An improved Rogowski coil configuration for a high speed, compact current sensor with high immunity to voltage transients

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***Abstract*— Rogowski current transducers are often used to measure transient and pulsed currents in power electronic applications. They are small, clip-around and flexible making them easy to insert in circuits with a high power density, have a wide-bandwidth, and negligible insertion impedance.**

Recent advances in GaN and SiC semiconductor switches mean that the next generation of Rogowski transducers need to have:

- **Higher temperature operation.**
- **Better high frequency bandwidth, enabling measurement of of rise times of 5-20ns with good fidelity and a predictable measurement delay for power measurements.**
- **Improved rejection of common mode interference from close coupled capacitive interference due to voltage transients >20V/ns, whilst retaining high frequency capability and accuracy with conductor position in the sensor loop.**
- **Size reduction as semiconductor package sizes shrink.**

The aim of this paper is to examine the relative advantages of screened and unscreened Rogowski coils and to show that screened coils are capable of providing the high bandwidths and noise immunity required for semiconductor switching current measurements.

Keywords—Rogowski coils; wide-band current measurement

I. SCREENED VS. UNSCREENED CONVENTIONAL ROGOWSKI COILS

A paper discussing the advantages and disadvantages of screening Rogowski coils [1] was published in 2004. At that time it was concluded that the addition of a screen, whilst reducing dV/dt interference, also reduced the bandwidth due to the extra capacitance per unit length. However since then significant advances have been made to screened coils as will be reported in the present paper.

A screened Rogowski coil ideally has a thin cylindrical co-axial conductor outside the coil with a narrow slit or insulated overlap along the length of the coil to prevent the screen acting as a shorted turn which would impair its performance [2].

The major advantage of unscreened coils, with a central return conductor along the coil axis, are they are much easier to manufacture and, for a given coil sensitivity, may be expected to have a lower capacitance and therefore a higher bandwidth [1]. The major disadvantage with unscreened coils is the interference from adjacent voltage transients due to capacitive coupling to the coil. The level of interference due to the significantly increased dV/dt with new GaN/SiC switching devices has now become unacceptable in certain applications.

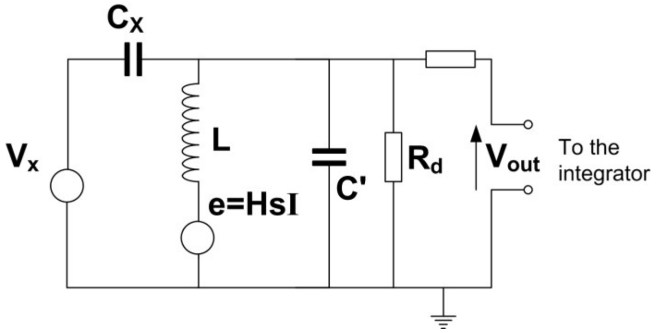

Fig. 1. The lumped parameter model of a Rogowski coil showing a voltage disturbance coupled to the coil winding via stray capacitance C_x

Fig. 1 illustrates the relative effect of the interference. It shows the well-known [3] lumped parameter model of the Rogowski coil where H is the coil sensitivity (Vs/A), L is the coil inductance, C' is the equivalent winding to return conductor capacitance (related to the distributed coil capacitance C by $C' = C(4/\pi^2)$) and R_d is the terminating (damping) resistance. Without the interference source V_x the output voltage is given by

$$\frac{V_{out}}{e} = \frac{1}{(1 + 2\xi T_c s + T_c^2 s^2)} \qquad (1)$$

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where $T_c = \sqrt{(LC')}$ and $\xi = \sqrt{((LC')/2R_d)}$. It should be noted that this simplified model only applies to frequencies for which the coil phase delay is not greater than 90° [3]. This has implications for very high frequency behaviour.

Fig. 1 also shows the simplified addition of an interference voltage source V_x coupled to the coil by capacitance C_x. In practice the coupling is likely to be distributed along the coil length. The coil is connected to ground at one end and to the integrator input at the other. If all the coupling is at the ground end then the injected current I_x flows to ground and has no effect on the integrator output. If all the coupling is at the other end (as shown in Fig 1) then the injected current has the maximum effect on the integrator output. For simplicity and illustrative purposes this situation is assumed. In practice for distributed coupling the effect may be approximately half.

It may be shown [1] that for equation (1) the induced voltage, e, should be replaced by

$$e = sH(I + sN_tV_xC_x) \qquad (2)$$

where N_t = total coil turns (for a close packed coil).

At a specific interference voltage frequency ω (rad/s) the effect of the interference is an error measurement $I_{error}=\omega N_tV_xC_x$. For example for ωV_x=20V/ns pk, N_t=500 and C_x=10pF (typical values), I_{error} = 100A pk. This would clearly be unacceptable for most applications.

A further disadvantage of unscreened coils, not well appreciated, is that at high frequencies the coils behaviour deviates from that of a conventional transmission line. This has been partly reported in [4]. The coil behaves as an aerial, propagating radially besides axially and the overall sensitivity is affected by the proximity of the coil to external surfaces. This is similar to external coupling capacitances which affect the damping of the coil. Screening the coil eliminates this effect and the coil approximates to the conventional transmission line. The capacitance is constant and its behaviour can be more accurately predicted.

The screen also eliminates or largely reduces the interference. The capacitive coupling C_x shown in Fig 1 terminates on the screen and not on the coil so that, provided the screen is of relatively low impedance and connected to ground, the injected current I_x flows to ground and not to the integrator input. However, there are several alternative screen configurations and policies of connecting the screen to the integrator as examined in Section II.

II. SCREEN CONNECTIONS

Fig. 2 shows three different screen configurations. The first comprises a conventional Rogowski coil with a central return conductor for connection to the integrator input. The screen surrounds the coil and is connected to ground, preferably at the integrator output. However, it reduces the overall high frequency bandwidth (-3dB) by adding capacitance C_s in parallel to C’ (2) such that $T_c=\sqrt{L(C'+C_s)}$. The damping ratio $\xi=\sqrt{(L/(C'+C_s))}/2R_d$ can be adjusted by choice of R_d to give a satisfactory value.

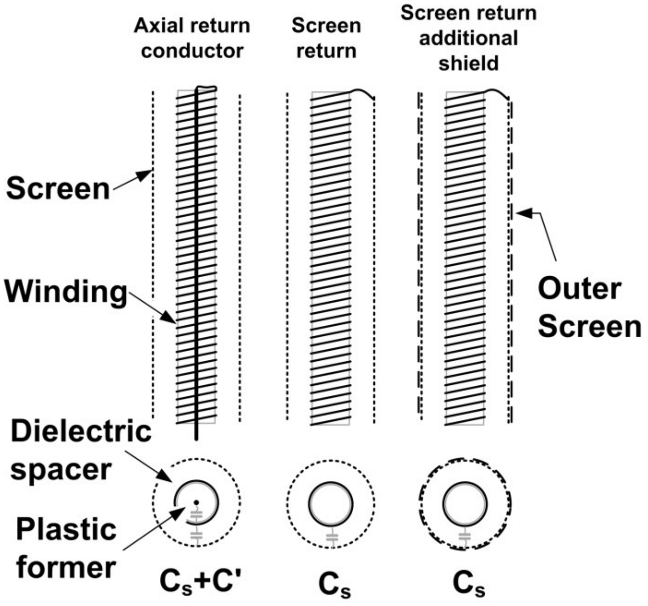


Fig. 2. Different configurations for the screened coils

Clearly it is possible to reduce the number of turns to improve the dynamic response of a screened Rogowski coil by reducing the inductance L. However this also reduces the coil sensitivity H and thus the overall low frequency signal to noise ratio of the transducer for a given low frequency bandwidth [5].

An alternative construction of Rogowski coil, which eliminates one source of coil capacitance but maintains H for a given coil cross section diameter, is to remove the central return conductor and to use the screen as the return conductor (shown as the second configuration of Fig. 2).

To differentiate from the conventional coil with a central return, this configuration will henceforth be referred to as **the inverted coil**. This is not a new idea. The foundation Rogowski coil paper by Cooper in 1963 [6] used an inverted coil. It has the obvious benefit of eliminating C’ and thereby improving the hf response.

However, there are two main disadvantages. The first is that adding a screen increases the outer diameter of the coil unless the winding diameter is significant reduced, and a reduced turn area reduces the coil sensitivity H with the reduction of low frequency bandwidth already mentioned.

Secondly the screen is now doing two tasks – firstly it connects the coil signal to the integrator input and secondly it provides a path for the interference current I_x as shown in Fig. 3a.

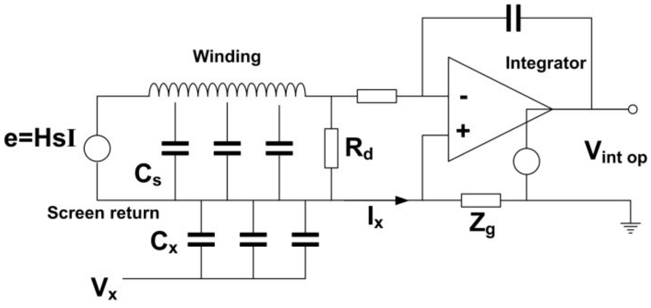


Fig. 3a. Showing the effect of parasitic impedance Z_g and the displacement current I_x creating a common mode error on $V_{int\ op}$

The screen return must be connected directly to the integrator common (+) input rather than to ground at the output. Due to PCB track resistance and other parasitics there will be some impedance Z_g between these points. The interference current I_x will therefore cause some additional input to the integrator which will appear as interference, albeit reduced from the non-screen case.

The problem is overcome by the addition of a second screen [2] shown as the third configuration in Fig 2. The connection to the integrator is shown in Fig 3b. For simplicity the coupling capacitance C_x is not shown in this figure.

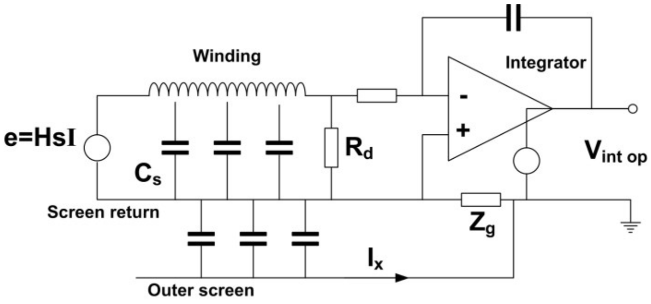
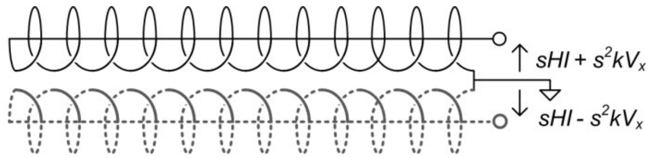


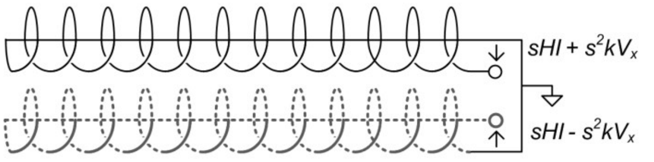
Fig. 3b. Showing the elimination of the common mode error due to Z_g by connecting to outer screen to ground at the output.

III. DIFFERENTIAL COILS THAT ELIMINATE VOLTAGE INTERFERENCE

Interference can be eliminated or significantly reduced by utilising two coils in a differential mode [7]. In principle two Rogowski coils, either sharing a plastic coil former or in very close proximity and both with an axial return, are wound or connected in anti-phase. Inverting the output signal of one of the coils and summing it with that from the other coil output produces a voltage, V_{out}, proportional to 2H.dI/dt. The parasitic voltage produced by stray capacitance coupling the windings to the noise source V_x is cancelled.



a. Opposing directions



b. Wound in the same direction

Fig. 4. Two different implementations of a differential Rogowski coil

Two possible differential Rogowski coil configurations are shown in Fig. 4. In Fig. 4a the coils are wound in opposing directions; this can be implemented on a single former where the coils cross over each other. It is claimed [7] that the coil capacitance C' is smaller than the screened case for a coil with a low turns density and that the differential coil can produce a higher (-3dB) bandwidth for a given H, and a given cross section diameter, than for an inverted coil. This obviously limits the low frequency performance but high bandwidths can indeed be achieved. In the limit, if the coil cross section diameter needs to be small, then to achieve a reasonable H, the winding will tend toward the configuration of the *'Axial return conductor'* in Fig 2. as the second winding overlaps a significant portion of the first winding. However, as with any winding configuration there are limitations, and it is not correct to say that a screened coil cannot provide equivalent high frequency performance as will be shown in the Results sections.

The major disadvantage of this configuration is that it is extremely difficult to wind coils with opposite turn directions, even with a single low density winding, and it is harder still to ensure that the second winding is identically superimposed (necessary in a differential coil to ensure correct voltage cancellation). Additionally the accuracy of a Rogowski coil in relation to the position of the current in the coil loop and its ability to reject currents external to the Rogowski coil is dependent on the uniformity of the turn's density, and the consistency of the coil former cross section. This is again very difficult to achieve.

A second differential coil implementation wound with either a twisted pair winding wire, or a bi-filar wire, is also proposed [7] and shown in Fig. 4b. The major problem is that each coil is grounded at a different end. This configuration only really achieves its objective if the voltage disturbance is symmetrically coupled along the length of the coil or concentrated at its middle. However with a point source conductor touching the internal edge of the coil at some other point, as is usually the case in power electronics, the different impedance to ground between the two coils means the cancellation is no longer effective. This also applies to the position of the current being measured. If the current is adjacent to a point on the coil other than the middle then the delay in reaching the integrator input will be different for the coils and will affect the high frequency behaviour. In addition there is capacitive coupling directly between the two coils which will significantly increase C', being at least comparable if not worse than a screened coil with the same sensitivity and thickness.

Finally in both implementations shown in Fig. 4 C_x changes the dynamics of the Rogowski coil even if the parasitic error voltage is correctly cancelled. Thus the overall high frequency dynamics of the Rogowski coil are affected by the environment in the same way as an unscreened coil as mentioned in Section 1. This is not the case for a screened Rogowski coil as will be shown.

IV. TEST RESULTS FOR CLIP-AROUND PROBES

Various tests were undertaken to demonstrate that screened, clip around, Rogowski probes are capable of accurately measuring fast step responses whilst also eliminating interference due to high dV/dt pick-up.

a. Step response tests with a 30 MHz screened probe

The commercially available probe has a rated current of 300A and a bandwidth (-3dB) of 50Hz to 30MHz. The coil length and thickness are 100mm and 4.5 mm respectively. The coil is connected by a 1m cable to an electronic integrator.

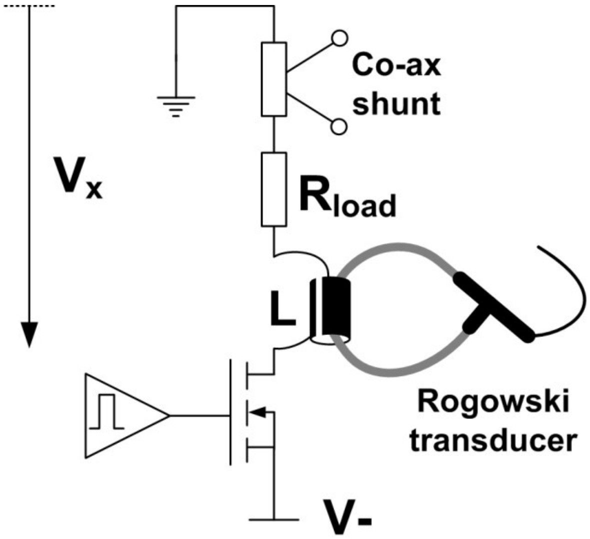


Fig. 5a. Test pulse circuit schematic

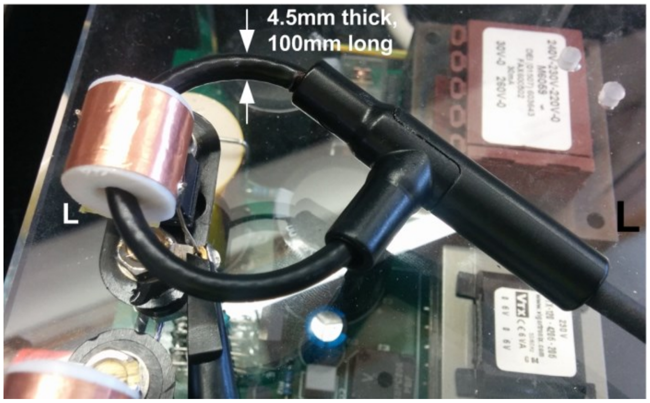


Fig. 5b. Test pulse circuit

The test circuit is shown in Figs. 5a and 5b. The measured current is 12A and the step transient has a 10-90% rise time of 25ns in the in the presence of a dV_x/dt of approximately 19V/ns. The photograph of Fig. 5b shows the voltage is close coupled and distributed over at least 15% of the coil length, with a coupling capacitance C_x of 1.8pF.

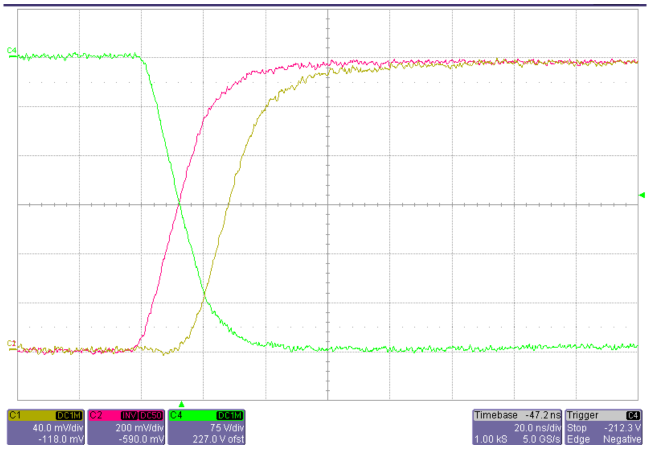


Fig. 5c. Response with intrinsic coil, cable, integrator delay of 17.5ns

In Fig. 5c the measurement shows the inherent delay of the coil, cable and integrator. These delays are all predictable and total 17.5ns for this probe, which applies to all rise-times up to 20ns. Fig. 5d shows the measured step accurately fits the original by "de-skewing" the output by 17.5ns. Since the screened coil is immune to the influence of C_x , the delay isn't affected by the environment, thus the scope can be used for the accurate measurement of power loss during switching transients.

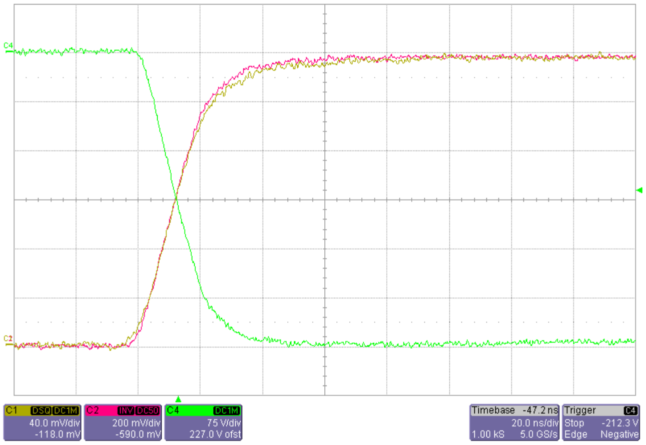


Fig. 5d. Response with 17.5ns de-skew

There will always be a limit to the rise time for accurate measurement. Faster transients than 20ns for this probe will cause additional delay and increasing distortion of the measured waveform (i.e. the measured step will not match the original as in Fig.5d).

For the waveforms of Fig. 5.

Ch1 - YELLOW: 300A peak rated Rogowski transducer, (-3dB) 50Hz to 30MHz, 40mV/div (2A/div)

Ch2 - RED leading rising edge: Co-ax shunt SDN-414-10 DC-2GHz, 200mV/div (2A/div)

Ch4 - GREEN falling edge: Voltage, V_x, 75V/div, dV_x/dt=19V/ns

Time-base: 20ns/div

b. Step response tests with a 50 MHz screened probe

The same physical configuration of coil, cable and integrator, as described in Fig. 5 is used except that the probe bandwidth is increased by reducing the turns density of the coil. To maintain the low frequency signal to noise ratio of the probe the low frequency bandwidth is also adjusted to give an overall (-3dB) bandwidth of 100Hz to approximately 50MHz. The test circuit remains the same.

The test results are shown in Fig. 6 for which the waveforms are

Ch1 - YELLOW: 300A peak rated Rogowski transducer, (-3dB) 50Hz to 30MHz

Ch2 - RED: Co-axial shunt, (-3dB) DC to > 800MHz in all cases

Ch3 - BLUE: 300A peak rated Rogowski transducer, (-3dB) 100Hz to approx. 50MHz

To show the difference between the performance of the two probes there is a 'low frequency (lf) comparison'. Fig. 6a shows the inherent integrator noise and Fig. 6b shows the droop distortion, both of which are related to the low frequency bandwidth [5]. Despite the difference in lf bandwidth, the peak to peak noise is very similar.

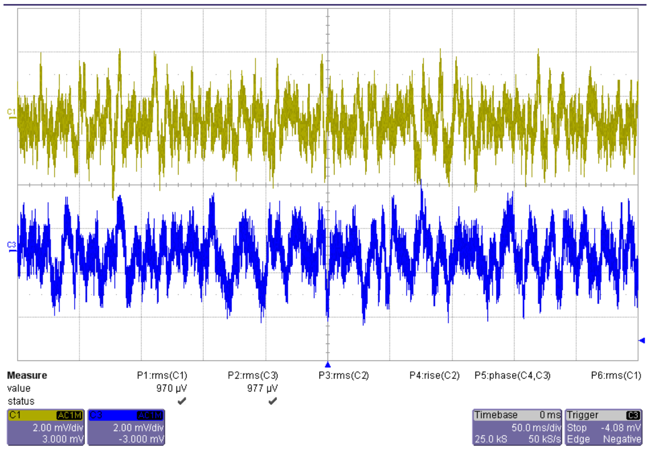


Fig. 6a. Noise (AC coupled to remove small variations in DC offset)
Both channels 2mV/div (0.1A/div) - Timebase: 50ms/div

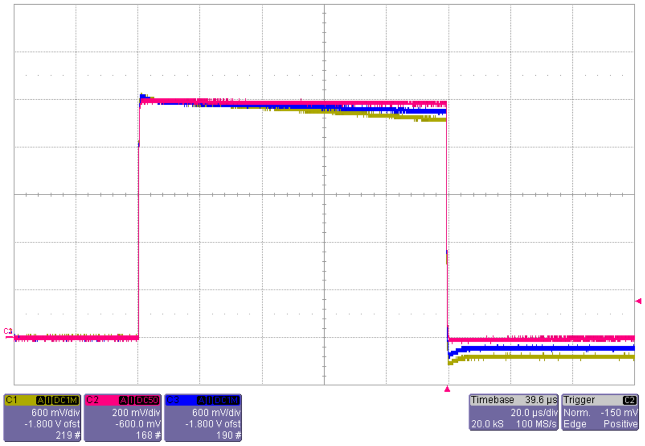


Fig. 6b. Showing difference in droop distortion on a 100µs pulse
All channels 30A/div – Time-base: 20µs/div

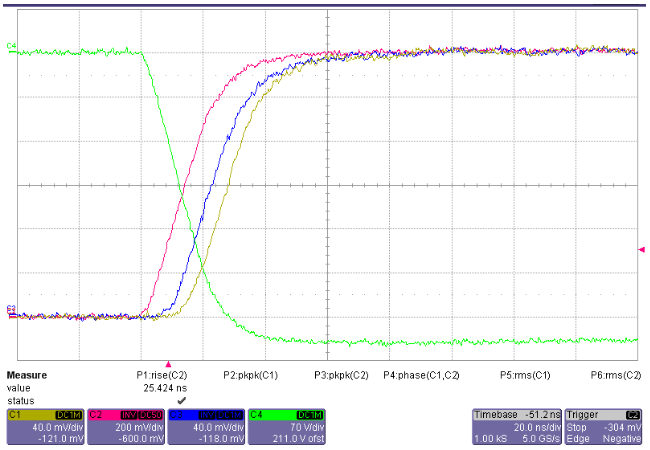
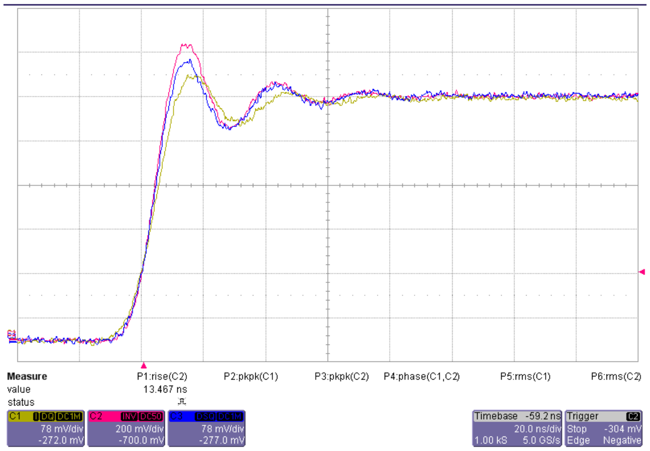
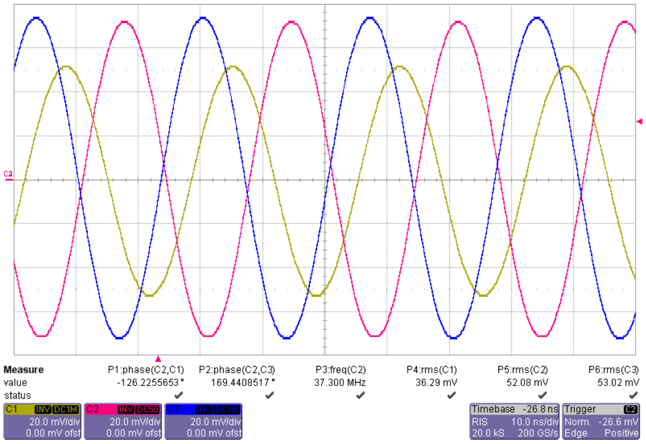


Fig. 6c. 12A, 25ns rise-time, dV_x/dt 19V/ns (CH4 Volts)
All channels 2A/div – Time-base: 20ns/div



Measure	P1:rise(C2)	P2:pkpk(C1)	P3:pkpk(C2)	P4:phase(C1,C2)	P5:rms(C1)	P6:rms(C2)
value	13.467 ns					
status						

Fig. 6d. 12A, 14ns rise-time, with >40MHz pk overshoot.
Both traces de-skewed
All channels 4A/div – Time-base: 20ns/div



Measure	P1:phase(C2,C1)	P2:phase(C2,C3)	P3:freq(C2)	P4:rms(C1)	P5:rms(C2)	P6:rms(C3)
value	-126.2255653 °	169.4408517 °	37.300 MHz	36.29 mV	52.08 mV	53.02 mV
status	✓	✓	✓	✓	✓	✓

Fig. 6e. A 37.3MHz sinusoidal current
The measured phase corresponds to probe delay
All channels 1A/div – Time-base: 10ns/div

The ‘high frequency comparison’ is shown in Figures 6c to 6e. Fig. 6c includes the same pulses with a 25ns rise time as in Fig. 5c but also has the response using the higher bandwidth 50MHz Rogowski probe. The delay of this probe is 12.5ns and this is valid for rise-times of up to 14ns using this 100mm coil.

Fig. 6d shows the same pulses as for Fig. 6c except that (i) the rise time is decreased from 25ns to 14ns and (ii) the probe outputs are de-skewed by 17.5ns and 12.5ns respectively. The the 50MHz probe measurement matches the 14ns rising edge of the pulse as measured by the shunt. However the 30MHz transducer shows some distortion and attenuation of the pulse overshoot.

Finally, in Fig. 6e, the measurement of a 37.3MHz sinusoidal current further demonstrates the difference in the high frequency capability of the two screened probes.

c. *Interference immunity tests*

The step responses shown in Figures 5c and 6c did not show any significant interference due to the transient dV/dt. However it is necessary to check the immunity over a wide frequency range which may highlight issues that a transient voltage with limited harmonic content may not show.

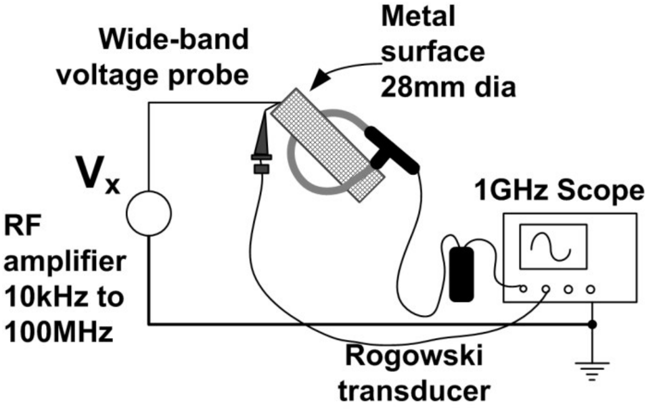


Fig. 7a. Schematic of the rf voltage test source

A simple test rig shown in Figures 7a and 7b was developed using a signal generator and a Vectawave VBA100-110 rf amplifier connected to a 28mm copper bar located inside an EMC chamber. The amplifier is capable of generating 40Vrms, 100kHz to 80MHz, a frequency range that reasonably mimics commonly encountered voltage slew rates in power converters. The Rogowski coil is clipped around the copper bar with the integrator electronics located outside the chamber. A 1 GHz scope records the integrator output voltage resulting from the coupled voltage V_x. The coupling capacitance is large, approximately 9pF.

The unit under test is the 300A ≈50MHz Rogowski transducer.

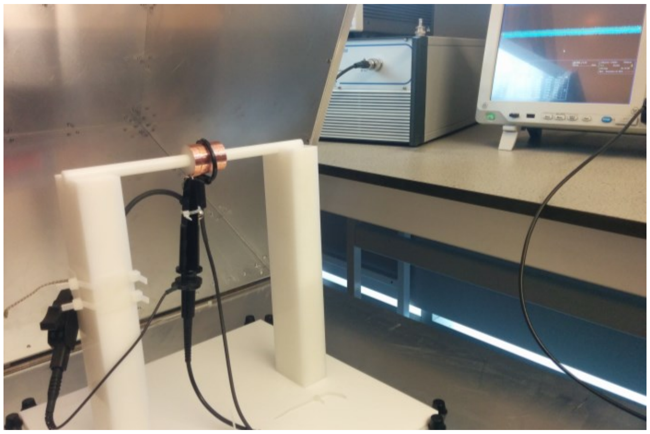


Fig. 7b. Photograph of the rf voltage test source

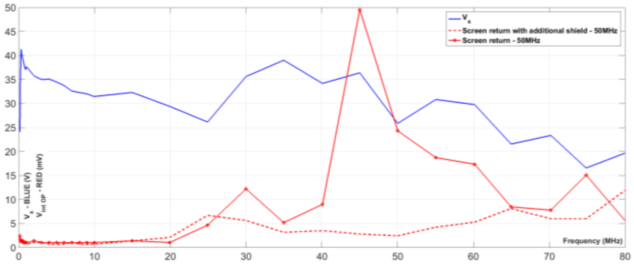


Fig. 7c. The response of the $V_{int\ OP}$ to a disturbance V_x over the frequency range 150kHz to 80MHz.

Fig. 7c shows V_x and the integrator output voltage for two cases:

- Screen return (see Fig 3a)
- Screen return with additional shield (See Fig 3b)

The additional screen improves the CMRR of the probe. Without the additional screen there is a peak in the response at approximately 45MHz of approximately 50mV (this is still less than 1% of the full scale output of the Rogowski transducer). The peak is not a function of a coil resonance; it is assumed that it is the complex interaction of C_x and the distributed impedance of the connecting cable and electronic integrator. This analysis is beyond the scope of this paper but the authors will hope to provide further analysis in a future publication. The additional screen prevents this resonance.

V. TEST RESULTS FOR A FIXED CORE COIL

Section IV. has provided test results for inverted clip-around Rogowski probes. For embedded applications and to improve accuracy, a fixed core Rogowski coil with no clip-around discontinuity is preferable. This can also utilise the inverted coil principle with an additional screen and can be constructed to be very much smaller to give very high bandwidths with excellent noise immunity.

Fig. 8 shows such a coil, which with its integrator is designed to have a (-3dB) bandwidth in excess of 60MHz.

Fig. 9 shows the response of the probe to a 10.2ns rise time current step in the presence of a dV_x/dt of approximately 12V/ns. The test is intended to specifically highlight the minimal interference. The probe is designed for 600A peak so the current peak of 7A represents only just over 1% of full scale current.

These are very preliminary test results and the best damping resistor value needs verifying together with the bandwidth for the probe. Nevertheless the measurements indicate that Rogowski probes with a 10ns step current capability can be achieved. It is expected that the response will be improved in time and further demonstrations provided at the conference.

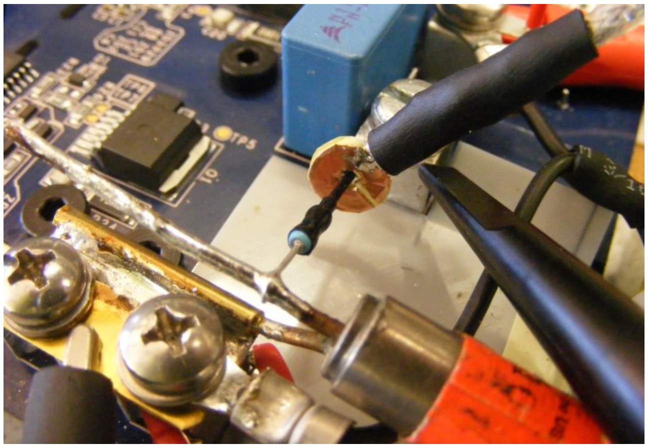


Fig. 8. A fixed core Rogowski coil 1.5mm thick and 10mm dia., with an inner hole of 2.5mm dia. shown in-situ. The test cct is as per Fig. 5. but with a faster SiC switch.

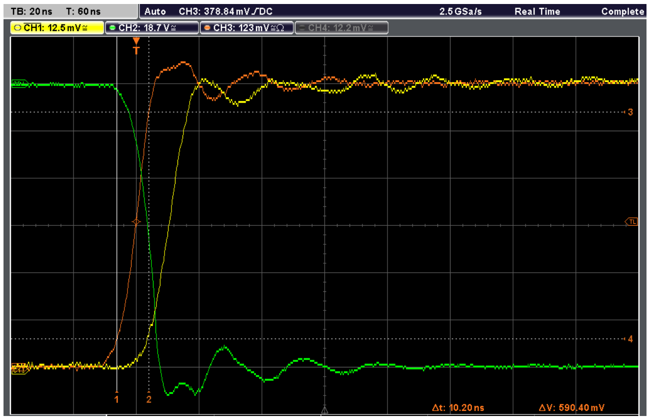


Fig. 9. Measurement of a 10.2ns rise-time on an oscilloscope with a 1GHz bandwidth

Ch1 - YELLOW: 600A peak rated Rogowski transducer with fixed core coil, (-3dB) 100Hz to estimated 60MHz, 12.5mV/div (1.25A/div), delay is approximately 11.4ns

Ch2 - RED leading rising edge: Co-ax shunt SDN-414-10 DC-2GHz, 123mV/div (1.23A/div)

Ch3 - GREEN falling edge: Voltage, V_x, 18.6V/div, $dV_x/dt \approx 12V/ns$

Time-base: 20ns/div

CONCLUSION

An inverted Rogowski coil with an additional screen provides higher interference immunity and improved high frequency performance compared with a simple inverted coil, or a conventional Rogowski coil with an axial return and screen, without sacrificing coil size or low frequency performance.

The paper demonstrates that a wide-bandwidth Rogowski clip-around current probe can be achieved using this construction with a high frequency bandwidth (-3dB) of approx. 50MHz utilising a 100mm long, 4.5mm thick coil.

Practical evidence of the ability of these screened coils to reject fast transient, close coupled, $dV_x/dt > 12V/ns$ over a wide frequency range is provided. Additionally the results demonstrate that the Rogowski coil high frequency dynamics are not altered by C_x, the parasitic coupled capacitance.

Finally, fixed core Rogowski coils of smaller dimensions are feasible and can measure current steps with rise times of 10ns.

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