Optimizing signal chain cost and accuracy for isolated current sensing in energy metering

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Precision analog-to-digital converters

Introduction

As we move toward a more sustainable energy grid with sources such as solar and wind power, the need arises for energy metering devices to obtain detailed insights into individual power consumption in order to identify areas for improvement, optimize usage, and reduce costs. The types of electronic end equipment that require an energy metering subsystem include smart electrical meters, electric vehicles (EVs) charging stations, power supplies and power distribution units, smart appliances, street lightning, and building automation components. The sheer number of these products drives the need for the lowest possible cost for energy metering solutions, while regional metering standards such as American National Standards Institute C12 (in the U.S.) or Measuring Instruments Directive (in Europe) impose strict accuracy and safety requirements [1], [2].

Figure 1 illustrates a typical signal chain inside an energy metering application, showing only one phase for simplicity. An analog-to-digital converter (ADC) simultaneously measures and digitizes voltage and current for each phase. Subsequently, digital signal processing extracts metrology parameters such as active and reactive power and energy, line-to-line voltages, fundamental power and energy, and harmonics [3].

The fundamental buildings blocks of the signal chain are:

- Line voltage sensing front end (A in Figure 1).
- Current measurement sensor (B).
- Front-end and signal conditioner between the current sensor and the ADC (C).
- ADC (D).
- Digital signal processing hardware (E).
- Galvanic isolation (F).

While the line voltage sensing front end is in most cases implemented using simple resistor-dividers [3], various options exist for the choice of every other building block. For each of these signal-chain components, performance, size and cost trade-offs exist. This article focuses on the performance vs. cost trade-offs for the current measurement sensor and signal conditioning, as well as the ADC.

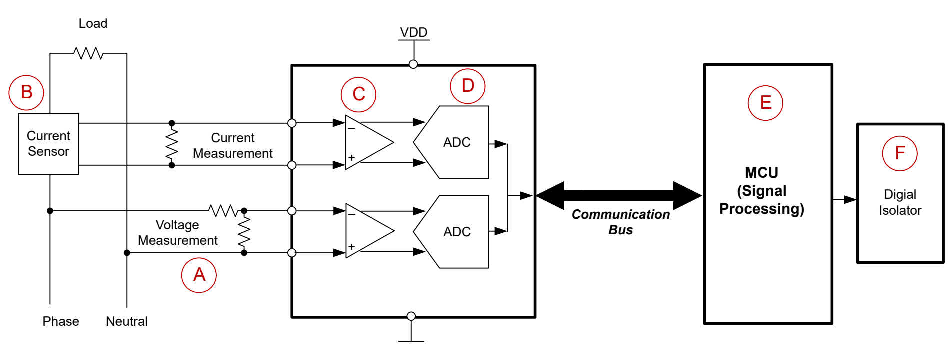


Figure 1. *Energy metering subsystem signal chain.*

Comparing current-sensor elements used for energy metering

Table 1 summarizes the performance benefits and challenges vs. cost for three current-sensing technologies used in energy metering applications. Current transformers are the most popular sensors given their wide dynamic range, durability and low insertion impedance (noninvasive current measurement) [4]. Their cost is most likely the highest of all current-sensing technologies, however. Shunt resistors (shunts) are very attractive given their magnetic immunity, smaller size and reduced cost, but lack isolation and provide less accuracy at higher currents because of thermal self-heating [5].

Rogowski coils are an interesting alternative to the other two sensors and are the lowest-cost option, especially when considering printed circuit board (PCB) coils vs. bulk Rogowski coils [6].

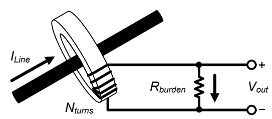
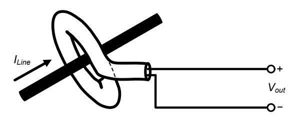
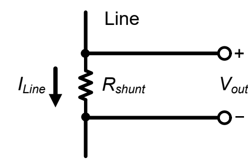
Sensor Type	Current Transformer	Rogowski Coil	Shunt
Block diagram			
Transfer function	$V_{out} = \frac{I_{line} R_{burden}}{N_{turns}}$	$V_{out} \propto \frac{dI_{line}}{dt}$	$V_{out} = I_{line} R_{shunt}$
Benefits	• Provides isolation • High linearity • High durability • High accuracy	• Provides isolation • Saturation not possible • Small form factor (PCB) • High linearity • Fast response time • Low power-loss	• Not isolated • Antimagnetic • Small form factor
Challenges	• Saturation possible • Power loss in burden resistors • Phase calibration required • Size and weight	• Integration required • Cannot measure DC • PCB coils can have lower sensitivity	• Resistance may vary when self-heated • Less reliability for overload signals
Cost	≥$0.21 (no shield) ≥$0.26 (with shield)	<$0.10 for some PCB coils ≥$0.10 for bulk coils	≥$0.10 (manganese)

***Table 1.** Current-sensor comparison.*

Because of their low cost and flexibility of installation, PCB Rogowski coils are attractive for low-cost energy metering applications [7], [8]. Let's analyze the benefits and challenges of a PCB Rogowski-based metering design and how to optimize the signal chain for the lowest possible cost while complying with regional metering standards.

Sensitivity of PCB Rogowski coils used in energy metering vs. ADC noise performance

PCB Rogowski coil sensitivity is typically specified in microvolts per ampere and depends on the geometry (number of turns, coil dimension); core material (if any); current frequency; and environmental factors (temperature, humidity, external magnetic fields) [9]. Common sensitivities range from tens to a few hundred microvolts per ampere [9].

It's a common accuracy requirement for residential electricity meters to measure a 250mA root-mean-square (RMS) phase current with 2% accuracy [1]. For example, with a 200µV/A Rogowski coil, the signal at the input of the ADC is only 200µV/A × 0.250A = 50µV for this phase current. The required ADC performance (that is, the noise which determines the effective resolution) to measure this signal with 2% accuracy is as low as 0.02 × 200µV/A × 0.250A = 1µV, as defined by **Equation 1**:

$$V_{nADC} = \text{tol} \times k \times I_{phase-rms} \quad (1)$$

where, V_{nADC} is the required noise level of the ADC, tol is the specified measurement accuracy in percentage for a given phase current, $I_{phase\text{-}rms}$ in amperes, and k is the sensitivity constant of the Rogowski coil in microvolts per ampere.

Therefore, in this example, the total noise of the ADC (the quantization noise plus white noise) needs to be lower than 1µV.

Comparing the 1µV ADC noise requirement to the specification of a precision ADC such as the Texas Instruments (TI) **ADS131M08** [10], it is clear that achieving the intended performance level may require additional averaging of the ADC samples. **Table 2** illustrates this averaging, and also shows the total ADC noise in RMS microvolts for various gain settings and data rates as defined by the oversampling ratio (OSR). With gain of 1 and a sample rate of 4kSPS (OSR = 1,024), the ADC noise is approximately 5µVrms. As noise improves at a factor of √2 for doubling the time of averaging, achieving the requirement of <1µV of ADC noise requires a time period of ≥16ms. This is acceptable for most energy metering systems, which commonly require an update rate of 20ms [1]. This type of averaging may be practically implemented with a combination of ADC internal oversampling using the delta-sigma ADC's internal oversampling ratio (OSR) feature and external post-averaging.

Another option suggested by **Table 2** is to select a higher gain for the programmable gain amplifier (PGA) internal to the ADC, as it reduces the noise referred to the input [10]. Alternatively, you could precondition the signal with an external gain stage before it arrives at the ADC. An external gain stage increases the cost of the signal chain significantly, however.

Averaging Time (ms)	OSR	Data Rate (kSPS)	Noise (µVrms), Gain 1	Noise (µVrms), Gain 128
16	65,392	0.0625	0.95	0.07
8	32,696	0.125	1.34	0.10
4	16,384	0.25	1.90	0.42
2	8,192	0.5	2.39	0.57
1	4,096	1	3.38	0.77
0.5	2,048	2	4.25	1.00
0.25	1,024	4	5.35	1.20
0.125	512	8	7.56	1.69
0.0625	256	16	10.68	2.40

Table 2. *ADC noise performance vs. speed, averaging time and OSR.*

Sensitivity analysis of an ADC signal chain for Rogowski coil-based current sensors

The primary concern for systems using a low-cost PCB Rogowski current sensor is that the signal amplitude at the sensor output is typically very small – in most cases only a few microvolts. You must design the signal chain carefully to meet the accuracy requirements driven by the metering standard. The signal conditioning of such a small signal must include significant differential gain, either by selecting a high-resolution ADC with internal gain or by cascading an external gain stage between the sensor and the ADC. Adding an external gain stage is often detrimental, as it increases total cost; therefore, it makes more sense to quantify which solutions require external gain stages and when you can avoid them.

Table 3 introduces three different Rogowski coils in order to analyze the effectiveness of an external gain stage:

- Coil A is a PCB Rogowski coil based on the High Accuracy AC Current Measurement Reference Design Using PCB Rogowski Coil Sensor [11], with a sensitivity of approximately 20µV/A.
- Coil B is another proprietary Rogowski coil with a sensitivity of approximately 100µV/A.
- Coil C is a commercially available bulk Rogowski coil (Pulse PA3209NL) [12] with a sensitivity of approximately 500µV/A.

Number	Type of Coil	Source	Sensitivity (µV/A)	Cost
A	PCB	TI reference design	20	Low
B	PCB	Proprietary	100	Medium
C	Bulk	Pulse PA3209NL	500	High

Table 3. *Rogowski coils characterized during signal-chain analysis.*

Figure 2 illustrates the measurement setup for the sensitivity analysis. The output of each individual Rogowski coil, shown in Table 3, connects to a signal-conditioning interface board where you can select or bypass the TI INA188-based gain stage [13] with four jumpers. The gain-defining resistor R_G (see Figure 2) is 390Ω, yielding an optional external gain of 128.

The output of the instrumentation amplifier (INA) interface board connects to the phase 1 current input of the Three-Phase Current Transformer E-Meter Reference Design with Standalone ADC [3]. This reference design does include burden resistors R37 and R38, which are required only when connecting to a current transformer and were physically removed for this analysis. The ADC on the e-meter reference design is the TI ADS131M08, a high-precision, eight-channel, simultaneous-sampling delta-sigma ADC with internal gain options ranging from 1 to 128.

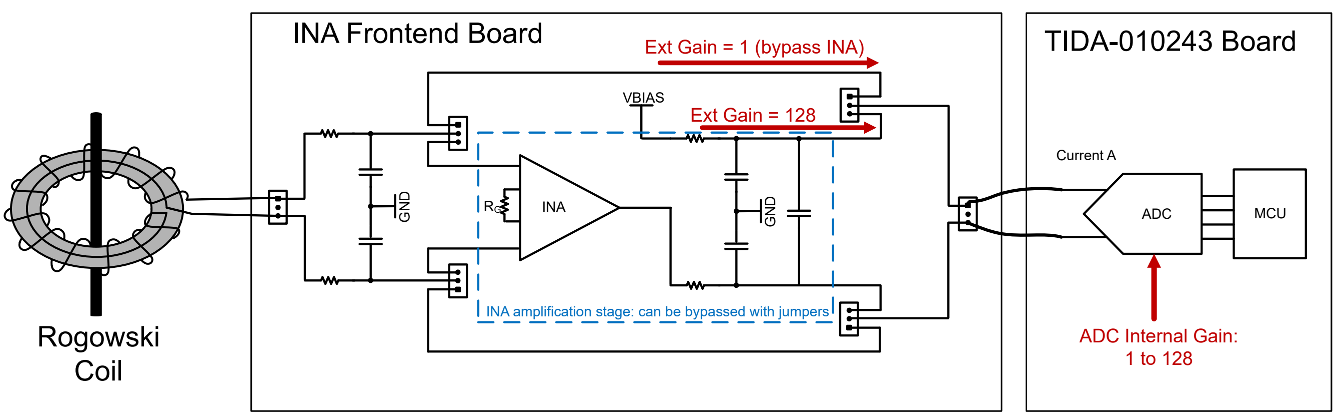


Figure 2. *Measurement setup for the signal-chain analysis.*

Figure 3 and **Figure 4** show the measured current accuracy for a 50Hz line current from 100mA to 10A using MTE's PTS3.3C source generator and reference meter. Using the same test procedure as in [3], samples of current and energy are averaged over a 20ms time period. We implement the Rogowoski signal integration in the digital domain following the procedure outlined in [11]. The alternative would be analog active integration as shown in [14], however this technique is ignored for our analysis as the two methods usually yield similar results.

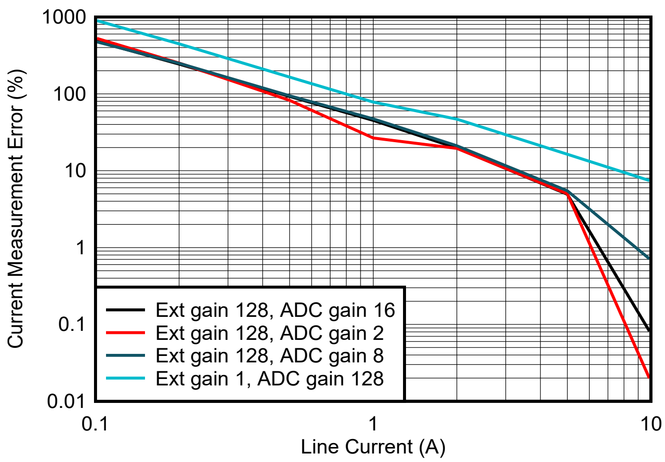


Figure 3. *Measured current accuracy for the 20µV/A coil with different gain settings.*

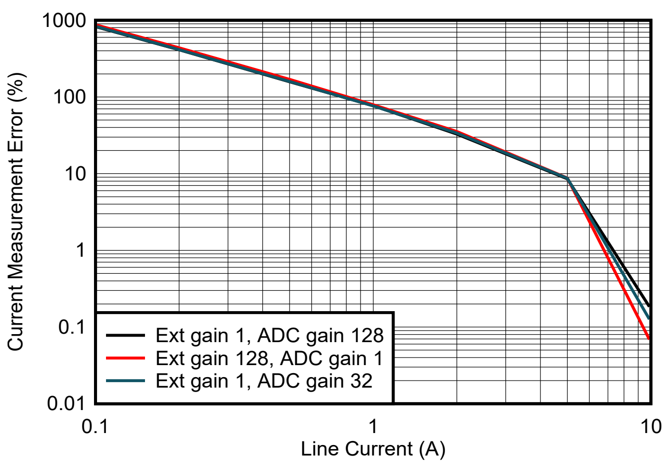


Figure 4. *Measured current accuracy for the 100µV/A coil with different gain settings.*

For a PCB coil with very low sensitivity (for example, 20µV/A), there is significant improvement when using an external gain of 128 by cascading the INA stage (see **Figure 3**). The internal PGA gain (even with a gain of 128) of the ADS131M08 alone does not sufficiently raise the small input signal above the quantization noise level, as explained previously.

When using PCB coils with a sensitivity of ≥100µV/A (see **Figure 4**), the selection of internal vs. external gain results in a comparable error, indicating that the sensor output amplitude is now well above the quantization noise level for the relevant phase current range. The absolute value of the resulting error is higher than acceptable for some revenue-grade energy metering systems, which target ≤0.5% accuracy. This increased error is the result of a simplified calibration procedure applied in this setup: a single-point (gain) calibration. In a typical metering design, applying up to three calibration steps (offset calibration, gain calibration and phase calibration) can further reduce the absolute error.

Figure 5 and **Figure 6** illustrate the dependency of the measurement error on the sensitivity of the Rogowski coil for the three different coils listed in **Table 3**.

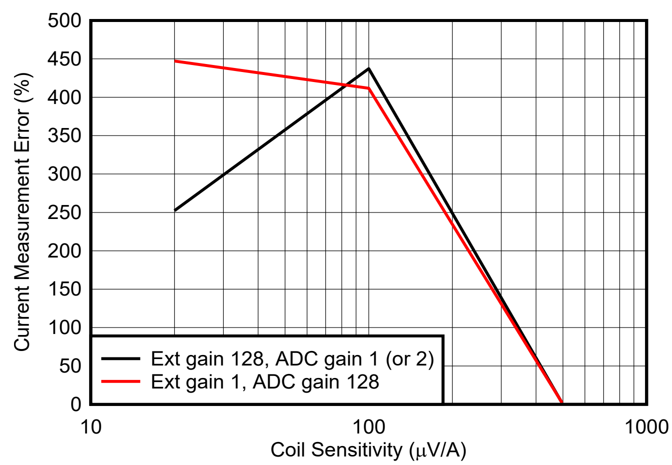


Figure 5. *Measured current accuracy for three coils at a line current of 200mA.*

Both in the case of small phase current (200mA, **Figure 5**) and mid-level phase current (5A, **Figure 6**), the 20µV/A Rogowski coil achieves a significant improvement (a smaller error) by employing the external gain stage. As expected, all errors scale to smaller values when detecting the larger line-current value (5A, **Figure 6**). For the 100µV/A and 500µV/A Rogowski coils, applying an external gain of 128 vs. using the internal ADC gain results in comparable accuracy.

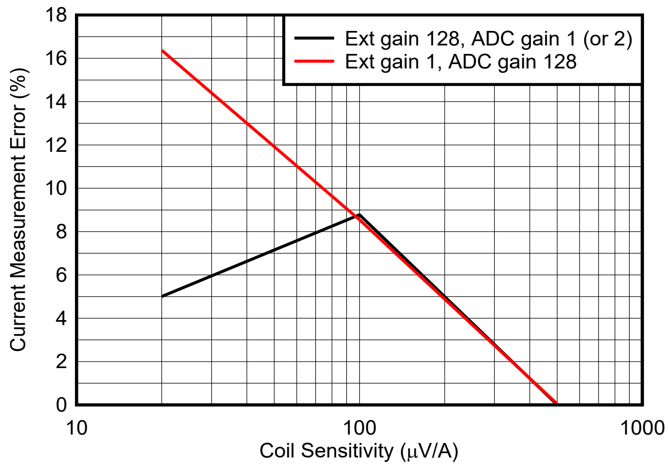


Figure 6. *Measured current accuracy for three coils at a line current of 5A.*

Conclusion

For ≥100µV/A Rogowski coils, the external gain stage is not necessary, resulting in a reduced cost for an energy metering signal-chain solution. For <100µV/A Rogowski coils, external gain may be needed to meet residential electricity metering accuracy when using the TI ADS131M08 or a comparable ADC. Or alternatively, a lower-noise, higher cost ADC may be considered to avoid the additional circuitry.

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