voltage pick up.

Figure 10. shows the measurement without a screen. The measurement should have less delay than the screened version and the initial output from the Rogowski transducer indicates that this is the case. However clearly the additional capacitance added to the Rogowski coil by the excitation coils and the coupled voltage causes unwanted ringing on the output of the measurement.

The aim of a 30MHz bandwidth transducer with a screened Rogowski coil has been achieved but in order to attain such a measurement the coil sensitivity has been reduced to 2.6nVs/A. This transducer has the same overall sensitivity (10.0mV/A) and the same coil and cable length as those discussed in sub-section C. so it is interesting to compare the low frequency performance of the 30MHz transducer with the transducers described in sub-section C. With the same low frequency noise as in Fig .7, the low frequency (-3dB) bandwidth of the Rogowski transducer with H=2.6nVs/A is 60.5Hz (cf 3.5Hz). This is due to the inherently poorer noise performance of the integrator op-amp with T_b=0.8ns (it is true to say that improved GBW products always comes at the expense of poorer lf and broadband noise figures) and the reduction in coil sensitivity from 20nVs/A to 2.6nVs/A.

CONCLUSIONS

Fitting a screen to a Rogowski coil reduces its susceptibility to measurement interference through capacitive coupling of dV/dt transients onto the coil winding. The additional capacitance between screen and coil winding reduces the high frequency performance.

Setting the coil sensitivity H largely determines the low frequency performance of a Rogowski transducer. Different winding configurations will achieve the same H but produce different values for the distributed inductance, L, and capacitance, C, of the coil. The LC product determines the coil hf performance of the Rogowski coil and this can be optimized for a given H. Practical results showing this optimization process have been presented. It is however fair to say that only modest gains in high frequency performance can be achieved.

Of more interest are the results of the Rogowski transducer with a screened coil length of 445mm and overall (-3dB) transducer bandwidth of 30MHz. This demonstrates two important results:

- The delay of the measurement transient is very close to the predicted delay (and this is when measuring a current step with a 40ns rise time). The delay is not affected by the close coupled voltage source.
- The pick-up interference though not completely attenuated is very small, this is in the context of measuring 60Apk in close proximity to a 25kV/µs transient.

The compromise in achieving a 30MHz hf bandwidth is limiting the low frequency performance, where to achieve a noise of typically 8.0mVp-p with a sensitivity 10mV/A, the lf (-3dB) bandwidth has to be increased to around 60Hz.

Finally, it was the authors intention to present some results on a method of using a high frequency common mode choke to minimize I_x. Initial results show this idea works and merits the submission of a full paper at a future date.

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