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Abstract

This application note is one of a three-piece series about using PCB Rogowski coils for current sensing applications. This application note provides a detailed explanation of the operating principles of Rogowski coil current sensor. Additionally, the document explains the unique design challenges associated with PCB-based Rogowski coils and presents optimized design methodologies to overcome these challenges.

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1 Introduction

A Rogowski coil is an indirect current sensor consisting of a helical coil of wire wound around a non-magnetic core (air core), designed to measure alternating current (AC) by producing a voltage proportional to the rate of change of the current flowing through a conductor. Unlike traditional current transformers, Rogowski coils do not require a magnetic core that saturates, allowing for highly customizable and lightweight sensor geometries. For modern, compact, and cost-effective applications, these sensors can be fabricated using PCB materials, enabling precise winding patterns and integration into high-density electronic assemblies.

This application note explores critical issues such as low signal amplitude, noise sensitivity, and the necessity of high-performance integration, while offering practical solutions involving TI's recommendations for an analog front end and an optimized coil generation tool. Furthermore, this document builds upon the [Benefits of Switching to Rogowski Coil in E-metering](#) application brief, ultimately providing a comprehensive *Guide to Electricity Meter Design: From Current Sensors to KWh*.

2 Working Principles

The Rogowski coil relies on the principles of electromagnetism to sense current. Specifically, the Rogowski coil exploits the direct interaction between the magnetic flux generated by a current-carrying conductor and the turns of a coil wound around an air-core or other non-magnetic structure.

2.1 Electromagnetic Induction

The fundamental operation of a Rogowski coil is rooted in Faraday's law of induction and Biot-Savart law, which states that a time-varying magnetic field generated by the flow of current in a wire through a closed loop induces an electromotive force (EMF), or voltage, proportional to the rate of change of the magnetic flux.

The flow of alternating current (I_p) generates a circular magnetic field around a current carrying conductor according to the Bio-Savart law. As I_p fluctuates over time, the magnetic flux (Φ) passing through the area (dA) enclosed by the Rogowski coil also fluctuates.

Because the output of a Rogowski coil is tied to the derivative of the magnetic flux, it is inherently a frequency-dependent sensor that responds to the rate of change of the current rather than its absolute magnitude. The Rogowski coil responds to the rate of change of the current rather than the absolute magnitude of the current itself.

2.2 Mathematical Model and Sensitivity

For a Rogowski coil implemented on a PCB, the geometry is constrained by the substrate thickness and the layout area. The induced voltage for a rectangular or cylindrical PCB winding can be modeled by the following relationship:

The Rogowski coil (V_{out}) is as shown in [Equation 1](#):

$$B_0 = \frac{\mu_0 I_p \sin(\omega t)}{2\pi R} \quad (1)$$

Where:

- B_0 = magnetic field around a wire generated by the flow of current (Biot-Savart)
- μ_0 = permeability of free space
- ω = angular frequency = $2\pi f$
- I_p = primary current
- R = distance from center of wire to a measuring point

The magnetic flux across the conductive trace is given in [Equation 2](#) as:

$$\Phi = \int_a^b B_0 \times dA \quad (2)$$

Where:

- Φ = The magnetic flux across the conductive trace
- $dA = dr \times h$, which is the rectangular cross section area for element (dr) with PCB height (h)

Where:

- dr = infinitesimal conductance at a distance R from the center of wire.
- h = height of PCB

So, the total flux across the conductive trace is as shown in [Equation 3](#):

$$\Phi = \frac{\mu_0 I_p \sin(\omega t)}{2\pi} \times h \times \ln\left(\frac{b}{a}\right) \quad (3)$$

Where:

- b = outer radius
- a = inner radius

Proportional voltage to the rate of change of the magnetic flux (Faraday's law of induction) is as shown in Equation 4. Assuming primary current (I_p) and angular frequency (ω).

$$V_{out} = N \left(\frac{d\Phi}{dt} \right) \quad (4)$$

Where:

- N = number of turns

Substituting:

$$V_{out} = \frac{N\mu_0 h}{2\pi} \times \ln\left(\frac{b}{a}\right) \times \frac{dI_p \sin(\omega t)}{dt} \quad (5)$$

Solving the derivative:

$$V_{out} = \frac{N\mu_0 h}{2\pi} \times \omega I_p \times \cos(\omega t) \times \ln\left(\frac{b}{a}\right) \quad (6)$$

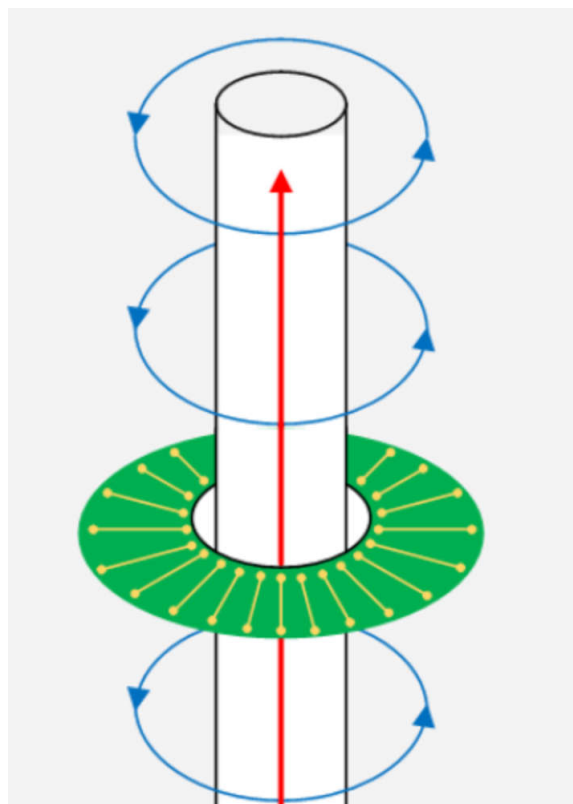
Note

(V_{out} : I_p) is referred to as sensitivity, typically measured in $\mu V/A$.

Note

Mutual inductance is part of V_{out} .

$$M = \frac{N\mu_0 h}{2\pi} \times \ln\left(\frac{b}{a}\right) \quad (7)$$



2.3 Phase Shift: 90° Offset

A critical characteristic of the Rogowski coil is its phase relationship with the primary current. Because the coil functions as a differentiator (outputting a signal proportional to dI / dt), the output voltage waveform is mathematically a derivative of the input current waveform.

For the example case of a sinusoidal current:

$$I(t) = I_p \sin(\omega t) \quad (8)$$

Output voltage is the derivative of the primary current times the mutual inductance of the PCB coil.

The derivative of the primary current:

$$\frac{dI}{dt} I(t) = \frac{dI}{dt} I_p \sin(\omega t) = \omega I_p \times \cos(\omega t) \quad (9)$$

$$V_{out} = \frac{N\mu_0 h}{2\pi} \times \omega I_p \times \cos(\omega t) \times \ln\left(\frac{b}{a}\right) \quad (10)$$

Cosine wave is shifted by 90° relative to the sine wave. Consequently, the Rogowski coil's raw output is always 90° out of phase with the actual current waveform. To reconstruct the actual current waveform for measurement, the system must include an integrator circuit in the signal chain. The integrator performs the inverse operation of differentiation, mathematically "undoing" the 90° phase shift and restoring the signal to a waveform that is in phase with the primary current.

3 Design Challenges and Workarounds

3.1 Low Signal Amplitude ($\mu\text{V/A}$)

Issue: PCB Rogowski output voltage is small due to its low sensitivity ($\mu\text{V/A}$).

Cause: physical constraints such as the PCB thickness is typically only 0.4mm to 2mm, limited number of turns, and the permeability of free space (lack of magnetic core) are all key factors to the low sensitivity of the coil highlighted in [Equation 6](#).

Plugging in coil dimensions into [Equation 6](#) from a previously designed coil (35mm outer diameter by 15mm inner diameter, and 235 turns), sensitivity is approximately $61.3\mu\text{V/A}$. This means that with every amp of current flowing through the wire going through the center of the coil, Rogowski output is $61.3\mu\text{V}$.

Workaround: need to gain the signal to a level above the noise floor of any measuring device such as an analog-to-digital converter (ADC).

3.2 Sensitivity to Noise

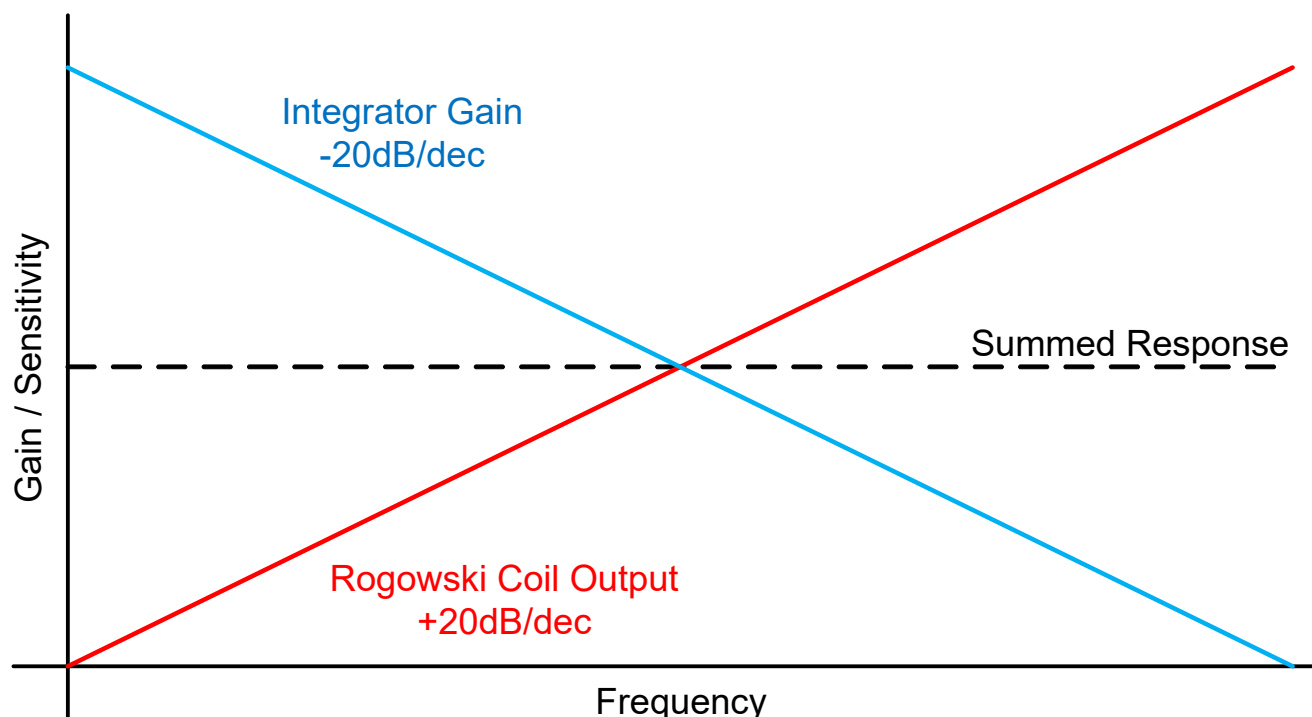
Issue: the Rogowski coil is inherently a frequency dependent sensor. Thus, when high frequency noise couples into the wire, Rogowski coil amplifies the noise.

Cause:

$$V_{\text{out}} = M \times \omega I_p \times \cos(\omega t)$$

As frequency increases, di/dt becomes larger, which increases sensitivity. Sensitivity of a Rogowski coil increases at a rate of 20dB per decade of frequency.

Workaround: need an integrator with a frequency response opposite that of the Rogowski coil (-20dB/dec). The combined frequency response becomes flat across the bandwidth, resulting in an output that is dependent on the actual current amplitude rather than frequency.

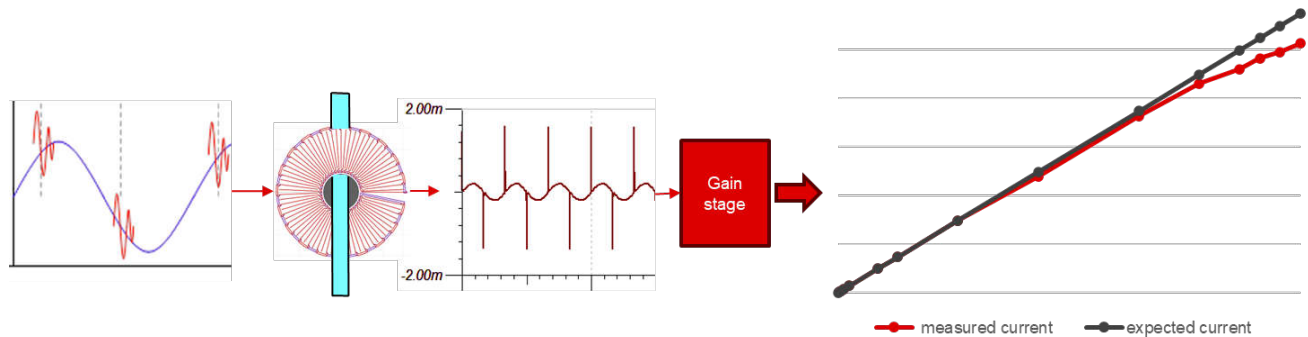


3.3 Effect of Artificial Load

Issue: in real-world applications, primary current waveforms are not clean sinusoidal waves but can have some distortion. Rogowski coils amplify this distortion and cause non-linear behavior.

Cause: conducted interference caused by non-resistive loads – inductive and capacitive loads – such as washer, dryer, drills, and stove tops.

Workaround: need to design a circuit that handles integration and amplifying Rogowski signal in the same stage so the distortion does not propagate to the entire signal chain.



3.4 Integration needed

3.4.1 Integration Theory

Issue:

- Rogowski coil output is 90° out of phase with the actual primary current waveform
- Low-frequency noise that couples into the signal chain is amplified and causes instability

Cause:

Deriving **V_{out}** as a function of primary current [$I_p \sin(\omega t)$], the coil output is a cosine wave – a signal shifted 90° relative to the sine wave of the primary current. An integrator is required after the coil to restore the correct phase relationship and recover a signal proportional to I_p itself.

For an active integrator (op-amp with feedback capacitor C and feedback resistor R in parallel), transfer functions are:

- Gain at frequency F is:

$$\frac{R_F}{R_I} \left(\frac{1}{\sqrt{1 + (2\pi F \times R_F \times C)^2}} \right) \quad (11)$$

- Phase response at frequency F is:

$$\tan^{-1}(2\pi F \times R_F \times C) \quad (12)$$

This circuit only behaves as a true integrator with constant -90° phase shift at frequencies greater than two decades above its corner frequency:

$$F_c = \frac{1}{2\pi \times R_F \times C} \quad (13)$$

Below F_c , the circuit behaves like a simple amplifier (gain flattens, phase shift collapses toward 0°) instead of an integrator. A feedback resistor R_F is required to limit DC gain — without it, the gain of the ideal integrator approaches infinity as frequency approaches zero (DC), so any DC offset or low-frequency noise coupled into the input is amplified without limit, saturating the op-amp output and causing instability.

3.4.2 Choosing Integration Frequency: Phase and Gain Margin Versus Number of Decades

Gain and phase response shrink rapidly as the measurement frequency F moves further above F_C . Generally, placing F_C one decade below the lowest frequency of interest keeps phase error under about 6° ; two decades keeps phase error under approximately 0.6° . Start by choosing a capacitor resistor pair for the desired F_C , then select R_I to set the gain.

Example Component Values:

For $F_C = 5\text{Hz}$ (1 decade below 50Hz):

Setting $C = 68\text{nF}$ (C0G/NP0)

$$R_f = \frac{1}{2\pi F_C C} = \frac{1}{2\pi(5\text{Hz})(68\text{nF})} \cong 470\text{k}\Omega \quad (14)$$

For $F_C = 0.5$ (2 decades below 50Hz):

$$R_f = \frac{1}{2\pi F_C C} = \frac{1}{2\pi(0.5\text{Hz})(68\text{nF})} \cong 4.7\text{M}\Omega \quad (15)$$

Instead of increasing feedback resistance R_f , the integration capacitance can be increased to higher than 68nF to maintain same performance at lower cutoff frequency while changing R_I to maintain gain at desired F . However, higher value C0G/NP0 capacitors are harder to find, expensive, and come in bigger packages.

Note how moving the corner down a decade requires a $10\times$ larger capacitance or feedback resistance interchangeably. Keeping in mind that large resistors increase thermal (Johnson) noise contribution and are more sensitive to PCB leakage paths and humidity.

Workaround:

To achieve the best integration accuracy:

- Use C0G/NP0 capacitors for C , these have near-zero temperature coefficient and voltage coefficient, critical since drift in C directly shifts F_C and reintroduces phase/gain errors.
- Use matched, low-tolerance resistors ($\leq 0.1\%$) for R_f and R_I to preserve gain accuracy and channel-to-channel matching in multi-phase applications.
- Use a low-noise, zero-drift (chopper-stabilized) amplifier to minimize the DC offset and $1/f$ noise that the high DC gain of the integrator can otherwise amplify. Otherwise, consider an AC coupled stage to remove DC offset.
- For best and manageable performance, a 68nF capacitor and $1\text{M}\Omega$ resistor is recommended for 2.5Hz of corner frequency, while maintaining low noise performance of the signal chain.

Recommended device:

Device Number	Voltage Rails	Input voltage noise $f = 0.1\text{Hz} - 10\text{Hz}$	Vos
TLVx387	± 3	177nVppk	1 μV
TLVx888	± 18	180nVppk	3 μV
TLVx825	± 3	320nVppk	3 μV

3.5 Stray Magnetic Fields Interference

Issue: Rogowski coils pick up stray magnetic fields close to the sensing element from nearby wires or tampering attempts.

Cause: Rogowski coils rely on detecting alternating current through the derivative of the change in magnetic flux.

Workaround: need to design a differential coil with matched and evenly distributed loops. When exposed to external magnetic fields, the differential configuration generates a common-mode signal, which can then be rejected by the analog front end.

3.6 Crosstalk

Issue: inaccurate current measurements due to the influence of external magnetic fields generated by coils placed close to one another.

Cause: The Biot-Savart law describes the magnetic field produced by a straight current-carrying wire at any point away from the center of the wire

$$B_1 = \frac{\mu_0 I_p \sin(\omega t)}{2\pi r_1} \quad (16)$$

Where B_1 is the magnetic field generated by wire 1 at any point distance (r_1) from the center of the wire.

$$B_2 = \frac{\mu_0 I_p \sin(\omega t)}{2\pi r_2} \quad (17)$$

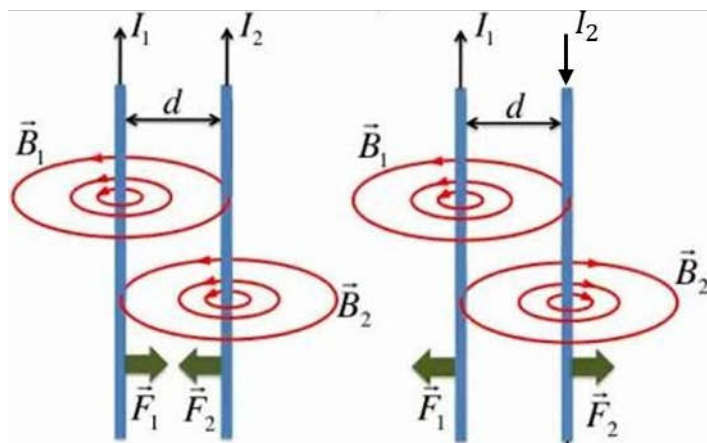
Where B_2 is the magnetic field generated by wire 2 at any point distance (r_2) from the center of the wire.

The sum of magnetic fields at any point between the wires is as shown in [Equation 18](#):

$$\Sigma B = B_1(r_1) + B_2(r_2) \cos(\theta) \quad (18)$$

Where (θ) is the orientation between B_1 and B_2 and (θ) can only be 180 or 0 if the two wires are parallel to one another.

- Case 1: If (θ) = 180°, the currents flow in the same direction, and the magnetic fields oppose each other. The sum of magnetic fields increases as distance is closer to either wire and cancel at midpoint between the two wires if current magnitudes are equal.
- Case 2: If (θ) = 0°, the currents flow in opposite directions and the magnetic fields are in the same direction reinforcing one another, producing a uniform net field between the wires. The sum of fields increases as the spacing between the wires decreases and decreases as the spacing increases.
- Case 1 and case 2 are worst case scenarios for multi-sensor system. In real world applications such as balanced 3-phase systems, the summed magnetic field is a combination of both cases. Therefore, the effect of a real-world application will be much less severe than the worst cases.



Workaround:

- Design a differential coil with matched symmetrical loops to make sure that external magnetic fields generate a common-mode signal that can be managed by the analog front end.
- Implement software calibration and crosstalk compensation to improve signal integrity.

3.7 Mechanical Considerations

Issue:

1. Wasted PCB area due to non-circular conductors such as bus bars
2. Noisy signal chain due to far placement of sensing element from signal conditioning and data acquisition
3. Increased manual labor and time spent on installment in cases where a wire is already installed

Cause:

1. Using a circular coil to wrap around a non-circular conductor creates a lot of unused space. This unused area can result in loss of extra sensitivity that can increase sensor accuracy.
2. Rogowski coil output is too small and is susceptible to noise. If coil is placed far from signal conditioning, signal is highly prone to pick up noises along the way.
3. The requirement to disconnect and reconnect wires to install a closed loop Rogowski coil creates significant operational downtime. This manual intervention increases installation time and introduces the risk of connection errors or mechanical wear during the reconnection process

Workaround:

1. A flexible or openable coil design that can simply be wrapped around a conductor or busbar offers a more practical and less intrusive alternative
2. Signal conditioning placement close to sensing coil

3.8 Errors From Non-Ideal Coil Design

Issue: Distorted output voltage due to asymmetric coil turns.

Cause: Placing coil turns in a 2-layer circular PCB coil requires complex trace routing. Mismatched loop areas and input connection contribute to noise coupling into the output.

A magnetic field generated by the flow of current in a wire is typically uniform around the wire's circumference at a distance R from the center. A Rogowski coil exploits this by using two matched winding loops (Coil 1 and Coil 2), wound with opposite sense and connected differentially, so that a uniform field sensed by the primary current produces a differential output while an external, non-uniform interference field produces a common-mode signal that is rejected by the differential measurement.

Each coil couples to the primary current (I_p) through mutual inductance M, but the two coils are also exposed to external interference. Those interference sources can be classified as inductive coupling (I_N) or capacitive coupling (V_N). The output of each coil is the combination of all three effects:

Coil 1 output:

$$V_1 = M \frac{dI_p}{dt} + M_{n1} \frac{dI_N}{dt} + \left(\frac{C_{c1}}{C_{c1} + C_p} \right) V_N \quad (19)$$

Coil 2 output (opposite winding, so the primary current term (I_p) is inverted relative to Coil 1):

$$V_2 = -M \frac{dI_p}{dt} + M_{n2} \frac{dI_N}{dt} + \left(\frac{C_{c2}}{C_{c2} + C_p} \right) V_N \quad (20)$$

Differential output:

$$V_{diff} = V_1 - V_2 = 2M \frac{dI_p}{dt} + (M_{n1} - M_{n2}) \left(\frac{dI_N}{dt} \right) + \left[\left(\frac{C_{c1}}{C_{c1} + C_p} \right) - \left(\frac{C_{c2}}{C_{c2} + C_p} \right) \right] V_N \quad (21)$$

If Coil 1 and Coil 2 are perfectly symmetric – identical turns density, loop area, and standoff distance in all three dimensions (x, y, z) relative to both the primary conductor and any external noise source – then each coil sees the same inductive coupling and the same capacitive coupling to the interferer: $M_{N1} = M_{N2}$ and $C_{C1} = C_{C2}$. The noise terms cancel exactly, leaving only the doubled desired signal:

$$V_{\text{diff}} = 2M \frac{dI}{dt} \quad (22)$$

Why symmetry in x, y, z matters: This cancellation depends entirely on the assumption that both coils occupy geometrically equivalent positions relative to every external field source. Symmetry in the x-y plane (the winding plane) makes sure both loops enclose the same area and see the same average field from the primary conductor and from in-plane interference. Symmetry in z makes sure both loops sit at the same standoff distance from out-of-plane interferers – a common source of asymmetry is via loops where one loop can sit fractionally closer to a noise source than the other. If any of these symmetries are broken, $M_{N1} \neq M_{N2}$ and $C_{C1} \neq C_{C2}$ and the bracketed noise terms in V_{diff} no longer cancel – an external field that typically produces a purely common-mode signal instead leaks into the differential output as measurement error.

Workaround: Automated coil design process. The PCB placement is done via software algorithmically to maximize symmetry and sensitivity. A novel quad-interleaved coil topology is utilized to maximize coil sensitivity and symmetry providing >55% higher sensitivity and >98% greater EMI immunity over our first-generation coil topology (patent pending).

4 Summary

This application note examined the operating principles of PCB-based Rogowski coil current sensors and the eight key design challenges engineers face when implementing them: low signal amplitude, noise sensitivity, nonlinear load distortion, the need for integration, stray magnetic field interference, inter-phase crosstalk, mechanical placement constraints, and asymmetric coil geometry from manual layout. For each challenge, practical mitigation strategies were presented — including a combined integration and amplification stage using a zero-drift op-amp with C0G/NP0 capacitors and matched 0.1% resistors, a differential coil topology for common-mode noise rejection, and close proximity placement of the signal conditioning circuit. To address the root cause of geometric asymmetry, engineers are strongly encouraged to use TI's automated PCB Rogowski Coil Design Tool, which algorithmically places coil turns to maximize symmetry and sensitivity.

5 References

1. Texas Instruments, [TIDA-011013](#), reference design
2. Texas Instruments, [TIDA-010971](#), reference design
3. Texas Instruments, [TIDA-010987](#), reference design
4. Texas Instruments, [PCB Rogowski Design Tool](#)
5. Texas Instruments, [Designing for high common-mode rejection in balanced audio inputs](#), analog design journal

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