The effect of electrostatic screening of Rogowski coils designed for wide-bandwidth current measurement in power electronic applications

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***Abstract*— Rogowski current transducers are ideal for monitoring pulsed and transient currents in power electronic applications as they have a high bandwidth and low insertion impedance.**

It is sometimes necessary to fit an electrostatic shield to the Rogowski coil. Large dV/dt disturbances in close proximity to the coil produce measurement interference due to capacitive coupling. A shield eliminates this coupling. However Rogowski coils are not normally fitted with an electrostatic shield since the resulting increase in coil capacitance reduces the high frequency bandwidth. Also the coil is bulkier, less flexible and more difficult to manufacture.

There are applications where local dV/dt disturbances are so large that fitting a screen is a necessity. This paper examines the compromise between the high frequency performance of the Rogowski transducer and the effective electrostatic shielding of dV/dt interference. A theoretical model for the mechanism by which large close coupled sources of dV/dt affect the behaviour of the Rogowski coil is presented. In addition the paper describes a model for the high frequency performance of a shielded Rogowski coil. These models are verified using a purpose built test rig capable of generating large dV/dt disturbances in excess of 40kV/us.

I. INTRODUCTION

Rogowski current transducers have proved to be very popular for measuring pulsed currents and switching transients. They have the following advantageous features

- a thin, flexible, and clip-around coil
- high frequency 3dB bandwidth's up to 20MHz
- low insertion impedance, typically only pH's.

It is often recommended [1,2] to fit an electrostatic shield around the Rogowski coil when a measurement is carried out in close proximity to a large source of dV/dt external to the measurement. The shield reduces the effect of measurement interference due stray capacitance between the source of dV/dt and the transducer. This is particularly a problem in power electronic circuits where large sources of dV/dt are common-place and circuit construction dictates that there is little space in which to site transducers away from the dV/dt source.

In practice electrostatic screens are rarely fitted to Rogowski coils and relatively little has been published concerning their effect. The shield increases the capacitance of the Rogowski coil which reduces the high frequency bandwidth of the Rogowski transducer and makes the coil bulkier, less flexible and more difficult to manufacture. It is also the case that for a majority of applications dV/dt sources are less than 1kV/us or sufficiently far from the coil to cause negligible measurement disturbance. However there are a number of applications where are shield is a necessity, for example strip line conductors for pulsed power applications.

II. SIMPLIFIED EQUIVALENT CIRCUIT OF ROGOWSKI COIL AND CAPACITVELY COUPLED VOLTAGE DISTURBANCE

An example of the effect of such a disturbance is shown in Figure 1. which shows the response of a CWT30 Rogowski current transducer with a sensitivity of 1.0mV/A, a high frequency 3dB cut off of typically 16MHz and a Rogowski coil circumference of 300mm. The Rogowski coil is not shielded. The coil is laid directly on an aluminium plate covered in t=1.5mm thick insulation of relative permittivity ε_r=1.7 as shown in Figure 2. The potential of the plate is raised and lowered on a repetitive basis subject to a peak of 46kV/us.

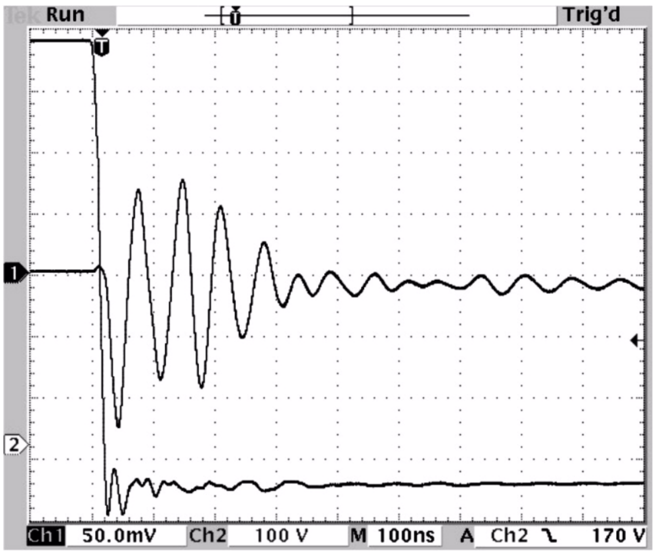

Figure 1. Measurement interference on a CWT30 Rogowski transducer due to a 46kV/us disturbance
ch1: *CWT30 transducer50A/div*
ch2: *Measured voltage on plate 100V/div*
Timebase: *100ns/div*

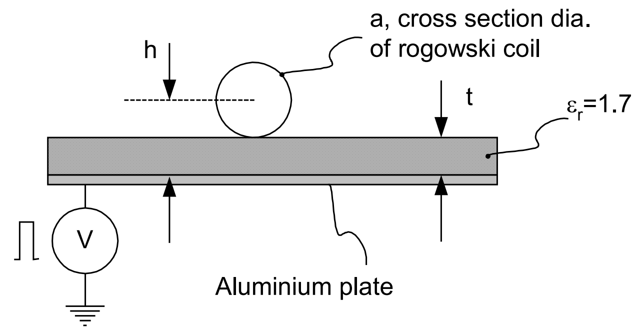

Figure 2.Experimental set-up for exposing Rogowski coil to high dV/dt

Figure 1. clearly shows that the dV/dt disturbance gives rise to measurement interference in the form of a damped sinusoid of approximate frequency 14.2MHz with a peak output from the CWT30 of 125mV. To explain this behaviour it is instructive to examine the approximate effect of stray capacitance using the previously used [3,4,5] lumped parameter model of the Rogowski coil shown in Figure 3a.

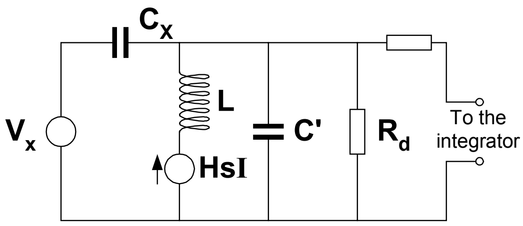

Figure 3a.

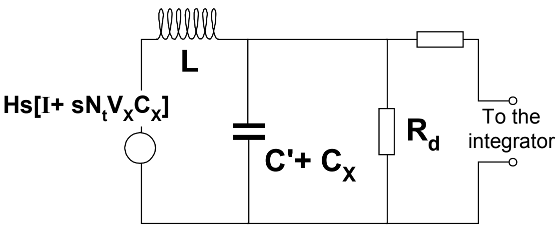

Figure 3b.
Simplified lumped parameter circuits representing the interaction between the Rogowski coil and the dV/dt disturbance coupled to the coil by capacitance C_x

For this simple model it is assumed that the distributed stray capacitance is equivalent to a single capacitor C_x linking the signal end of the coil. From the experimental set-up shown in Figure 2. we can estimate the coupled capacitance per unit length as

$$C_x = \frac{2\pi\varepsilon_o\varepsilon_r}{\ln[(4h-a)/a]} \qquad (1)$$

The distributed capacitance of the coil is approximated by $C'=(4/\pi^2)C$ where C is the measured capacitance [5]. H is the sensitivity of the coil in (Vs/A) and the distributed inductance of the coil is $L=HN_t$, where N_t is the number of coil turns. The coil is terminated by an impedance $R_d=\sqrt{(L/C')}$, to ensure good damping [5]. Further manipulation of the equivalent lumped parameter model results in the circuit shown in Figure 3b. The capacitances C_x and C' are in parallel. The coil is no longer correctly damped. The step dV/dt disturbance thus causes the 'ringing' observed in Figure 1.

Using the equivalent circuit of Figure 3b, and a simple time delay to represent the integrator the overall response of a Rogowski transducer can be modelled [3] as

$$\frac{V_{out}}{R_{SH}I_x} = \frac{1}{(1+T_bs)(1+2\xi T_cs+T_c{}^2s^2)} \qquad (2)$$

where the coil delay $T_c=\sqrt{L(C'+C_x)}$, T_b is the integrator delay, $\xi=\sqrt{(L/(C'+C_x))}/2R_d$. The input I_x is the error current predicted by the equivalent circuit model

$$I_x = C_xN_t\frac{dV_x}{dt} \qquad (3)$$

where I_x is a step of peak current 430A starting at time t=100ns.

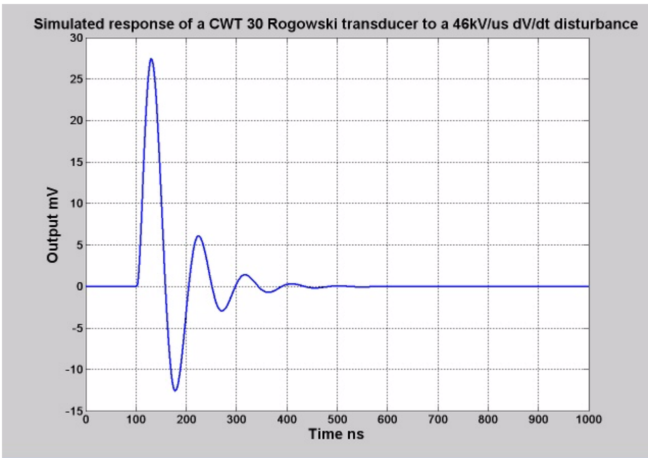

Figure 4. Simulation of CWT30 with 300mm coil response to a step disturbance 46kV/us
Timebase: 100ns/div

Figure 4 is a simulation of (2) where T_b=10ns, L=6.0uH, C'=3.65pF and $C_x\approx$32.1pF. It is apparent from Figure 4. that the model correctly predicts an under-damped response to the step disturbance. However the frequency of this oscillation (10.6MHz), peak overshoot and damped behaviour are significantly different from the practical case of Figure 1. The simple lumped parameter model is useful in so far that it enables a relatively easy assessment to be made but it only provides a very approximate prediction of the Rogowski transducer behaviour to a step dV/dt. The major reason is the coupling capacitance is not concentrated at the signal end of the coil but is distributed along its length.

III. TRANSMISSION LINE MODEL OF ROGOWSKI COIL AND CAPACITVELY COUPLED VOLTAGE DISTURBANCE

To better understand the interaction between the capacitively coupled dV/dt disturbance and the Rogowski coil it is instructive to look at the simpler system of a coil only terminated by its characteristic impedance (i.e. no integrator) and subjected to a high dV/dt.

Figure 5. Measurement interference on a 30cm Rogowski coil due to a 24kV/us disturbance
ch1: *Measured voltage on plate 50V/div*
ch2: *Coil only output 20V/div*
Timebase: *50ns/div*

Figure 5. shows the response of a coil terminated by $R_d \approx \sqrt{(L/C)}$, to a dV/dt of 24kV/us. The experimental set-up is as per Figure 2. The coil L, C and coil length are the same as the coil of the CWT30 Rogowski transducer used in Figure 1. Figure 5. shows two distinct oscillations and FFT analysis shows that these frequencies are centred around 13.5MHz and 34.5MHz. The simple equivalent system (2) of the Rogowski coil predicts only one mode of resonance.

A more representative model of the Rogowski coil and evenly distributed coupled dV/dt is shown in Figure 6.

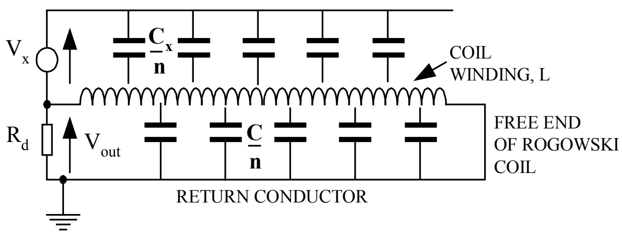

Figure 6. Transmission line 'schematic' of the Rogowski coil showing n elements

The analysis of this system is complicated. For the purposes of this paper the mathematical relationship for V_{out}/V_x is simply stated (6) and the model predictions compared with the practical results. The authors intend to provide a full derivation in a future publication.

$$F_n(\theta) = q[(2q-1)(1-\cos\theta) + (1-q)\theta\sin\theta] \qquad (4)$$

$$F_d(\theta) = [\cos\theta + q(1-q)(2(1-\cos\theta) - \theta\sin\theta)] + j\frac{Z_o}{Rd}\sin\theta \qquad (5)$$

$$\frac{V_{out}}{V_x} = \frac{F_n(\theta)}{F_d(\theta)} \qquad (6)$$

where

$\theta = \omega T_c$
$\theta = \omega\sqrt{L(C+C_x)} = 15.7\text{ns}$
$Z_o = \sqrt{L/(C+C_x)} = 382\Omega$
$R_d \approx \sqrt{L/C} = 910\Omega$
C, coil capacitance = 9.0 pF
C_x, total coupled capacitance ≈ 32.1pF

$$q = \frac{C_x}{C + C_x} = 0.781 \qquad (7)$$

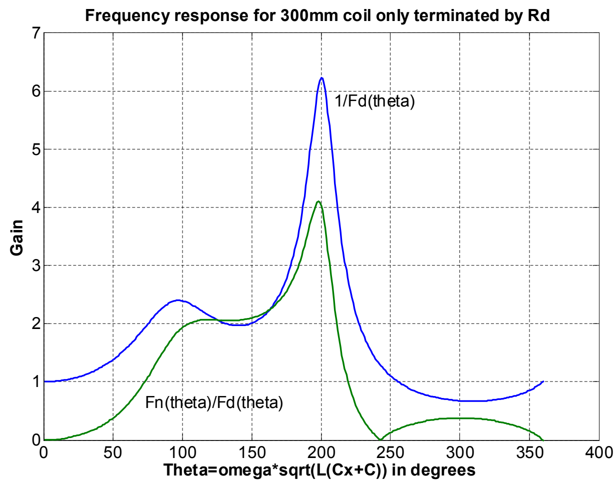

Figure 7. Simulated frequency response of a 300mm coil terminated by Rd using the transmission line model of equation (6)

On first inspection of (6) it seems probable that there should be resonance at $\theta \approx \pi$. The simulated frequency response of (6) in Figure 7. shows this is indeed the case with a sharp resonance at $\theta = 200^{\circ}$ f=35.4MHz. It is also apparent from the frequency response that equation (6) predicts a second lesser resonance at a lower frequency around $\theta = 95^{\circ}$ f= 16.8MHz. Bearing in mind that C_x is only an estimated value both resonant frequencies agree tolerably well with the frequency of oscillations that occur in the response of the Rogowski coil to a step dV/dt in Figure 5.

The transmission line representation although not perfect, does appear to give a better representation of the coil behaviour.

IV. The Effect of Electrostatic Shielding on the Rogowski Coil

To improve measurement immunity it is advisable to fit an electrostatic shield to the coil. Care must be taken to ensure that the shield does not form a shorted turn around the Rogowski coil. This will dramatically reduce the bandwidth of the transducer limiting it to measurement of frequencies substantially less than a cut-off frequency determined by the skin depth of the shield. For example the Rogowski coil of Figure 5. encircled by a copper braid of thickness 0.22mm at a diameter of 5mm, is estimated to have a bandwidth of only 7.8kHz. If however the shield is split in the median plane so as not to form a shorted turn then the restriction on bandwidth is much less severe. One way of ensuring that the shield does not form a shorted turn, yet provides good shielding, is to cover the coil in a close packed helical winding of thin copper tape ensuring that each adjacent turn has sufficient gap so as not to touch it's neighbour. Figure 8. shows the effect of such a shield on the CWT30 Rogowski transducer with 300mm coil.

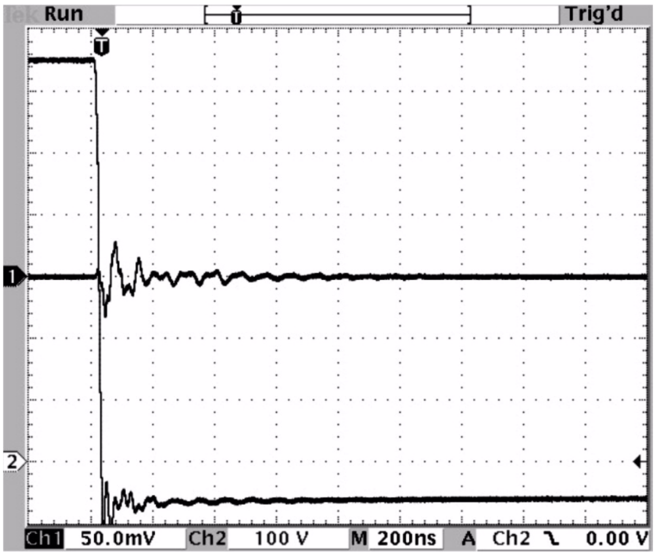

Figure 8. Measurement interference on a CWT30 Rogowski transducer with helical electrostatic shield due to a 46kV/us disturbance
ch1: *CWT30 transducer 50A/div*
ch2: *Measured voltage on plate 100V/div*
Timebase: *100ns/div*

Although the shield greatly improves the immunity of the measurement to external dV/dt it also affects the dynamic performance of the coil. With the same shielded coil of Figure 8. a step of current of 1400A changing at a rate of -6.3kA/us is measured. The response of the Rogowski transducer with shielded coil is shown in Figure 9. The comparative measurement is made with a high bandwidth current transformer (CT).

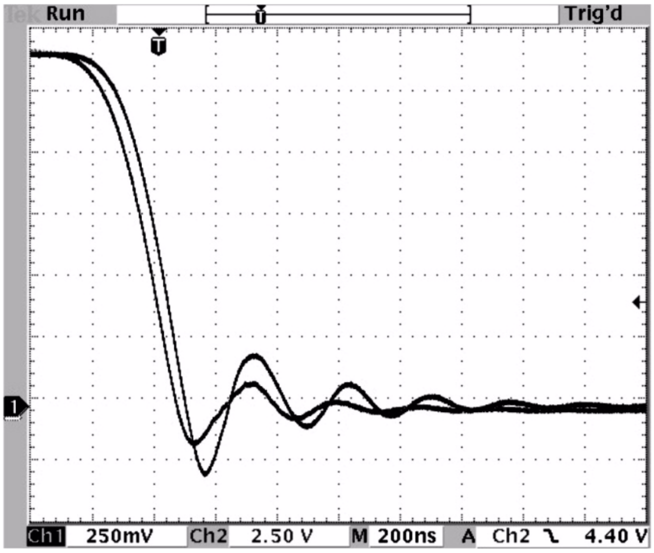

Figure 9. Response to CWT30 Rogowski current transducer with electrostatic shield to a 1400A pulse
ch1: *CWT30 transducer250 A/div*
ch2: *Pearson 411 current monitor 250A/div hf -3dB 20MHz*
Timebase: *200ns/div*

The response of the CWT30 transducer is underdamped. With the shield fitted the measured capacitance/m of the coil increases to 590pF/m. The coil is no longer correctly damped as the Rogowski transducer in this example has a terminating resistor, R_d, determined by the L and C of the coil with no account taken for the increased capacitance due to the shield. As a result of the shield the coil has a damping ratio $\zeta \approx 0.1$ and the response of the transducer is oscillatory as observed in Figure 9.

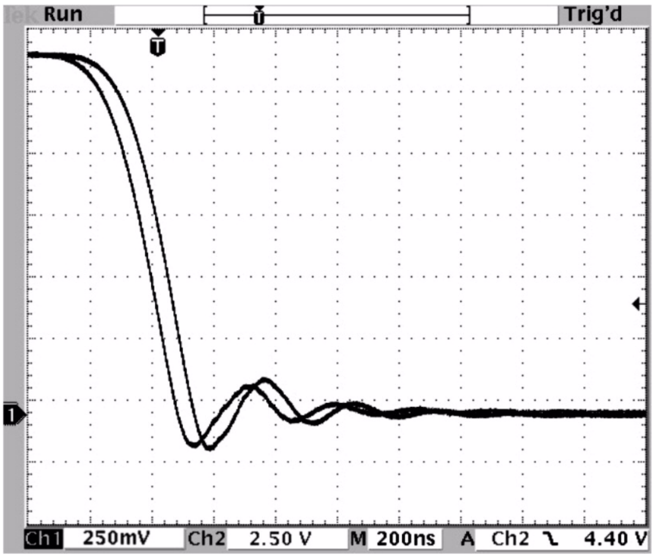

Figure 10. Response of CWT30 Rogowski transducer with electrostatic shield and correct damping
ch1: *CWT30 transducer 200 A/div*
ch2: *Pearson 411 current monitor 200A/div h.f. 3dB 20MHz*
Timebase: *200ns/div*

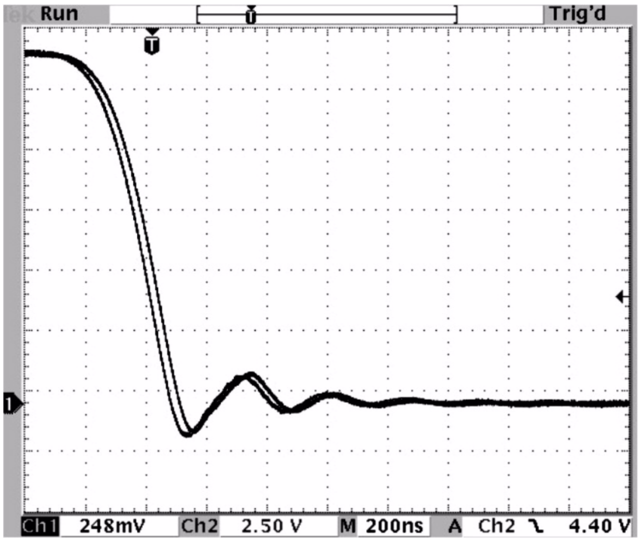

Figure 11. Response of CWT30 Rogowski transducer without electrostatic shield but with correct damping.
ch1: *CWT30 transducer 200 A/div*
ch2: *Pearson 411 current monitor 200A/div h.f. 3dB 20MHz*
Timebase: *200ns/div*

The two oscilloscope traces, Figures 10 and 11, show a comparison of the CWT30 Rogowski coil with an electrostatic shield and a CWT30 that has no shield, both having the correct coil terminating impedance to ensure that the transducer response is not oscillatory. It is apparent from Figure 10. that the response of the coil with shield is slower. This is seen by the increased delay for the measurement compared with the Pearson CT. Unfortunately the step time is insufficiently fast to show the time delay more clearly. The increase in capacitance from the electrostatic shield causes a reduction in the CWT30 Rogowski transducer 3dB bandwidth.

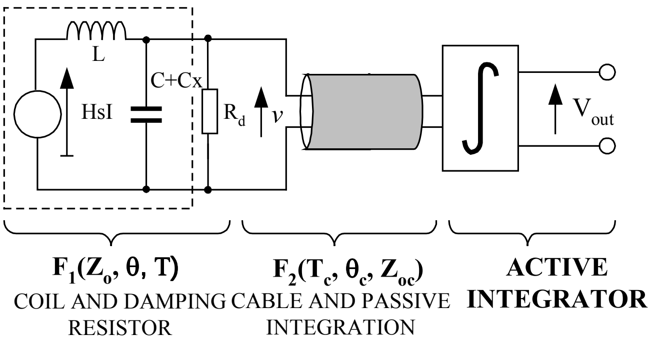

Figure 12. Rogowski current transducer comprising coil, cable and integrator

The extent of the reduction in high frequency 3dB bandwidth due to an electrostatic shield can be estimated from the complete Rogowski transducer model of Figure 12. A relationship for the dynamics of a Rogowski coil capacitively coupled to an external voltage source was given in (6). The shielded coil is a very similar system and the only modification to (6) occurs in the numerator term which gives

$$F_1(j\omega) = \frac{v}{H.j\omega I} = \frac{\cos(\theta/2)}{F_d(\theta)} \qquad (7)$$

where the measured current I is located adjacent to the coil edge, halfway around the circumference of the coil, and $F_d(\theta)$ is a per (5).

The dynamics of the coaxial cable connecting the Rogowski coil to the integrator approximate to $F_2(j\omega)\approx 1$ up to several times the bandwidth of the transducer. It should be noted that in both the theoretical and practical frequency response the intrinsic transport lag $e^{-j\theta c}$ of the co-axial cable is eliminated from the results.

The dynamics of the integrator can be represented by a simple first order delay where T_b=10ns

$$F_3(j\omega) = \frac{1}{1 + j\omega T_b} \qquad (8)$$

Thus the overall transfer function relating the measured current to the output voltage can be described as

$$\frac{V_{out}}{I} = R_{SH}.F_1(j\omega)F_2(j\omega)F_3(j\omega) \qquad (9)$$

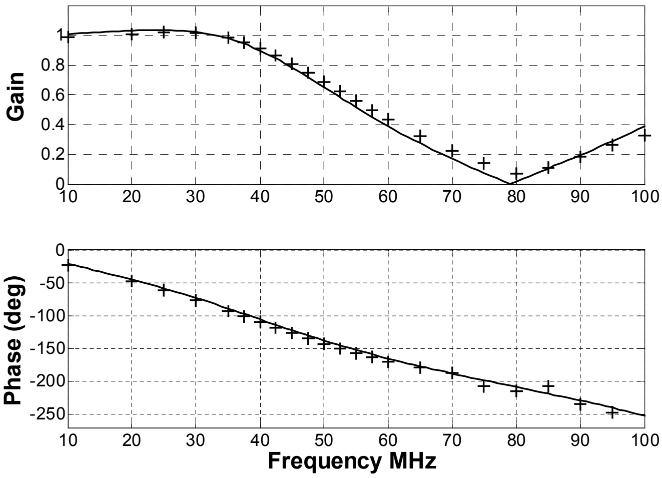

Figure 13. Frequency response of a 10mV/A, 500mm coil Rogowski current transducer also showing simulated prediction.

A practical example of the reduction of 3dB bandwidth due to a close fitted electrostatic shield on the Rogowski coil is shown in the frequency response of Figure 13. Without an electrostatic shield the predicted high frequency 3dB bandwidth of the transducer exceeds 16MHz. The Rogowski transducer under test has a sensitivity of 10.0mV/A, a 500mm coil and 2.5m cable connecting coil to integrator. The Rogowski coil has an inductance L=11.0uH and capacitance C=16.5pF. The coil is fitted with a shield where the measured shield to coil capacitance is C_x = 346.6pF. The coil terminating impedance is R_d=230Ω. The solid line in Figure 13. is a simulation of the transducer with a shield. The simulation shows the 3dB bandwidth is reduced to 4.8MHz due to the shield. The plotted points are results from a practical frequency response of the transducer. The high frequency test current is generated from a precision signal generator feeding a 10 turn coil which forms part of a resonant circuit. The Rogowski coil is fed through the 10 turn excitation coil which is located halfway around the coil circumference. The reference measurement is a 1.019Ω SDN-100 coaxial shunt with a high frequency 3dB bandwidth of 800MHz. The practical frequency response gives a 3dB bandwidth of 4.9MHz. This is in excellent agreement with the simulated case.

At frequencies above 5MHz the theoretical and practical results are in fairly good agreement. Over the frequency range of interest 1 to 10MHz the coil dynamics are dominant. The model predicts that the sensitivity becomes a minimum at f=7.9MHz, with a phase lag of 206 degrees which is found to be close to the actual values.

The differences are due to the fact that the transmission line model given in Section III is not perfect. It is based on the assumptions that the shield inductance and resistance are negligible. Of these the shield inductance is probably the most significant. However with self-integrating coils where $R_d \ll Z_o$, the coil and shield resistances also have a significant effect. In addition it should be noted a very simple model for the integrator has been used in the simulation. In reality the high frequency dynamics of the op-amp including the effect of parasitic impedances on the PCB are significantly more complex.

Nevertheless the transmission line model gives an acceptable prediction of the coil behaviour, much better than the lumped parameter model of section II.

V. Conclusion

Experience over the past ten years suggests that in a few cases, where a Rogowski coil is in very close proximity to a large source of dV/dt, the dV/dt can cause measurement interference. This paper presents a practical example of such a disturbance, a dV/dt of 46kV/us very close coupled to a 16MHz bandwidth, 1.0mV/A Rogowski transducer. To explain the transducer response a model of the interaction between the Rogowski coil and dV/dt disturbance has been developed. The model is ultimately obtained from the transmission line equations describing the coil and coupled source. Although the transfer function between coupled source and coil output is not derived in this paper, experimental results are presented which tend to verify the relationship.

When an electrostatic shield is subsequently fitted to the Rogowski coil the dV/dt interference is largely eliminated. However, the coil termination impedance must be adjusted to take account of the increased capacitance due to the shield, otherwise the high frequency performance of the transducer tends to be under-damped. Even with correct coil termination an electrostatic shield significantly reduces the high frequency 3dB bandwidth of the Rogowski transducer. A practical frequency response of a Rogowski transducer with shielded coil shows that the high frequency bandwidth of the transducer is reduced to 4.9MHz, compared with 16MHz for the unshielded case. The practical results from the frequency response were found to be in good agreement with the model prediction for a Rogowski transducer with shielded coil.

Of course the extent of the reduction in bandwidth due to the electrostatic shield depends to some extent on the application. For example spacing the screen much further from the Rogowski winding would reduce the coil – shield capacitance with no loss of shielding capability. However it is often the case that space is limited and where there is a large dV/dt in close proximity to the coil there is usually a need for substantial insulation on the Rogowski coil. Often it is these practical considerations that set the parameters for determining the high frequency performance of the Rogowski transducer with a shielded coil.

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