APPLICATION NOTE

Rogowski Coil Calibration with Rejustors

1 Introduction

Rogowski coils perform passive current measurement and are used in test and measurement devices and power monitoring activities. Calibration is required to account for manufacturing variations in the coil and provide uniform device-to-device sensitivity. Traditionally coils are compensated with an amplifier making both the coil and the amplifier a matched pair. Rejustors provide a passive compensation solution for Rogowski coils, enabling coil manufacturers to produce devices with uniform performance increasing interchangeability while reducing manufacturing complexity.

This application note describes the design process for identifying the correct Rejustor value and presents a calibration process. The coil used in this design is manufactured with 5% tolerance. Rejustors improve the accuracy to less than 0.5%.

2 Rogowski Coils Background

Rogowski coils are named for their inventor, Walter Rogowski. The coil consists of a length of wire (or conductor) wrapped around a substrate to form a circle with a hollow center. The lead from one end returns through the centre of the coil to the other end so that both terminals are at the same end of the coil. The Rogowski coil is an electrical device for non-evasive monitoring and measuring alternating current (AC) or high speed current pulses through a conductor. The coil is wrapped-around a conductor (to be measured) where changing currents induce an electrical field in the coil. The coil detects voltage signal (EMF) proportional to the *change* in the current passing through this wire.

There are two advantages to the Rogowski coil. First, it can be made open-ended and flexible, allowing it to be wrapped around a live conductor without disturbing it. Secondly, unlike conventional transformers that have an iron core, the transformer in a Rogowski coil uses an air core which provides both low impedance and there is no danger of saturating the core (as can occur in iron core transformers).

Since the voltage induced in the coil is proportional to the rate of change (derivative) of current in the straight conductor, the output of the Rogowski coil is usually connected to an integrator circuit and amplifier in order to provide an output signal that is proportional to current in the primary conductor. Figure 1 provides a simplified block diagram of the basic architecture of a system using a Rogowski coil to measure changes in current and convert it to a representative voltage output.

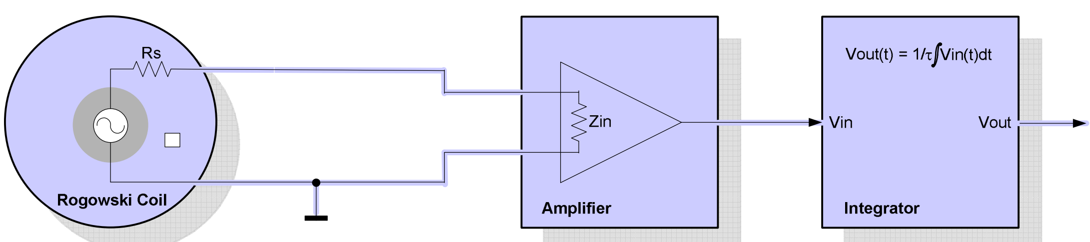

Figure 1: Simplified diagram of Rogowski coil connected to Amplifier and Integrator.

The problem with mass-producing coils is that their output voltage is susceptible a variety of manufacturing variations in the production of the coil. The challenge for designers is to find a method to calibrate each coil to produce a uniform output voltage or signal sensitivity.

Designers have typically configured their systems such that the amplifier and integrator are calibrated to match the properties of the coil. Using this configuration, the entire assembly (coil, integrator and amplifier) must be treated as a single, field-replaceable assembly. For example, current probes are sold as a coil with integrated electronics. With this configuration, users can't replace the coil without also purchasing a matching amplifier (or visa versa).

This paper proposes a change to the architecture to split the design allowing the coil and amplifier to operate as independent, field-replaceable units. This is useful in applications where an all-passive system is required – for example on a power-line where no DC-power is available or to allow current probe manufacturers to sell replacement coils without the integrated amplifier.

2.1 Rogowski Coil – Theory of Operation

The cross section of a Rogowski coil is shown on Figure 2. From Faraday's law of induction it follows that EMF (which represents the output signal of Rogowski current sensor) induced in this coil is proportional to the time-derivative of the measured current, number of turns in the coil and their area. The exact equation for output signal of N-turn rectangular Rogowski coil can be found in literature [1]:

$$EMF = (\mu NL / 2\pi)\ln(c/b)di(t)/dt \qquad (1),$$

Where L, b and c are height, inner and outer diameter of the coil respectively.

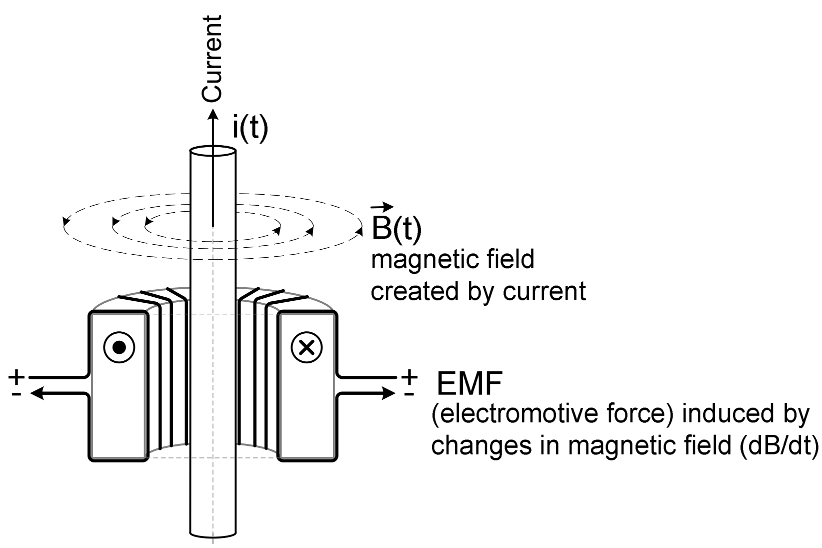

Figure 2: Inside a Rogowski Coil

The use of a PCB to implement the coil facilitates mass-production and also provides accommodation to support passive components like inductor(s), capacitor(s), resistor(s) and Rejustor(s). Since EMF is proportional to the loop area, the PCB should be relatively thick.

Another useful feature of a Rogowski sensor is immunity to far-field interference. Figure 3, below, shows that two components of EMF induced by the same far field source will cancel each other. Two components of EMF induced by the current passing through the wire inside the coil will be added to each other (Figure 2 and 3). This behaves similarly to a Common-Mode Rejection effect typically seen in electronics.

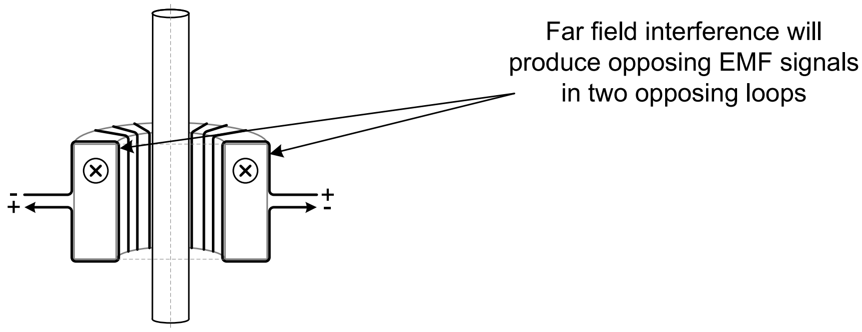

Figure 3: Far field interference cancellation

One disadvantage of the coil is that the Rogowski coil produces EMF proportional to di/dt. Therefore at connecting or disconnecting moments, the EMF goes “infinite”. Transient Voltage Suppressors (TVS) or other protection has to be considered to prevent overloading the downstream electronics.

2.2 Rejustors

Rejustors are precision adjustable resistors for applications such as Rogowski coil calibration. The resistance can be set to 0.1% precision or better, depending on the accuracy of the measurement equipment. After adjustment, Rejustors maintain their set resistance indefinitely with no external memory or stand-by power requirements. The resistance is set using electrical signals from a Rejustor Calibration Tool. This means that the complete assembly can be manufactured and encapsulated prior to calibration, which improves manufacturability and accuracy of the system.

3 Rejustors for Rogowski coil calibration

There are several good reasons to consider a Rejustor with the Rogowski coil:

1. Both Rejustors and Rogowski coils are passive devices. This feature is especially important for field applications where a current sensor is supposed to consume no power.
2. Both are high bandwidth devices. This is the key feature for applications where monitoring of current waveforms is required.
3. Both are low cost devices.
4. Rogowski coils are low impedance devices (typically tens of Ohms) while Rejustors are manufactured with much higher resistance, starting at around 5kΩ. Therefore, adding Rejustors to the coil doesn’t require a buffer.
5. Rejustors are tiny devices. There is a plenty of room for a 3mm x 3mm QFN package.
6. Both devices are well immune to temperature change. Temperature Coefficient of Resistance (TCR) for a standard Rejustor is less than 100ppm/K.

The combination of Rejustors with Rogowski coils allows manufacturers the ability to produce fully compensated coils as field replaceable assemblies. In this way, the electronic system (integrator and amplifiers) can also be manufactured with a fixed gain. This architectural change improves interchangeability – allowing any coil to be used with any amplifier and integrator while reducing in-field calibration and maintenance costs.

3.1 Choosing the Right Rejustor

The simplified diagram (applicable only for low frequencies) in Figure 4 shows a Rogowski coil with Rejustor-attenuator Rj1/Rj2 onboard. The diagram shows Rs connected in series with the AC sensor source, representing the resistance of the wire (copper for example), that was utilized to build the coil. An integrator (analog or digital) is added to make the output signal Vout proportional to the current (instead of proportional to the time-derivative of the current) and therefore to make the output frequency-independent.

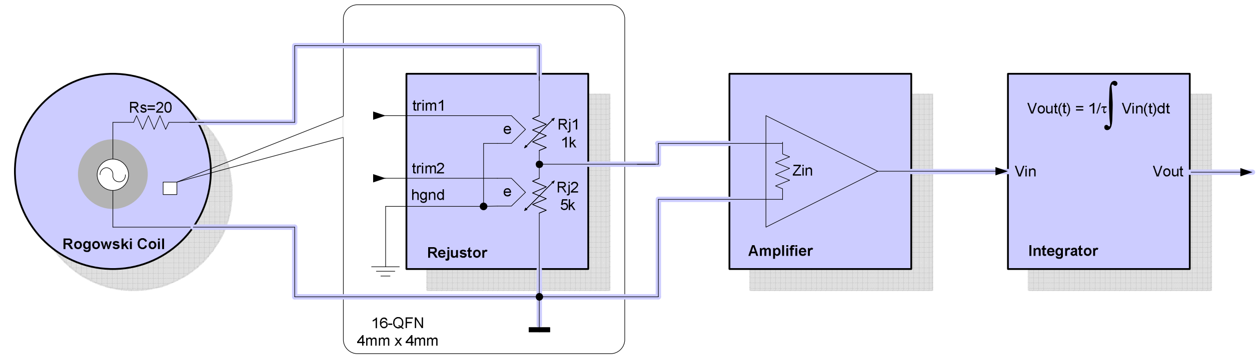

Figure 4: Simplified diagram of Rejustor-calibrated Rogowski coil connected to Amplifier and Integrator.

3.2 Design Considerations

Due to manufacturing process variations the sensitivity of the Rogowski coil is typically manufactured to an electrical tolerance of ± 5% while the target accuracy of the device after calibration may be an order-of-magnitude better, say ± 0.5% (we assume 0.5% is required accuracy for the analysis below).

For example, consider a Rogowski coil designed to measure 60Hz, 1000A current passing through a conductor. Initial sensitivity of the sensor is measured at 30μV/A, ±5%; expected target sensitivity is 24.75μV/A ± 0.5%.

The following steps outline the process to determine the correct Rejustor value for to compensate manufacturing variation in the coil.

3.2.1 Step one: Choosing attenuation ratio

A 1:5 resistor divider provides attenuation ratio 5/6 and reduces initial sensitivity from 30μV/A to 25μV/A which is quite close to the target.

3.2.2 Step two: Choosing Rejustor resistance.

From the diagram in Figure 4, it follows that in order to match input/output impedances Rejustor resistance should comply with these rules:

$$Rj1 + Rj2 \gg Rs \qquad (2)$$
$$Rj1 \,//\, Rj2 \ll Zin \qquad (3)$$

Where Rs is the resistance of the coil (in our example 20Ω) and Zin is the input impedance of the amplifier (typ >1MΩ)

Keeping in mind that high-resistance devices suffer more from EMI, we need to find out what minimum resistance can be used for Rj1 and Rj2. To make this decision let's consider:

3.2.2.1 Change in sensitivity vs. Rload

The simulation result in Figure 5 shows a loss of sensitivity of the coil (due to drop voltage across Rs) as a function of resistance of the balance Rejustors. When Rj1+Rj2 ≈ 5Rs, an expected loss of 16% occurs in the overall sensitivity of the coil (which is a reasonable loss using passive compensation techniques).

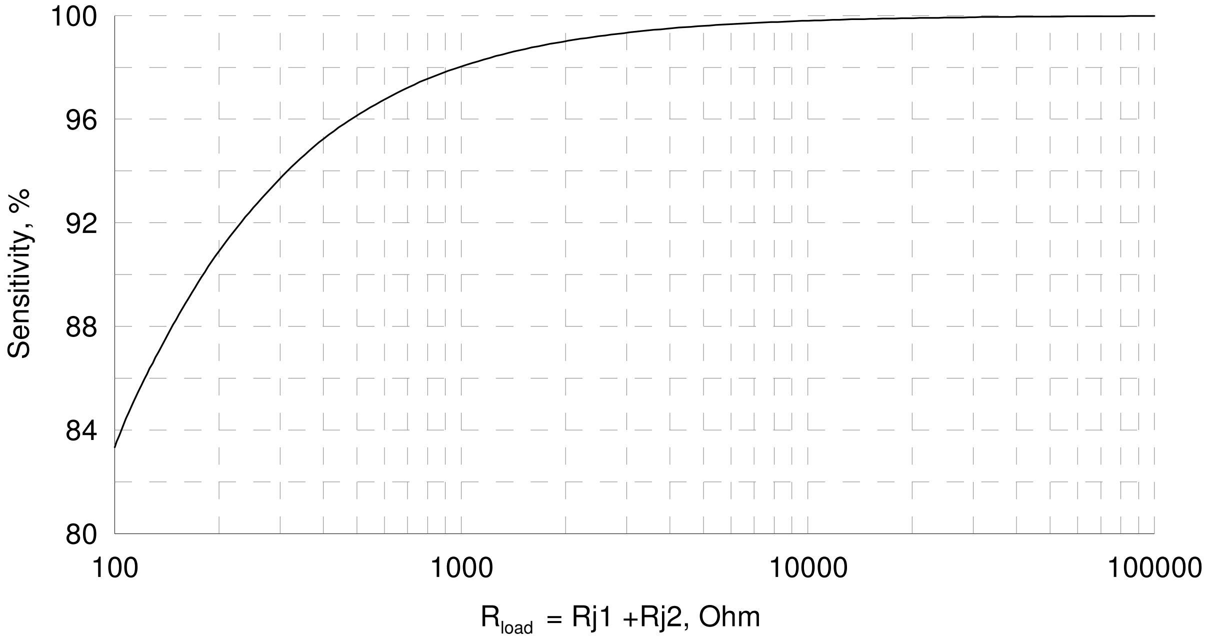

Figure 5: Simulated Sensitivity loss as a function of Rj1+Rj2 Resistance

3.2.2.2 Change in sensitivity over temperature.

Even though each of the Rogowski coil and Rejustor (separately) don't drift much with temperature, the combination of Rs and Rload can make the combined device sensitive to a temperature change.

For example, if a copper wire or copper PCB traces were used to build the coil, the TCR of Rs should have TCR of copper (4300 ppm/K) while Rj1 and Rj2 have a maximum TCR of ±100ppm/K.

Simulation in Figure 6 shows the impact of temperature dependant Rs on the overall sensitivity for three different cases:

1) "Low Rj1, Rj2", (line with +++). The device becomes overly susceptible to temperature.
2) "Medium Rj1, Rj2", (line with □□□). The device accuracy complies with requirements over wide temperature range.
3) "High Rj1, Rj2", (line with xxx). Temperature dependence is negligible.

For all three cases above it was assumed that TCR of Rj1 and Rj2 is 0, Rs=20 Ohm.
For comparison, line with ◊◊◊ shows the effect of the Rejustors' TCR mismatch. Here we assume that TCR_{Rs} = 0ppm/K and $\Delta TCR = TCR_{Rj1} - TCR_{Rj2}$ = 100ppm/K.

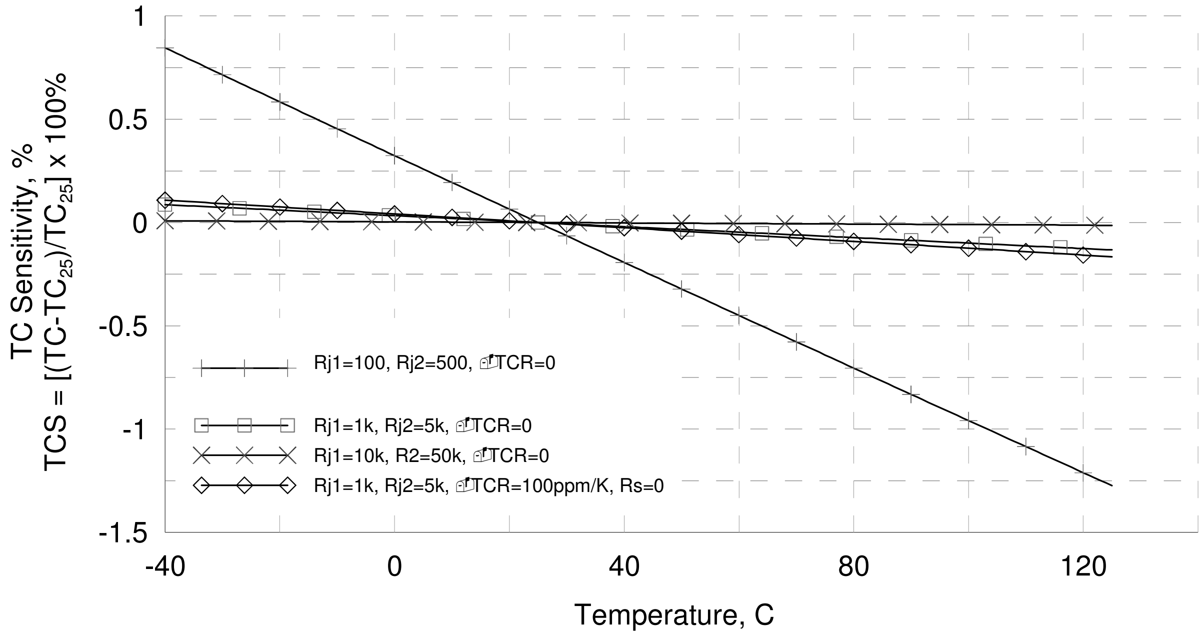

Figure 6: TC Sensitivity vs. Temperature

Having decided on Rj1, Rj2 values, it is reasonable to check what influence may be expected from the Amplifier side. The plot in Figure 7 shows that an amplifier with input impedance higher than 1 mega-ohm will not impact significantly the sensitivity of the system when Rj1 ≤ 1k and Rj2 ≤ 5k.

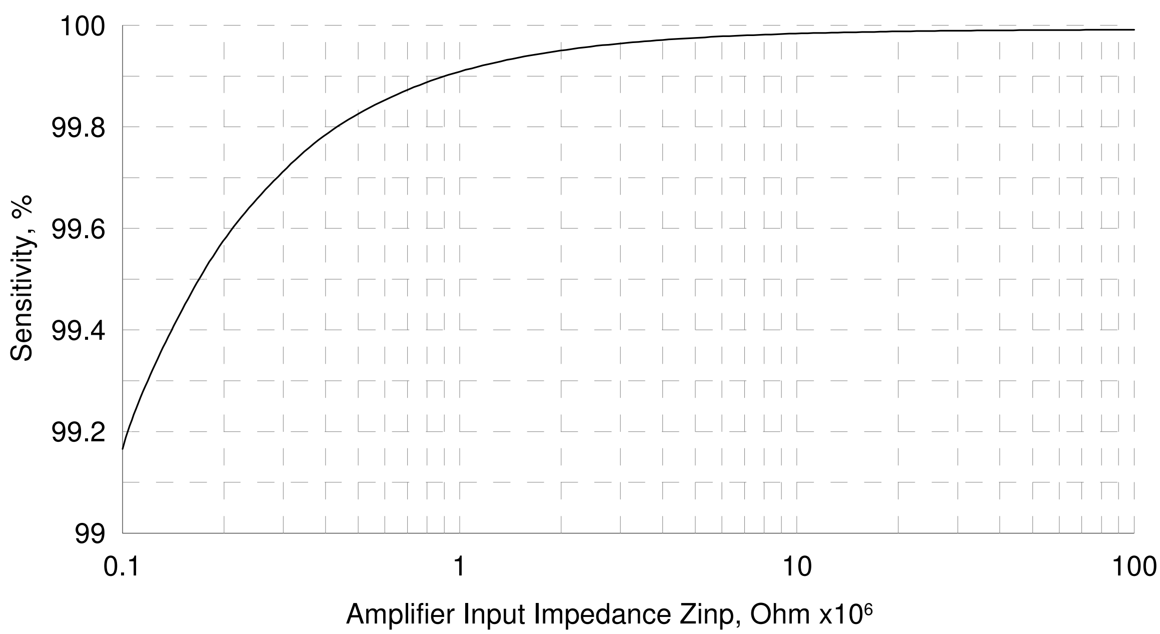

Figure 7: Sensitivity vs. Amplifier Input Impedance

3.2.3 Step three: Check adjustment-range.

The last step is to verify that 30% Rejustor adjustment range is sufficient to compensate for extreme values of initial sensitivity. The sensitivity of 30μV/A +/-5% after attenuation corresponds to

$$30\mu V / A \times 1.05 \times \frac{5}{6} = 26.25\mu V / A\text{, and}$$

$$30\mu V / A \times 0.95 \times \frac{5}{6} = 23.75\mu V / A$$

The result of simulation in Figure 8 shows that both extreme cases of manufacturing variation in the coil (5% high through 5% low) can be brought to the target assuming a 30%-down adjustment range for each Rejustor. The relationship between adjustment range and output voltage as each Rejustor is adjusted is shown graphically in Figure 8.

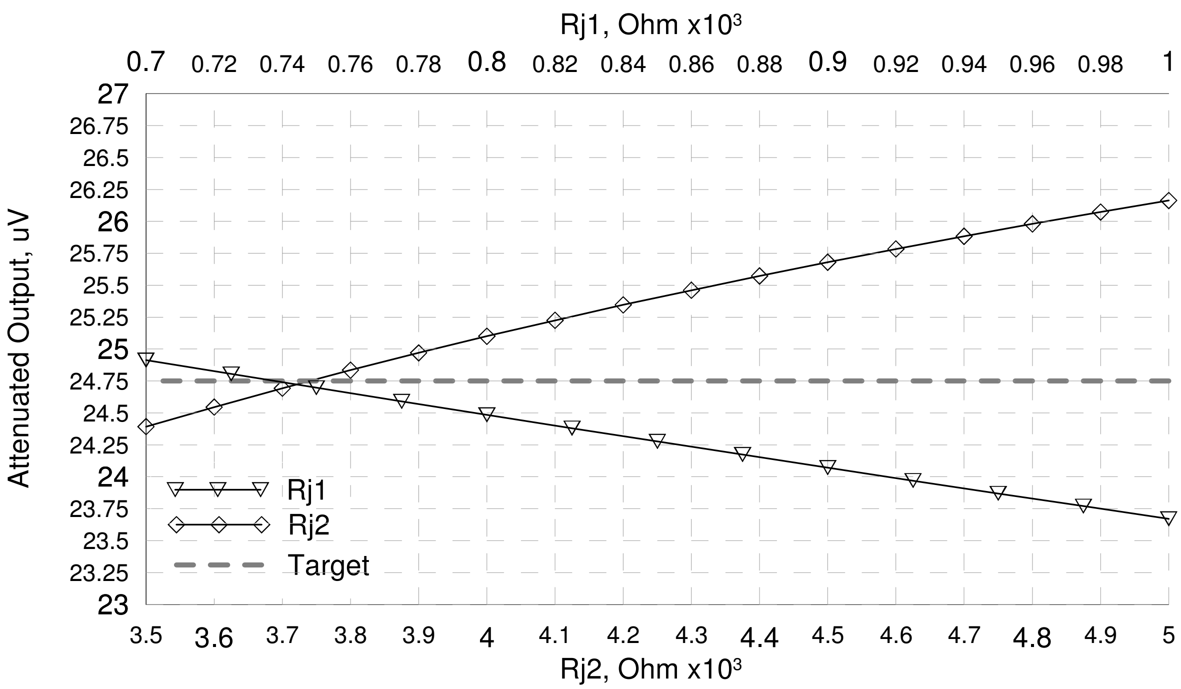

Figure 8: Output Signal as a Function of Rejustor adjustment Range

3.2.4 Determining Ideal Rejustor Values Summary

In summary, the use of the MBD-472-CL with Rj1 =1KΩ and Rj2 = 5kΩ provide sufficient adjustment range to compensate for ±5% coil variation and meet the output voltage specification for the system without impacting amplifier sensitivity or temperature behavior.

3.3 Developing the Calibration Setup

In general the calibration process can be split on two parts – sensitivity *measurements* and Rejustor *adjustment*. For low signal applications (such as sensors applications) Rejustor dividers are linear devices with known transfer function. Therefore Rejustor adjustment (and coil calibration) is easy to automate.

3.3.1 Measurements

It's not hard to believe that no one wants to use 1000 amperes for calibration. A couple of amps would be easier to generate and safer.

3.3.2 Calibration Challenge

For a final Rogowski coil accuracy of 0.5% the measurements during calibration have to provide accuracy of about 0.1%. The use of 2 ampere, 60Hz excitation current will create close to 50μV output signal. This would have to be measured with resolution of ~50nV!

Thermal noise voltage produced by Rejustor is

$$Vt = \sqrt{4kTBR} \ , \qquad (4)$$

where *k*=1.38 x 10^-23, *T* = absolute temperature (K), *B*=bandwidth (Hz), *R*≈Rj1//Rj2 (Ohm).

From (7) follows that at room temperature and B=100Hz, Vt ≈ 40nV.

A good low-noise amplifier will contribute another hundred of nanovolts making the whole picture even less attractive. It will require a special technique to accurately measure the signal totally buried in noise.

Notice however that by increasing the frequency of the input signal, the output voltage increases proportionally (from equation 1). Using 900Hz instead of 60Hz will increase output signal 15 times In this case the required resolution of 750nV will be above noise level.

3.3.3 Measurement Setup

Figures 9 and 10 show two generic approaches that can be used for measurement and calibration.

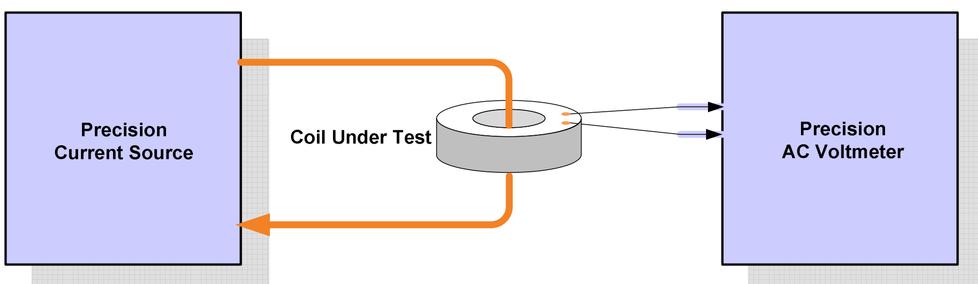

Figure 9: Simple Calibration Setup

The first one is a straight forward solution and looks pretty simple. However the method requires both "fancy" equipment and excellent skills in low signal measurements (like proper shielding, grounding, filtering et cetera). It also requires high levels of user interaction since the signal generation and signal measurements are isolated from each other.

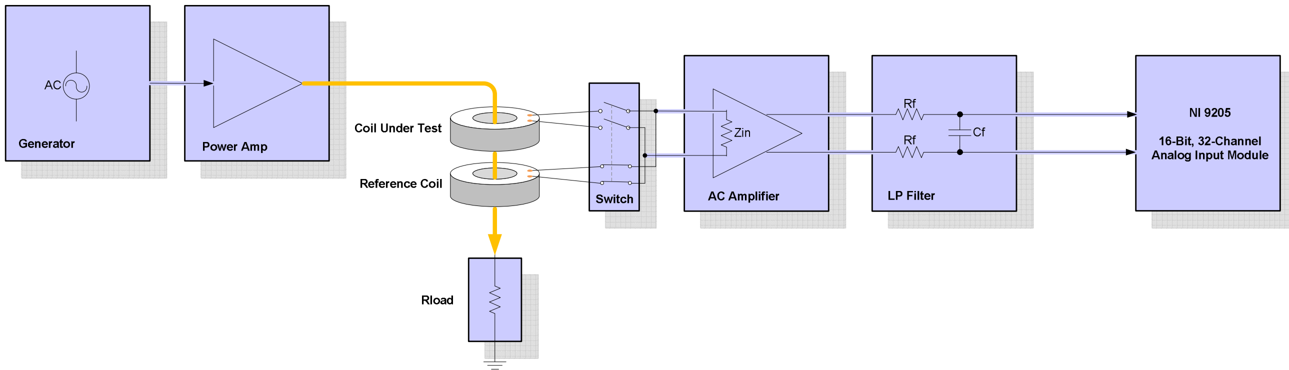

Figure 10: Calibration Setup using Reference Signal

The core of the second method is a high quality reference Rogowski coil with accurately-known sensitivity. The use of the reference coil will significantly reduce requirements (tolerance) for the whole chain of equipment. A simple low-noise AC amplifier, preferably with differential output and a low-pass (or band-pass) filter, placed in close proximity to the coil, allows the use of an inexpensive voltmeter or data acquisition board (DAQ). It also protects small signals from EMI in harsh environment. If an AC amplifier is used, make sure that the Gain Bandwidth product (GBW) doesn't distort the signal.

In the end, the best method, or combination to choose is the matter of experience, equipment availability and personal preference.

3.4 Rejustor-Adjustment

Rejustor adjustment is an adaptive, successive–approximation process. It consists of series of voltage pulses (30 to 60) applied to pins "trim1" and "trim2" (see Figure 4 and Figure 11). Automated adjustment procedure includes output signal measurement after each pulse. The entire process is complete in 2 to 3 seconds

Since Rejustor is a simple resistor-divider (meaning a linear device), the AC excitation signal can be substituted by a DC signal during the adjustment process. To implement this AC-to-DC replacement one can use the diagram shown in Figure 11. In general, it only requires DC voltage reference source (DC Vref) and an analog Switch. The Buffer/Amplifier and low-pass LP Filter are optional but still recommended devices. They can be placed on the same PCB with DC Vref and analog Switch. For example, in our setup we used the voltage reference with on-board output switch REF191, instrumentation amplifier INA128 and fully differential amplifier THS4131 as the first and the second stage of Buffer/Amplifier. The rest of the adjustment setup is not optional. It works with dedicated *Multical* software from Microbridge and includes two modules ADC NI9205, DAC NI9263 from National Instruments and from one to four Microbridge *Multical* Modules (MB121/MB122/MB123/MB124) shown in Figure 12. Each MB12x adjustment module can simultaneously handle up to four sensors. Note, just one sensor is shown on Figure 11 for clarity. Multiple simultaneous adjustment dramatically increases production through-put.

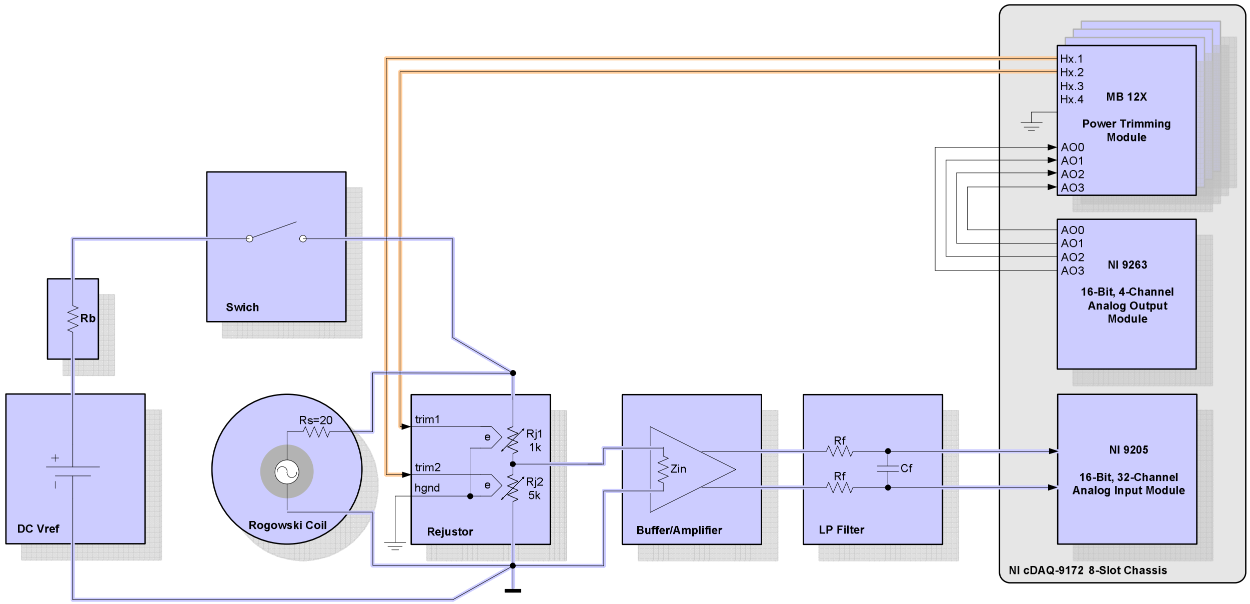

Figure 11: Production Configuration

Figure 12: Multi-Cal Modules with NI-DAQ Chassis

3.4.1 Determining appropriate DC Vref for Calibration

On one hand, the voltage has to be big enough to provide sufficient signal-to-noise ratio. On the other hand, it should not draw too much current through the very low Rogowski coil impedance. A ballast resistor Rb can be used to adjust this voltage. Simple estimation and further experiments confirmed that 500mV<Vref<800mV gives a good result provided that Buffer/Amplifier's Gain ≈ 10.

3.4.2 Calibration Process

The flowchart on Figure 13 illustrates the Rogowski coil calibration process.

The First step is AC measurements. The goal of this part in the process is to determine the Target Ratio "X" – the ratio between sensitivity of the coil under test and target sensitivity.

The second step is the adjustment itself. Applying DC signal, adjust one of two Rejustors until output DC signal will be changed X times in comparison with DC signal before adjustment.

The last step is to verify if the new sensitivity is within +/-0.5% of target. If necessary, repeat adjustment.

Note, all DC measurements are ratiometric and, therefore, there are no strict requirements for Vref and Buffer/Amplifier gain. In fact, the only requirement is that these devices must not drift during a single adjustment session (which usually takes a few seconds).

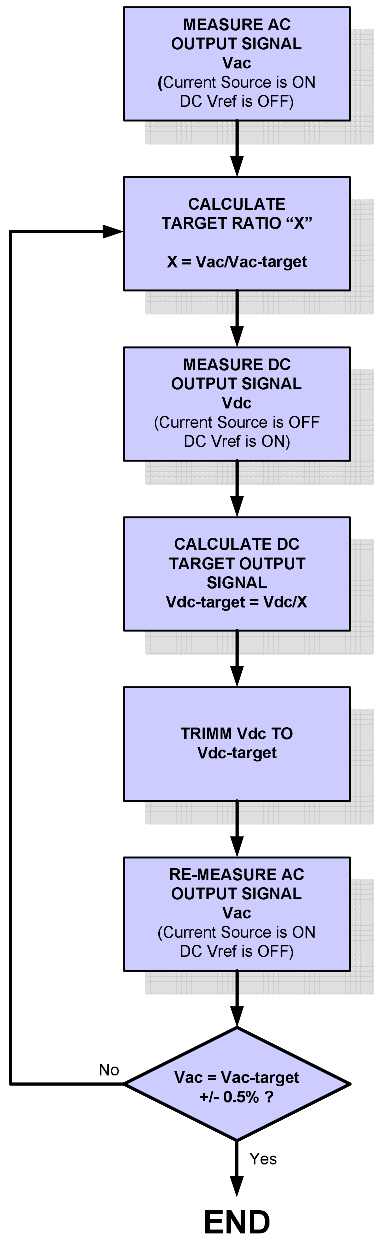

Figure 13: Calibration Process Flow Chart

4 Summary

Testing of Rejustor compensated Rogowski coils confirmed that the use of Rejustor with a Rogowski coil using the proposed calibration setup provides and accuracy of 0.5% or better. Calibration time is less than 5 seconds. Note that using Microbridge's scalable production-calibration hardware (based on the NI-DAQ platform from National Instruments) and Rejust-it software, multiple units can be calibrated simultaneously during roughly the same amount of time.

Rejustors facilitate mass-production of Rogowski coils without compromising accuracy. This total passive solution is ideal for applications where no DC power is available for a co-located amplifier. Rejustor compensation of the coil changes the demarcation points for field replaceable assemblies, allowing a technician the freedom to replace coil assemblies or amplifier assemblies independently – which is also ideal when the coil and amplifier are no co-located.

Rejustor Calibration uses an iterative feedback process in conjunction with either the MBK-408A Rejustor Calibration Tool or the MBK-600 Multi-trim system to automatically adjust the resistance of the Rejustors to achieve the current-to-voltage relationship.

Rejustors are not only the lowest noise adjustable resistor technology available; they are ideally suited for set-on-test adjustment for precision Rogowski coils and many other applications.

Literature

1. Current sensing for energy metering, William Koon, Analog Device, Inc.