

Empowering Modern Protection: How Relays With Low-Energy Inputs Unlock the Full Potential of Rogowski Coil Sensing

Anushka Dissanayake, Vinod Yedidi, Anurag Upadhyay, Jamison Ehlers,
and Marcos Donolo

Schweitzer Engineering Laboratories, Inc.

© 2026 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

This paper was presented at the 2026 IEEE IAS Petroleum and Chemical Industry Technical Conference.

EMPOWERING MODERN PROTECTION: HOW RELAYS WITH LOW-ENERGY INPUTS UNLOCK THE FULL POTENTIAL OF ROGOWSKI COIL SENSING

Copyright Material IEEE

Anushka Dissanayake
Member, IEEE
Schweitzer Engineering
Laboratories, Inc.
2350 NE Hopkins Ct
Pullman, WA
99163 USA
anushka_dissanayake
@selinc.com

Vinod Yedidi,
Member, IEEE
Schweitzer Engineering
Laboratories, Inc.
2900 Horizon Dr
King of Prussia, PA
19406 USA
vinod_yedidi
@selinc.com

Anurag Upadhyay
Schweitzer Engineering
Laboratories, Inc.
2900 Horizon Dr
King of Prussia, PA
19406 USA
anurag_upadhyay
@selinc.com

Jamison Ehlers
Member, IEEE
Schweitzer Engineering
Laboratories, Inc.
2350 NE Hopkins Ct
Pullman, WA
99163 USA
jamison_ehlers
@selinc.com

Marcos Donolo
Senior Member, IEEE
Schweitzer Engineering
Laboratories, Inc.
2350 NE Hopkins Ct
Pullman, WA
99163 USA
marcos_donolo
@selinc.com

Abstract – In this paper, we present the low-energy analog (LEA) relay as a protection solution optimized for low-power instrument transformers (LPITs), including low-power current transformers (LPCTs), Rogowski coils (Rcoils), and low-power voltage transformers (LPVTs). While the LEA relay supports all LPIT technologies, we focus on Rcoil sensors because of their wide bandwidth and saturation-free behavior. We demonstrate how the LEA relay processes high-fidelity Rcoil signals to provide accurate protection from low load currents to high-magnitude faults. Guidance is provided on Rcoil sensor selection and LEA relay configuration for feeder and transformer protection. Test examples illustrate the impact of sensor characteristics and relay settings on protection performance, highlighting that a single Rcoil type can support a wide range of applications without multiple CT ratios or classes. We present staged high-current fault test results. We also compare Rcoil and CT performance and evaluate special applications, including external Rcoil summation-based differential protection and hybrid schemes that integrate Rcoils with magnetic CTs.

Index Terms — Differential Protection, Low-Energy Analog Sensor, low-power instrument transformer, low-power current transformer, Rogowski Coil, low-power voltage transformer, wide bandwidth, saturation free.

I. INTRODUCTION

Presently, iron-core CTs are widely used in electrical power systems for protection and metering purposes. These CTs exhibit core saturation issues for high-magnitude fault events with DC offset. Careful considerations and selection criteria, depending on the application, have led to deployment of these CTs for multiple protection applications. These CTs were originally designed to provide the power required to energize the coils inside electromechanical relays. However, with modern microprocessor-based protective relays, the need for traditional CT- or PT-driven input power has been significantly reduced and is slowly paving the way for air-cored sensors, such as Rogowski coils (Rcoils) or low-power current transformers (LPCTs) and low-power voltage transformers (LPVTs). Advanced digital sensing techniques also allow these relays to accurately measure millivolt-level inputs, making some of these sensors suitable for both protection and metering applications. These sensors are physically connected using RJ45 cables and

additionally, if the relay supports IEC 61869-9 or IEC 61850-9-2 publisher capabilities, the analog measurements can be transmitted as data streams for protection applications.

Rcoils were introduced somewhere around 1912 [1]. However, they did not make it into mainstream protection systems due to the wide use of electromechanical relays, which required power. Rcoils are air-core sensing devices that generate mV-level signals. Rcoils have not been a preferred choice for protection engineers because of the additional circuitry needed to amplify the mV-level signal coming from the coil to usable levels [1].

To support low-power instrument transformers (LPIT) implementation, engineers have begun to develop standards. The IEC 61869 family of standards provides a complete overview. IEC 61869-9, -10, and -11 cover the performance of the LPITs, while IEC 61869-13 covers associated LEA input specifications [2] [3] [4] [5]. IEEE Std C37.235-2021, provides a good summary describing Rcoil use for protective relay purposes [1]. The IEEE Std C37.92-2023 [6] standard limits the length between the low-energy sensor and IED to below 10 m with longer distances possible in specially engineered applications, where cable lengths reported in actual Rcoil projects reach up to 300 m [7].

Recent technological developments have enabled Rcoil to replace CTs. Reference [8] summarizes the benefits of Rcoils and identifies implementation challenges of adopting Rcoil technology. References [9] [10] [11] and [12] discuss the deployment of Rcoils and LEA relays for protection applications. Reference [9] discusses development of a Rcoil sensor for medium-voltage switchgear applications and shares field performance results from applications, such as arc-furnace systems. Reference [10] demonstrates the successful results of the integration of this technology in gas-insulated switchgear with fault currents reaching 25 kA. Reference [11] compares internal hardware architectures of protective relays to measure primary currents using CTs versus Rcoils including the key design modifications required to support the wide-range capability of Rcoils. Reference [12] introduces differential protection for electric arc-furnace transformers using Rcoils. Field experience demonstrates fast, secure fault clearing for currents up to 250 kA and over 1,000,000 energizing cycles. The use of Rcoils in microprocessor-based protective relays is discussed in [13], which highlights its advantages, such as immunity to saturation, flexible design, and noise resistance.

In this paper, we first provide a brief overview of the operating principles of Rcoils and the LEA relay approach for managing the wide dynamic range of Rcoil sensors. Next, we outline key considerations and procedures for selecting and applying Rcoil sensors in feeder and transformer protection applications, supported by practical examples. Finally, we present experimental results comparing the performance of an Rcoil-based LEA relay with a CT-based relay under various fault scenarios and applications, followed by our conclusion.

II. RCOIL-BASED LEA RELAY

A. Rcoil LEA Sensing

An Rcoil is an electrical device that can be used to measure AC current. Unlike the conventional magnetic CTs, Rcoils have key advantages that are well documented [1] [6] [8] [9] [10] [12] [13]. Rcoils work on Faraday's law of electromagnetic induction, where an emf is induced in a coil due to the varying magnetic field. The Rcoil output voltage is proportional to the rate of change of the current passing through the primary conductor. Suppose the primary current is given by (1).

$$i(t) = \sum_{m=0}^M I_m \sin(m\omega t + \varphi_m) \quad (1)$$

where

- I_m is the peak current
- m is the harmonic number
- ω is the fundamental frequency in radians per second
- φ_m is the phase angle

If we pass this current through a Rcoil, the output voltage of the Rcoil ($v_{RC}(t)$) is proportional to the time derivative of (1). Even though it is not shown in (1), if there is any non-harmonic content in the primary current, the output signal will also contain the derivative of those components. The Rcoil manufacturers usually define the sensitivity of the Rcoil using two parameters, namely the rated sensor voltage (USR) at the nominal frequency (ω_n) and the rated primary current (IPR). The IPR of the rms current, if applied through the Rcoil, will result in a USR of voltage at the frequency ω_n . Hence, the proportionality constant is $USR / (IPR \cdot \omega_n)$. Now output of the Rcoil can be defined as (2).

$$v_{RC}(t) = \frac{USR}{IPR \cdot \omega_n} \sum_{m=1}^M I_m m\omega \cos(m\omega t + \varphi_m) \quad (2)$$

The individual harmonics are amplified by the ratio of $m\omega / \omega_n$. To get the primary current, we should integrate the signal $v_{RC}(t)$. Integration can be performed by using an analog circuit or digitally by using a signal processing algorithm. In this paper, we discuss relays with analog integrators.

The sensor sensitivity is typically specified using IPR and USR at 50 Hz or 60 Hz. Some manufacturers define sensor sensitivity as Rcoil transformation ratio (RR) in mV/kA or A/mV using the ratio of USR and IPR. Rcoil sensitivities can range from as low as 2 mV/kA to as high as 2,500 mV/kA. Some manufacturers offer custom Rcoils with output sensitivity tailored to your specifications. The rated continuous thermal current of these sensors can range from a few amperes to tens of kA in the primary, with dynamic primary current measurement capabilities for protection up to hundreds of kA.

B. LEA Relay Managing the Wide Dynamic Range

Due to its air-core design, the core saturation is eliminated and hence the dynamic range of the Rcoil is significantly larger compared to CTs. However, the analog-to-digital converter (ADC) in the relay has a finite dynamic range, limited by the chosen ADC resolution. The capability of the ADC determines the maximum current the relay can accurately measure before signal clipping occurs. A limit of 30 times the nominal current is assumed for discussion in this paper. Since a given digital relay has to support both CTs as well as LEA sensors, the ADC limits apply to both types of inputs.

Some LEA relays adjust a programmable gain amplifier (PGA) setting, enabling a single current sensor to support a wide range of primary currents. The current channel gain is controlled based on sensor sensitivity and the relay settings. The relay supports configurable base current settings (I_{RLY_BASE}) in primary amperes to adjust the PGA gains and optimize the ADC range for the intended application. Similar to the conventional relay secondary nominal current, the LEA relay uses the nominal voltage (V_{RLY_NOM}), as shown in (3).

$$V_{RLY_NOM} = \frac{I_{RLY_BASE}}{RR} \quad (3)$$

where, $RR = IPR/USR$

Similar to conventional relays, where ADC clipping occurs at 30 times the secondary nominal current, the LEA relay sets ADC clipping at 30 times the voltage produced at I_{RLY_BASE} ($30 \cdot V_{RLY_NOM}$). This voltage is sometimes referred to as the clipping voltage ($V_{RLY_30 \cdot NOM}$), which is limited to the maximum supported voltage of the hardware ($V_{RLY_HW_MAX}$) without ADC clipping. $V_{RLY_HW_MAX}$ can range from 100 to 200 V. Additionally, the ADC process requires a minimum level of accuracy and noise immunity; Therefore, LEA relays impose a limit on the lowest supported setting that can range from 1 to 10 percent of V_{RLY_NOM} above a minimum fixed value, typically 5 mV. These limits of the LEA relay are important and used in Section III for choosing the sensor for different applications.

III. SENSOR SELECTION, RELAY CONFIGURATION, AND TESTING

A. Sensor Selection and Relay Configuration

The Rcoil sensor has an inherently linear response over a wide range of primary currents, surpassing the limitations of CTs. While the Rcoil has a wide dynamic range, its limitations lie in the hardware capabilities of the LEA relay, making it important to consider the LEA relay capabilities as part of LEA sensor selection process.

Another interesting challenge comes from the fact protective relay settings are normally per-unitized or expressed as secondary quantities (1 A, typical in IEC and 5 A, typical in ANSI/NEMA), while the LEA sensors require additional attention to the primary quantities. To ease the transition, LEA-capable relays normally keep the secondary setting convention resulting in a purely numeric (1 A / 5 A) secondary concept. This approach allows for protection setting matching between the conventional and LEA based relays and simplifies the mixing of conventional instrument transformers and LEA sensors on the same relay.

Conventional relays typically support 1 A and 5 A as the nominal secondary current ($I_{RLY_HW_NOM}$) inputs. For simplicity,

we limited the discussion in this section to 1 A nominal secondary, but it could easily be extended to 5 A nominal secondary as well. For the examples in this paper, we used the Rcoil sensor IPR and USR settings at a nominal frequency of 60 Hz.

Users typically run into two scenarios in a sensor selection process:

1. A scenario where the sensor has been selected and the user needs to determine the suitability of the sensor for their application.
2. A scenario where the sensor needs to be selected between the available sensors in the market.

In either scenario the following information is typically required for selection.

- System information
 - Nominal primary current or full load current (I_{SYS_NOM}) of the apparatus to be protected (feeder, motor, transformer, generator, etc.) with the desired margin (e.g., 1.2 times the actual full load) accounted per the application need.
 - Maximum fault current (I_{SYS_MAX}) with the desired margin accounted for per the application need.
 - Inrush current or motor starting current.
- Application requirements
 - Sensitivity (I_{SYS_MIN}): Minimum set point required for the application for resistive fault coverage or minimum load current to be measured for control purposes.
 - Security for external faults (Is ADC clipping acceptable or not?).
- Capability of an LEA relay: This typically depends on the relay hardware (HW), such as internal circuitry (on board integrator, isolation to ground, etc.), ADC resolution, and processor (integer versus floating point).
 - Absolute minimum supported overcurrent set point in volts as seen by the LEA inputs ($V_{RLY_HW_MIN}$). This can range from 1 mV to 10 mV. For our examples, we chose $V_{RLY_HW_MIN}$ of 5 mV.
 - Absolute maximum supported voltage ($V_{RLY_HW_MAX}$) input without ADC clipping. This can range from 100 V to 200 V. For our examples, we chose $V_{RLY_HW_MAX}$ of 128 V.

Since most users have experience with conventional CT-based relays, it is helpful to compare them with the LEA relay to better illustrate the LEA relay capabilities.

- Capability of a conventional relay
 - Absolute minimum supported overcurrent set point ($I_{RLY_HW_MIN}$). For a CT with rated nominal current of 1 A; based on the manufacturer, $I_{RLY_HW_MIN}$ can range from 0.01 A (1 percent of nominal) to 0.05 A (5 percent of nominal). For our examples, we chose $I_{RLY_HW_MIN}$ of 0.05 A.
 - Absolute maximum supported current ($I_{RLY_HW_MAX}$) input without ADC clipping. The maximum symmetrical through-fault current seen by the CT should not exceed 20 times the nominal CT rating [14]. With this as a consideration, relay manufacturers may support $I_{RLY_HW_MAX}$ that can range from $30 \cdot I_{RLY_HW_NOM}$ to $50 \cdot I_{RLY_HW_NOM}$.

For $I_{RLY_HW_NOM}$ of 1 A, we chose $I_{RLY_HW_MAX}$ of 30 A for our examples.

The process of selecting a sensor is analogous to selecting a CT. In either case, the system information acts as the starting point. The CT or LEA sensor should be selected with application requirements and relay capabilities taken into account.

Figure 1 shows how the given system and application information map to the relay capabilities for a given CT ratio. In Figure 1, Y-axis is not Linear. If a suitable CT ratio and class are selected, then the system currents, I_{SYS_MIN} and I_{SYS_MAX} , fall within the relay capabilities, $I_{RLY_HW_MIN}$ and $I_{RLY_HW_MAX}$, respectively. This allows the protection engineer to set the relay to achieve the needed sensitivity and security. If a suitable CT is not available, then either or both the I_{SYS_MIN} and I_{SYS_MAX} currents may fall outside the $I_{RLY_HW_MIN}$ and $I_{RLY_HW_MAX}$. Based on the application needs, the protection engineer may choose a CT that results in less sensitive settings without having to compromise the security.

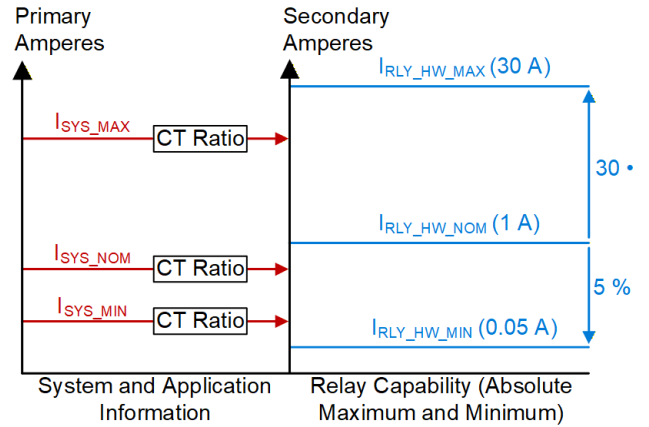
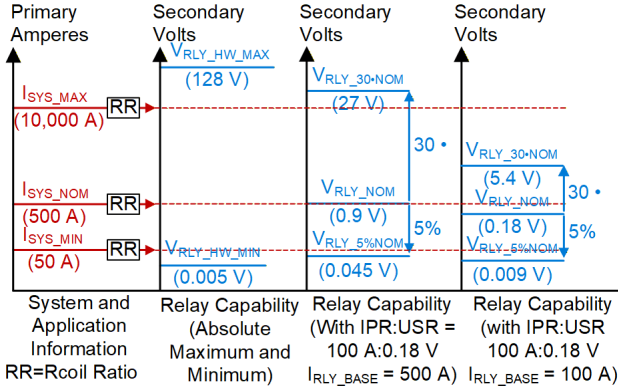


Figure 1 Mapping of System and Application Information to relay Capabilities for an Ideal CT

Figure 2 shows how the given system and application information map to the relay capabilities for a given Rcoil sensor with an IPR and a USR of 100 A and 0.18 V, respectively at 60 Hz, which is $RR = 555.556 \text{ A/V}$ (the chosen I_{RLY_BASE} settings in the relay are described later). In Figure 2, lower currents are compressed to fit the graph, and the Y-axis is not Linear. Note that Figure 1 and Figure 2 make use of the relay with the same ADC and processor. The only difference is that the relay in Figure 1 uses secondary currents provided by a CT, and the one in Figure 2 uses the secondary voltages provided by the Rcoil sensor. The dynamic range of the relay for a given nominal current or voltage remains the same. This allows us to equate the nominal secondary voltage in LEA relays to the nominal secondary current in conventional relays. If the nominal secondary current is selected as 1 A, then the nominal primary current (I_{SYS_NOM}) is equivalent to the primary rating of the CT in the case of conventional applications. For a given LEA sensor, I_{SYS_NOM} can be used to calculate the nominal secondary voltage (V_{RLY_NOM}) of the sensor using (3). The supported dynamic voltage range would then be 5 percent of V_{RLY_NOM} ($V_{RLY_5\%NOM}$) to 30 times V_{RLY_NOM} ($V_{RLY_30 \cdot NOM}$) but limited to $V_{RLY_HW_MIN}$ and $V_{RLY_HW_MAX}$, respectively.

It would be convenient to introduce I_{RLY_BASE} settings in the LEA relay that can be either set to I_{SYS_NOM} or to a desired value. The I_{RLY_BASE} setting can then be set to control the placement of

the dynamic range based on the application needs. Figure 2 shows the placement of the dynamic range for the choice of $I_{RLY_BASE} = 500$ A and 100 A. The resulting dynamic range with $I_{RLY_BASE} = 500$ A, provides coverage for the entire range of I_{SYS_MIN} and I_{SYS_MAX} currents. On the other hand, the resulting dynamic range with $I_{RLY_BASE} = 100$ A, provides excellent coverage for I_{SYS_MIN} but results in ADC clipping at I_{SYS_MAX} . The I_{RLY_BASE} setting, which translates to V_{RLY_NOM} , acts as a powerful tool for the protection engineer in defining the placement of the dynamic range and setting the relay, per the application needs.



If the nominal secondary current in an LEA relay is forced to 1 A, then I_{RLY_BASE} simply equates to the CT ratio ($CTR = I_{RLY_BASE} / 1$ A) in the case of CT applications. For applications with a single CT ratio, once the CT is installed, the CT ratio cannot be changed. For LEA sensor applications, I_{RLY_BASE} is a user-defined setting that is especially useful in case of feeder load growth, allowing the protection engineer to adapt the relay settings over time to match the system construction phases.

The dynamic range of the conventional and LEA relay can be quantified by (4) and (5), respectively. We use this information in the next section when determining the suitability of the sensor for a given application.

$$I_{RLY_MAX_MIN} = \frac{I_{RLY_HW_MAX}}{I_{RLY_HW_MIN}} = \frac{30 \cdot I_{RLY_NOM}}{5\% \cdot I_{RLY_NOM}} = 600 \quad (4)$$

$$V_{RLY_MAX_MIN} = \frac{V_{RLY_30\%NOM}}{V_{RLY_5\%NOM}} = \frac{30 \cdot V_{RLY_NOM}}{5\% \cdot V_{RLY_NOM}} = 600 \quad (5)$$

B. Procedure to Check if a Sensor is Suitable for an Application Given the Relay Specifications:

To check the suitability of a sensor for a given application, the following information needs to be identified.

- System information: I_{SYS_NOM} , I_{SYS_MAX} , I_{SYS_MIN}
- Relay specification: $V_{RLY_HW_MIN}$, $V_{RLY_HW_MAX}$ and $V_{RLY_5\%NOM}$, $V_{RLY_30\%NOM}$
- Sensor information: IPR, $USR@F_{NOM}$, where $F_{NOM} = 50$ Hz or 60 Hz, and I_{CTH}
- Application requirement: Desired sensitivity
- ADC clipping is acceptable or not

1) Example 1: Feeder Application With Normal Load and Normal Fault Current Levels ($I_{SYS_MAX} = 10,000$ A)

We consider a feeder protection application in this example. The sample system and sensor information are shown in Table I.

TABLE I
SAMPLE SYSTEM, RELAY,
AND SENSOR INFORMATION

Data	Description	Terminology	Value
System	Nominal load current	I_{SYS_NOM}	500 A
System	Maximum fault current	I_{SYS_MAX}	10,000 A
System	Minimum load/fault current	I_{SYS_MIN}	50 A
Rcoil	Rated current	IPR	100 A
Rcoil	Output @ 60 Hz	USR	0.180 V
Rcoil	Transformation ratio	RR	555.556 A/V
Rcoil	Rated continuous thermal current	I_{CTH}	4 kA

To measure the I_{SYS_NOM} , the rated continuous thermal current (I_{CTH}) of the sensor needs to be adequate.

The I_{SYS_NOM} is used as I_{RLY_BASE} , and (3) is used to calculate V_{RLY_NOM} and all the quantities identified in Table II (refer to Example 1).

In these examples, V_{SEN_NOM} , $V_{SEN_SYS_MAX}$, and $V_{SEN_SYS_MIN}$ are the sensor output voltages at I_{SYS_NOM} , I_{SYS_MAX} , and I_{SYS_MIN} respectively.

The limits shown in Figure 2 can be translated to simple checks, see Check 1 to Check 5 in Table II. These checks indicate if the application requirements can be met for the chosen sensor and I_{RLY_BASE} . If all the checks pass, the user may proceed with employing the sensor for the respective feeder application.

2) Example 2: Feeder Application With Normal Load and Higher Fault Current Levels ($I_{SYS_MAX} = 20,000$ A)

For this example, we used the same system and sensor as shown in Table I with the exception of $I_{SYS_MAX} = 20,000$ A. V_{RLY_NOM} and all the quantities identified in Table II are calculated using I_{SYS_NOM} as the I_{RLY_BASE} (refer Example 2a). Check 1 to Check 5 in the table are then applied.

Check 2 fails indicating that the relay will experience ADC clipping at I_{SYS_MAX} . Assuming a symmetrical fault, while the relay ADC can only measure up to 27.0 V, I_{SYS_MAX} will result in a voltage of 36.0 V, causing ADC clipping. Irrespective of whether the ADC clipping is a concern or not, it is advisable to first adjust the I_{RLY_BASE} setting such that the resulting $V_{RLY_30\%NOM} > V_{SEN_SYS_MAX}$. Equation (6) is used to calculate the new current base ($I_{RLY_BASE_NEW}$) that provides the minimum I_{RLY_BASE} to avoid ADC clipping. With $I_{RLY_BASE} = 666.7$ A, Check 1 to Check 5 pass, as shown in Table II, Example 2b. To account for asymmetrical faults, it is necessary to factor the system reactant to resistance ratio (X/R ratio) into the I_{RLY_BASE} calculation.

$$I_{RLY_BASE_NEW} = \left(\frac{V_{SEN_SYS_MAX}}{30} \cdot RR \right) = 666.7 \text{ A} \quad (6)$$

3) Example 3: Feeder Application With Normal Load and Very High Fault Current Levels ($I_{SYS_MAX} = 50,000$ A)

For this example, we used the same system and sensor shown in Table I with the exception of $I_{SYS_MAX} = 50,000$ A.

I_{SYS_NOM} is used as the I_{RLY_BASE} and (3) is used to calculate V_{RLY_NOM} and all the quantities identified in Table II (refer to Example 3a). Check 1 to Check 5 in the table are then applied.

TABLE II
EXAMPLE 1, 2, AND 3: VOLTAGE MEASURED BY THE RELAY AND APPLIED CHECKS

Type	Quantities	Example 1	Example 2a	Example 2b	Example 3a	Example 3b	Example 3c
Relay	I_{RLY_BASE}	500 A	500 A	666.7 A	500 A	1666.7 A	1000 A
Relay	$V_{RLY_NOM} @ I_{RLY_BASE} = I_{RLY_BASE} / RR$	0.900 V	0.900 V	1.200 V	0.900 V	3.000 V	1.800 V
Relay	$V_{RLY_30\%NOM} @ 30 \cdot I_{SYS_NOM}$	27.00 V	27.00 V	36.00 V	27.00 V	90.00 V	54.00 V
Relay	$V_{RLY_5\%NOM} @ 5\% \text{ of } I_{SYS_NOM}$	0.045 V	0.045 V	0.060 V	0.045 V	0.150 V	0.090 V
Relay	$V_{SEN_SYS_MAX} @ I_{SYS_MAX}$	18.00 V	36.00 V	36.00 V	90.00 V	90.00 V	90.00 V
Relay	$V_{SEN_SYS_MIN} @ I_{SYS_MIN}$	0.090 V	0.090 V	0.090 V	0.090 V	0.090 V	0.090 V
Check 1	$V_{RLY_MAX_MIN} > I_{SYS_MAX} / I_{SYS_MIN}$	Pass	Pass	Pass	Fail	Fail	Fail
Check 2	$V_{RLY_30\%NOM} \geq V_{SEN_SYS_MAX}$	Pass	Fail	Pass	Fail	Pass	Fail
Check 3	$V_{RLY_HW_MAX} > V_{SEN_SYS_MAX}$	Pass	Pass	Pass	Pass	Pass	Pass
Check 4	$V_{RLY_5\%NOM} < V_{SEN_SYS_MIN}$	Pass	Pass	Pass	Pass	Fail	Pass
Check 5	$V_{RLY_HW_MIN} < V_{SEN_SYS_MIN}$	Pass	Pass	Pass	Pass	Pass	Pass

Check 1 fails, indicating that the dynamic range of the LEA relay ($V_{RLY_MAX_MIN} = 600$) cannot accommodate the dynamic range of system currents ($I_{SYS_MAX} / I_{SYS_MIN} = 1,000$). Unlike Example 2, there is no particular choice of I_{RLY_BASE} that will meet the application requirements (desired sensitivity and no ADC clipping). Since the limitation is on the LEA relay, there would be no alternate Rcoil sensor to satisfy all the criteria. It is important to note that in addition to saturation, the CT would face the same dynamic range challenges in this example.

One of following options can be considered.

- If ADC clipping is of concern due to security or dependability reasons and Check 3 is a pass, $I_{RLY_BASE} = 1666.7$ A (calculated using (6)) should be chosen to avoid ADC clipping (Example 3b, in Table II). This approach desensitizes the protection settings.
- If sensitivity is of importance and ADC clipping is not a concern, I_{RLY_BASE} should be chosen such that $V_{RLY_5\%NOM} < V_{SEN_SYS_MIN}$, using (7) (Example 3c, in Table II). If the application has high-set overcurrent elements that operate on fundamental current, the user should ensure there is adequate margin between the high-set overcurrent setpoints and the fundamental current magnitude available after ADC clipping.
- If neither of the above are acceptable, a different, market-available, LEA relay needs to be chosen that satisfies the dynamic range of application.

$$I_{RLY_BASE_NEW} = \left(\frac{V_{SEN_SYS_MIN}}{5\%} \cdot RR \right) = 1000 \text{ A} \quad (7)$$

C. Procedure to Choose a Suitable Sensor From List of Available Sensors for a Feeder Application Given the Relay Specifications

Table III lists sensors available in the market from different vendors. Although only IPR and USR (60 Hz) information is listed, the user should ensure the sensor meets the rated continuous thermal current (I_{CTH}) for their application.

TABLE III
LIST OF SENSORS AND SETTINGS AT 60HZ

Sensor	IPR (A)	USR (V)	RR (A/V)
Sensor 1	80	0.18	444.44
Sensor 2	1,000	0.6	1,666.67
Sensor 3	1,000	0.12	8,333.33
Sensor 4	1,000	0.048	20,833.33
Sensor 5	1,000	0.024	41,666.67

In case of CTs, the system information is used in determining

the CT ratio and class. This information is then used to select the CT from the available list of CTs from a given manufacturer data sheet. The same can be applied to choosing Rcoil sensors. Since the sensors are linear, all that needs to be determined is the RR, given the system information and the relay specifications.

There are two ways to determine a suitable RR:

1. For each RR, Check 1 to Check 5 are applied to determine the suitability of the sensor. This approach is similar to the one used in Example 1, 2, and 3. This approach can get cumbersome if the user has to select a sensor from a large pool of available sensors.
2. The system and relay information is used to calculate the acceptable range of RR. Once the range of RR is calculated, the sensor is chosen from available list.

1) Example 4: Calculation of an Acceptable RR Range for the Given Feeder Application and Relay Specifications

Consider the same system and relay information presented in Table I. Since the limiting device is the LEA relay and not the sensor, we can establish the possible range of RRs by equating the system minimum and maximum currents to the corresponding LEA relay minimum and maximum supported voltages. RRs that result in $V_{RLY_HW_MAX}$ at I_{SYS_MAX} and $V_{RLY_HW_MIN}$ at I_{SYS_MIN} are given in (8) and (9).

$$RR_{SYS_MAX} = \left(\frac{I_{SYS_MAX}}{V_{RLY_HW_MAX}} \right) = \left(\frac{10,000 \text{ A}}{128 \text{ V}} \right) = 78.13 \text{ A/V} \quad (8)$$

$$RR_{SYS_MIN} = \left(\frac{I_{SYS_MIN}}{V_{RLY_HW_MIN}} \right) = \left(\frac{50 \text{ A}}{0.005 \text{ V}} \right) = 10,000 \text{ A/V} \quad (9)$$

The calculated RRs using (8) and (9) represent the range of RR (78.13 A/V to 10,000 A/V) suitable for the application in Table I. The RRs of Sensors 1, 2, and 3, in Table III, fall within the range and can be applied for this application. Checks 1 through 5, applied to Sensors 1, 2, and 3, all passed, indicating suitability. The sensor selection can be narrowed down further by applying additional margins to the system information and repeating the exercise.

D. Sensor Selection for Transformer Differential Applications

Sensors for feeder applications can be selected by applying Check 1 to Check 5 identified in Table II. In case of transformer differential (87T) applications, based on the number of windings and the voltage rating of each winding, it is possible to choose

one sensor for all the windings or different sensors for each winding. Check 1 to Check 5 still holds true for 87T applications. The checks should be applied to the sensors on each of the windings as well as the overall scheme to satisfy additional constraints associated with 87T applications.

Transformers have different voltage ratings on each winding. Likewise, the windings can be connected either in wye or delta configurations. As a result, for proper application of the differential protection principle, the scheme requires ratio compensation (also referred as TAP compensation), vector group compensation, and zero-sequence removal [15]. As our main goal was sensor selection, we limited the scope to ratio compensation only.

The CT ratio on the HV (CTR_{HV}) and LV (CTR_{LV}) side are typically chosen to offset the transformer ratio as closely as possible. The digital 87T relays support TAP settings for each of the windings to compensate for any ratio mismatch. TAP settings are typically calculated using (10) (where $n = HV$ or LV), using MVA rating, respective voltage rating of the winding, and respective CT ratio. The CTs are assumed to be connected in wye configuration. For applications with LEA sensors, the TAP settings can be calculated using (10) by simply replacing CTR_n with $I_{RLY_BASE_n}$.

$$TAP_n = \left(\frac{MVA}{\sqrt{3} \cdot V_{LL_n} \cdot CTR_n} \right) \quad (10)$$

87T settings are typically made in per unit of TAP. Microprocessor-based 87T relays, which support CTs, may impose the following constraints to limit the specified accuracy requirements of the relay within a range of TAP_n values. $INOM_n$ can be either 1 A or 5 A but is limited to 1 A for ease of discussion. While we used sample values of 0.10 and 30.00, these values can vary between relay manufacturers.

- The TAP_n setting needs to be within the range $0.10 \cdot INOM_n$ and $30.00 \cdot INOM_n$ (where $n = 1, 2$, or 3 winding).
- The ratio of the maximum (TAP_{MAXn}) to the minimum (TAP_{MINn}) is less than or equal to 30.00.

An 87T relay may be applied to transformer differential applications that support CTs alone, LEA sensors alone, or a combination of both. The relay discussed in this paper can be configured in a hybrid arrangement using a mix of RCOIL sensors and CTs without any external converter. In case of the combination, one of the windings would use CTs, while the other would use Rcoil sensors. Therefore, the above constraints are equally applicable for selecting CTs or LEA sensors.

1) Example 5: Calculation of an Acceptable RR Range for a Given Low-Ratio Transformer and Relay Specifications

Consider the transformer, system, and relay information presented in Table IV, Example 5. Similar to (8) and (9), we can establish the possible range of RRs (RR_{SYS_MIN} and RR_{SYS_MAX}) by equating the system minimum ($\min(I_{SYS_MIN_LV}, I_{SYS_MIN_HV})$) and maximum ($\max(I_{SYS_MAX_LV}, I_{SYS_MAX_HV})$) currents to the corresponding LEA relay minimum ($V_{RLY_HW_MIN}$) and maximum ($V_{RLY_HW_MAX}$) supported voltages. The calculated RR_{SYS_MIN} and RR_{SYS_MAX} are 10,000 A/V and 156.25 A/V respectively and are suitable for the application in Table IV, Example 5. The RR of Sensors 1, 2, and 3, in Table III, fall within the range and can be used for this application. Table V, Example 5 lists all the checks

to be applied on the HV and LV side to verify the suitability of Sensor 1, in Table III.

2) Example 6: Calculation of an Acceptable RR Range for a Given High-Ratio Transformer Application and Relay Specifications

Consider the transformer, system, and relay information presented in Table IV, Example 6. Similar to Example 5, we can calculate the possible range of RR values as $RR_{SYS_MIN} = 1,000 \text{ A/V}$ and $RR_{SYS_MAX} = 468.75 \text{ A/V}$. The calculated RRs represent the range of RR suitable for application in Table IV, Example 6. None of the sensors presented in Table III are suitable. A custom sensor with an RR of 500 A/V is chosen for this application.

Table V, Example 6 lists all the checks to be applied on the HV and LV side to verify the suitability of this sensor. Any additional application criteria not listed in the table should also be considered.

1. I_{RLY_BASE} on the LV side is chosen to match the full load current of the transformer but not on the HV side. But choosing $I_{RLY_BASE} (HV) = I_{SYS_NOM} (HV)$ will result in significant ADC clipping at $I_{SYS_MAX_HV}$. Therefore, $I_{RLY_BASE} (HV)$ of 400 A is chosen using Equation (6), such that the relay will not experience ADC clipping at $I_{SYS_MAX_HV}$. As a result, Check 4 fails on HV side, which implies that the required sensitivity cannot be met.
2. Failure of Check 1 indicates that the relay hardware cannot support the full dynamic range of application requirements. Consider the options provided under Example 3.

The sensor selection can be further narrowed down by applying additional margins to the system information and repeating the exercise.

E. Impact of ADC Clipping on Protection:

ADC clipping of the fault current introduces harmonics and reduces the fundamental magnitude compared to the true value. Symmetrical ADC clipping introduces odd harmonics, while asymmetrical ADC clipping introduces both even and odd harmonics. Asymmetrical ADC clipping can happen for high fault currents with large a DC offset. The result of ADC clipping can be undesirable. For example, feeder relays that use harmonic blocking to supervise overcurrent elements may end up blocking or slowing down the operation of overcurrent elements. Likewise, the harmonic restraint and blocking features of the transformer differential element (87T) can be negatively impacted. For example, the 87T element could get blocked due to harmonic blocking for an internal fault with ADC clipping. To avoid the possibility of ADC clipping, we recommended choosing a suitable sensor, as well as the I_{RLY_BASE} setting. If the ADC clipping cannot be avoided, ensure that the unrestrained element (87U) is set with adequate margin with respect to the available operate current after ADC clipping. ADC clipping can also impact the accuracy of breaker wear monitoring and transformer through-fault monitoring functions. When compared to CTs where clipping is never clean due to CT saturation effects, Rcoil clipping can be kept clean with adequate hardware design providing additional advantage in applications where clipping is acceptable.

TABLE IV
EXAMPLE 5 AND 6: SAMPLE SYSTEM, TRANSFORMER AND RELAY INFORMATION

Data	Description	Terminology	Example 5	Example 6
XFMR	MVA rating	MVA	10.4	3
XFMR	HV winding voltage rating	$V_{LL\ HV}$ (kV)	12.47	34.5
XFMR	LV winding voltage rating	$V_{LL\ LV}$ (kV)	4.16	0.48
XFMR	HV winding full load current	$I_{SYS_NOM\ HV}$ (A)	500	50
XFMR	LV winding full load current	$I_{SYS_NOM\ LV}$ (A)	1,500	3,608
System	Maximum HV fault current	$I_{SYS\ MAX\ HV}$ (A)	10,000	12,000
System	Minimum HV load/fault current	$I_{SYS\ MIN\ HV}$ (A)	50	5
System	Maximum LV fault current	$I_{SYS\ MAX\ LV}$ (A)	20,000	60,000
System	Minimum LV load/fault current	$I_{SYS\ MIN\ LV}$ (A)	150	361

TABLE V
EXAMPLE 5 AND 6: SENSOR SUITABILITY CHECKS

Type	Quantities	Example 5 (RR=444.4 A/V)		Example 6 (RR=500 A/V)	
		HV	LV	HV	LV
Relay	$I_{RLY\ BASE} = I_{SYS\ NOM}$	481.5	1,443.4	400	3,608
Relay	$V_{RLY\ NOM} @ I_{RLY\ BASE} = I_{RLY\ BASE} / RR$	1.083	3.248	0.80	7.216
Relay	$V_{RLY_30\%NOM} @ 30 \cdot I_{SYS\ NOM}$	32.50	97.43	24.0	216.5
Relay	$V_{RLY\ 5\%NOM} @ 5\% \text{ of } I_{SYS\ NOM}$	0.054	0.162	0.04	0.361
Sensor	$V_{SEN\ SYS\ MAX} @ I_{SYS\ MAX}$	22.50	45.00	24.0	120.0
Sensor	$V_{SEN\ SYS\ MIN} @ I_{SYS\ MIN}$	0.108	0.325	0.01	0.722
Check 1	$V_{RLY\ MAX\ MIN} > I_{SYS\ MAX} / I_{SYS\ MIN}$	Pass	Pass	Fail	Pass
Check 2	$V_{RLY\ 30\%NOM} \geq V_{SEN\ SYS\ MAX}$	Pass	Pass	Pass	Pass
Check 3	$V_{RLY\ HW\ MAX} > V_{SEN\ SYS\ MAX}$	Pass	Pass	Pass	Pass
Check 4	$V_{RLY\ 5\%NOM} < V_{SEN\ SYS\ MIN}$	Pass	Pass	Fail	Pass
Check 5	$V_{RLY\ HW\ MIN} < V_{SEN\ SYS\ MIN}$	Pass	Pass	Pass	Pass
Check 6	$0.1 \leq TAP \leq 30$	1.0 Pass	1.0 Pass	0.13 Pass	1.0 Pass
Check 7	$TAP_{MAX} / TAP_{MIN} \leq 30$	Pass	Pass	Pass	Pass

A. Optimize Percentage-Restraint Differential Characteristic With LEA Relays

The percentage-restraint differential element typically includes a minimum pickup and two slope characteristics (dual slope). The minimum pickup is set to accommodate steady-state errors and noise, which can arise from transformer magnetizing current, CT ratio mismatch, accuracy limitations, burden variations, small load unbalances, unmonitored loads, and measurement noise [15]. Typical minimum pickup values range from 0.2 to 0.5 pu of the winding current. Slope 1, the lower slope, addresses proportional errors that scale with current, such as CT ratio mismatch under high load or fault conditions, line charging current differences, transformer tap changer positions, and moderate CT saturation. This slope is commonly set to around 20–30 percent. Slope 2, the higher slope, is used in magnetic CT-based relays to handle transient differential currents caused by CT saturation during severe faults. Contributing factors include high X/R ratio faults with large DC offsets, CT remanence, heavy through-fault currents, and dynamic CT performance under short-circuit conditions. Slope 2 is typically set higher, in the range of 50–70 percent, to increase the restraint region under large restraint currents, improving security but reducing dependability [12] [15].

Since Rcoil is immune to CT saturation, Slope 2 can be eliminated to achieve the same level of sensitivity as Slope 1 for higher fault currents compared to the CT-based protection. In many Rcoil sensors, high-accuracy, linear response at low levels of currents may allow the minimum pickup, as well as the Slope 1 settings, to be reduced below conventional values. These optimizations make differential protection more sensitive and secure compared to CT-based systems.

B. Testing Rcoil Based LEA Relays

Testing of the LEA relay can be performed in several ways:

1. Secondary voltage injection
 - a. Direct voltage injection
 - b. Rcoil emulators
2. Primary current injection with an Rcoil sensor

Secondary voltage injections are the easiest method for testing protection logic that operates on the fundamental component. To perform this test, a voltage source is required that can deliver accurate voltages over an adequate range, based on the sensitivity of the sensor and the lowest and highest settings to be tested, without any DC offset. A DC offset can drive the integrator into saturation and produce erroneous results.

For example, to test a simple overcurrent element pickup set based on secondary current, such as $50P_{SEC} = 0.1$ A secondary, the setting is converted from secondary amperes to primary amperes. This can be done using the LEA scale (similar to CT ratio). Typically, this scaling is equal to I_{RLY_BASE} with the secondary nominal current assumed to be 1 A in LEA relays. To test this element using secondary voltage injection, the relay base current (I_{RLY_BASE}) is used to convert the $50P_{SEC}$ setting into primary amperes ($50P_{PRI} = 50P_{SEC} \cdot I_{RLY_BASE}$). Equation (3) is then used to calculate the proportional voltage the Rcoil will generate (V_{RLY}) for a primary current of $50P_{PRI}$.

Then an accurate voltage source is used to inject V_{RLY} to RJ45 inputs of the LEA relay to get 0.1 A secondary. Direct voltage injection introduces an additional 90-degree phase shift due to the integrator action in the LEA hardware. Therefore, a negative 90-degree phase shift should always be

applied to the injected voltage to maintain the correct phase when testing with steady-state signals.

Some relay test equipment manufacturers provide the option to emulate Rcoil behavior using their test sets. In these emulators, IPR and USR need to be configured in the fields labeled *display value* and *output value*, respectively. When IPR A is applied at the frequency where USR is defined, the corresponding output will provide USR mV with the correct phase shift. This voltage is then directly applied to the RJ45 input of the relay. No additional phase alignment is required when using emulators. Note that it is important to match the USR to the test frequency. Some emulators may provide the option to choose the frequency. Both of the above methods are suitable for testing steady-state fundamental protection elements.

Harmonics and decaying DC offset testing are also possible with these methods. As shown in (2), to obtain the harmonic voltage proportional to the input current, each harmonic magnitude must be multiplied by its harmonic number (m). For example, to get 10 A of primary second harmonic magnitude ($m = 2$) along with the fundamental, $2 \cdot 10 \cdot \text{USR/IPR}$ volts (at twice the fundamental frequency) should be applied in addition to the fundamental voltage. To apply different phases for harmonics, the 90° phase adjustment should be applied to each equivalent harmonic voltage individually.

Another approach is to compute the derivative of the primary current under test and generate the corresponding voltage to apply to the LEA inputs of the relay, as described in (1) and (2). This derivative method is also suitable to test transients, like decaying DC faults.

To test harmonics and decaying DC signals, another approach is to use the actual sensor with primary current injection. To boost currents, multiple turns can be applied around the sensor and then current is injected through the primary conductor. Whenever possible, the most accurate way to test the LEA relay for both fundamental and harmonic components is primary current injection using both the cable and sensor targeted for the application. It is important to note that when using multiple turns, the turns will seldom be uniformly distributed around the coil. Nonuniform turn distribution causes some ratio (sensitivity) error. This behavior is normal and will vary depending on the coil construction.

IV. EXPERIMENTAL RESULTS

We used a current amplifier system capable of supplying 2.5 kA for the testing. To increase the primary current, we wound multiple turns around the Rcoil sensor and CT.

A. LEA Relay Performance Under Decaying DC Fault Current

A fully offset, decaying DC signal of 24 kA, with an X/R ratio of 20, was applied to the Rcoil, and the magnetic CT. IPR, USR, and IRLY_BASE were set at 80 A, 180 mV at 60 Hz, and 1,900 A, respectively. CT class, CT ratio, and CT secondary winding resistances were C400, 1200 / 5, and 0.7567 Ohm, respectively. The CT excitation curve can be found in [16]. The fault current and the fundamental magnitude recorded by the LEA relay and the conventional relay are shown in Figure 3.

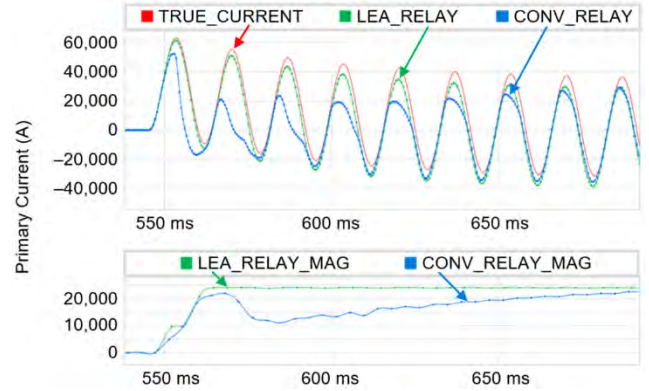


Figure 3 A 24 kA Fully Offset Fault Recorded by LEA Relay with Rcoil and Relay with CT

Figure 3 compares the true current with the currents measured by the Rcoil paired with a LEA relay and the magnetic CT paired with a conventional microprocessor-based relay. Due to the DC offset, the magnetic CT experiences heavy saturation during the first few cycles resulting in distorted current waveform. Once the signal transitions into the symmetrical region, the CT gradually recovers from saturation. This saturation causes incorrect (smaller) fundamental magnitude calculations in the relay, leading to issues, such as false differential current and potential misoperation of relay elements. In contrast, the response of the LEA relay is unaffected by saturation, and the waveform is fully restored with the correct phase angle.

To demonstrate the effect of signal clipping during a decaying DC offset fault caused by improper selection of the IRLY_BASE setting, we applied the same fault signal to the LEA relay with IRLY_BASE settings of 1,900 A and 500 A. The LEA relay captured the waveforms, and the combined second and fourth harmonic magnitudes are shown in Figure 4. For comparison, the C400 1200 / 5 CT waveform is also shown.

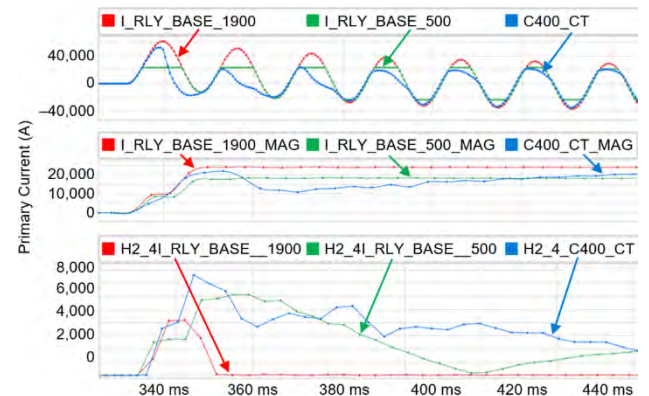


Figure 4 Decaying DC Fault and Combined Second and Fourth Harmonic Magnitudes With Different IRLY_BASE Settings

When signals are clipped, the fundamental magnitude is lower than the true value and harmonics are introduced, as shown in Figure 4. Depending on the degree of clipping, dependability for internal faults can be affected.

We use second and fourth harmonic restraint, or blocking, to detect transformer inrush. If the relay detects higher second and fourth harmonics, it either proportionally increases the

restraint region or blocks the differential element. Figure 4 shows that when clipping is greater due to a lower I_{RLY_BASE} setting, the combined second and fourth harmonic level remains high for a longer duration. This can delay, or even block, the operation of the differential element for internal faults. A high level of second and fourth harmonics can be observed in the CT response for a prolonged period. This experimental result highlights the impact of clipping on harmonic restraint and blocking and underscores the importance of selecting the I_{RLY_BASE} setting appropriately for your application.

B. External Rcoil Summation for Differential Protection

This method is particularly useful when a busbar has multiple feeders, or a transformer has multiple terminals associated with a given winding (dual breaker applications) that exceed the number of current inputs available on the relay. The approach involves externally summing the Rcoil secondary output voltages in series and feeding the resultant differential voltage to the relay for differential protection.

In this approach, it is essential to use Rcoils with matched sensitivity or ratio, preferably from the same manufacturer and model. Even when using Rcoils of the same manufacturer, model, and sensitivity, magnitude and phase errors may occur due to construction differences, potentially producing a false differential voltage at the output of the summed Rcoil secondaries. These errors should be considered when setting the pickup thresholds.

We used five split-core Rcoils and one solid-core Rcoil in the test. The sensors had an accuracy rating of 0.5 / 5P630. The magnitude and angle correction factors for all sensors were similar and negligible. To examine the variation in sensor output voltage for the same primary current, we applied 100 A through each sensor and measured the current reported by the relay. The combined error percentage of the sensors and the relay was less than 1.3 percent.

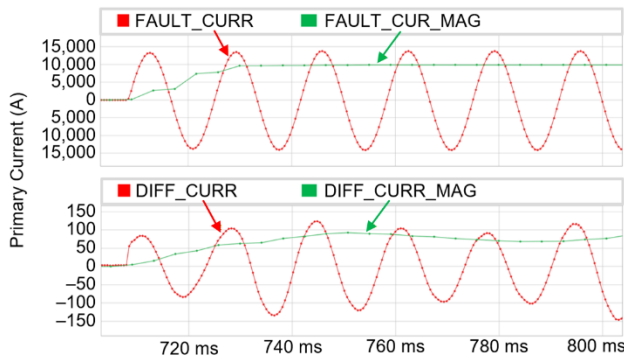


Figure 5 External Rcoil Summation With 10 kA Through-Fault Current

Figure 5 shows the experimental test results of an external Rcoil summation application. We simulated a six-feeder busbar and generated external faults of 5 kA, 10 kA, and 12.5 kA. Differential current measured for each fault was 38 A, 90 A, and 100 A primary. Although the same sensor was used, the false differential current primarily resulted from sensor mismatch. This false differential current is proportional to the through current. The percentage of differential current relative

to the through current is less than 1 percent, in this case. It is important to account for this error in the setting calculations of the protection scheme applied.

C. Hybrid Configuration With a Mix of Rcoil and Magnetic CTs

In certain installations, protection engineers may choose to retain existing magnetic CTs on one side of the transformer, while replacing or upgrading the other side with Rcoils. LEA relays support hybrid configurations that combine Rcoils and magnetic CTs within the same differential zone. There are no new settings required for a hybrid configuration; the individual Rcoil and CT-based settings are configured in the relay as they would if the differential zone contained only Rcoils or only CTs.

Figure 6 shows the experimental results of external faults simulating a 20:1, two-winding transformer with a hybrid configuration. We applied a symmetrical 48 kA fault. For per unit calculations, we assumed the winding voltages and transformer capacity as 69 kV to 3.45 kV and 15 MVA respectively. Note that the operate current (IOP) is approximately 0 pu, as expected.

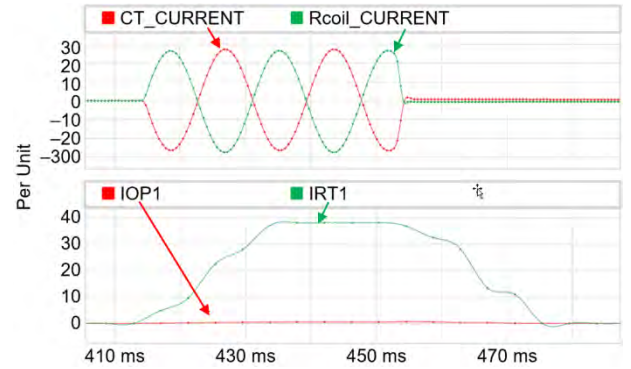


Figure 6 A 48 kA Symmetrical External Fault in a Hybrid Configuration

V. CONCLUSION

In this paper, we have demonstrated how LEA relays, when paired with Rcoil sensors, provide a robust and flexible alternative to CT-based protection. By leveraging the inherently linear, wide-bandwidth, and saturation-free characteristics of Rcoil sensors, LEA relays can accurately measure currents spanning from low-level load conditions to high-magnitude fault events, overcoming key limitations associated with magnetic CTs.

We propose a structured approach for selecting Rcoil sensors and configuring LEA relay settings for feeder and transformer differential applications. We demonstrate practical examples of how relay dynamic range, sensor sensitivity, and system fault levels interact, and how the I_{RLY_BASE} setting can be used to balance sensitivity and security. Our analysis shows that, within relay hardware constraints, a single Rcoil type can support a wide range of application requirements without the need for multiple CT ratios or accuracy classes.

The experimental results we present compare Rcoil-based LEA relay measurements with CT-based relays under high-current fault conditions, including events with significant DC offset. Our results confirm that Rcoil-based measurements

remain accurate and free of saturation-induced distortion, enabling improved protection performance and greater flexibility in protection scheme design. We demonstrate the feasibility of external summation of Rcoil outputs for use with bus and transformer differential applications. We also demonstrate the feasibility of hybrid protection schemes that use Rcoils and CTs within the same differential zone.

Overall, this paper demonstrates that Rcoil-based LEA relays provide a flexible and scalable protection solution that addresses many limitations of conventional CTs. As fault levels increase and protection systems continue to evolve, this technology offers a robust and adaptable foundation for modern feeder and transformer protection applications.

VI. REFERENCES

- [1] IEEE Std C37.235-2021, *IEEE Guide for the Application of Rogowski Coils Used for Protective Relaying Purposes*, New York, NY: IEEE.
- [2] IEC 61869-9, *Instrument Transformers – Part 9: Digital interface for instrument transformers*, Geneva, CH: IEC, 2016.
- [3] IEC 61869-10, *Instrument transformers – Part 10: Additional requirements for low-power passive current sensors*, Geneva, CH: IEC, 2017.
- [4] IEC 61869-11, *Instrument Transformers – Part 11: Additional requirements for low-power passive voltage transformers*, Geneva, CH: IEC, 2017.
- [5] IEC 61869-13, *Instrument transformers – Part 13: Stand-alone metering unit (SAMU)*, Geneva, CH: IEC, 2021.
- [6] IEEE Std C37.92-2023, *IEEE Standard for Low-Energy Analog Interfaces between Protective Relays and Power System Signal Sources*. New York, NY: IEEE.
- [7] L. Kojovic, and R. Beresh, "Practical Aspects of Rogowski coil applications to relaying," *IEEE PSRC Special Report*, September 2010.
- [8] P. Menke, V. Skendzic, and N. Fisher, "Low-Power Instrument Transformers: Ideal Solution for Modern Data Centers, High-Density Industrial applications, and Digital Secondary Systems," in *52nd Annual Western Protective Relay Conference Record*, 2025.
- [9] S. Broderick, C. Pestell, N. Kumar, and J. Payne, "Design and Use of Protection-Class Rogowski Coils for Medium-Voltage Switchgear," in *IEEE IAS Petroleum and Chemical Industry Technical Conference Records*, 2023, pp. 67-76.
- [10] L. Schulz, P. Schuhmann, J. Sanchez, O. Hartman, A. Stinskiy, and M. Rabinovich, "Protection Applications With Low-Power Instrument Transformers (LPIT): Proof of Interoperability Under Operating Conditions," in *Conference for Protective Relay Engineers Records*, 2025.
- [11] L. Napier, L. Cesky, and A. Pilarski, "Dynamic Protection System Performance using Rogowski Coils," in *Australian Protection Symposium Records*, 2024.
- [12] L. Kojovic, M. Bishop, and D. Sharma, "Innovative Differential Protection of Power Transformers Using Low-Energy Current Sensors" *IEEE Transactions on Industry Applications*, Vol. 49, No. 5, September/October 2013.

- [13] V. Skendzic and B. Hughes. "Using Rogowski Coils Inside Protective Relays." in *66th Annual Conference for Protective Relay Engineers Records*, College Station, TX, April 2013.
- [14] IEEE Std C37.110-2007, *IEEE Guide for the Application of Current Transformers Used for Protective Relaying Purposes*, New York, NY: IEEE.
- [15] M. Thompson, "Percentage Restrained Differential, Percentage of What?" in *64th Annual Conference for Protective Relay Engineers Records*, 2011.
- [16] "Datasheets," Amran Instrument Transformers, 2016. Online at <https://amranit.com/datasheets>

VII. VITAE

Anushka M. Dissanayake (S '18, M '20) received a BS degree in electrical and electronic engineering from the University of Peradeniya in Sri Lanka, in 2014. He went on to earn a PhD degree in electrical engineering from Oklahoma State University in 2020. In 2020, he joined Schweitzer Engineering Laboratories, Inc. (SEL), where he is currently a lead power engineer in Research and Development. His research interests include power system protection, digital signal processing, and microgrids.

Vinod Yedidi is a senior engineer in the Research and Development division of Schweitzer Engineering Laboratories, Inc. (SEL). He's been with SEL since 2006. Vinod received his MS in electrical engineering from University of Idaho in 2006 and his BS in electrical and electronics engineering from the Jawaharlal Nehru Technological University College of Engineering in Hyderabad, India, in 2002. He has been a member of IEEE for 25 years and is a registered professional engineer in Washington.

Anurag Upadhyay received his MS in electrical engineering from Michigan Technological University in 2016 and BTech in electrical engineering from The National Institute of Technology in Allahabad, India, in 2011. He joined Schweitzer Engineering Laboratories, Inc. (SEL) as a product engineer in 2020 and contributes toward the development of SEL-700 series protective relays.

Jamison Ehlers received a BS and MS in Electrical Engineering from Montana Technological University, Butte, MT in 2020 and 2022 respectively. After joining Schweitzer Engineering Laboratories in 2023, he has worked on developing protective relays for industrial applications as a hardware engineer.

Marcos Donolo (S '99, M '06, SM '13) received the BSEE degree from Universidad Nacional de Río Cuarto, Argentina, in 2000, the MS degree in electrical engineering, the second MS degree in mathematics, and the PhD degree in electrical engineering from the Virginia Polytechnic Institute and State University, Blacksburg, VA, USA, in 2002, 2005, and 2006, respectively. Since 2006, he has been with Schweitzer Engineering Laboratories, Inc. (SEL), where he is currently a Principal Engineer. He holds several patents and has authored numerous papers related to power system protection.

Previously presented at the 2026 IEEE IAS Petroleum and Chemical Industry Technical Conference (PCIC), Philadelphia, PA, September 2026.

© 2026 IEEE – All rights reserved.
20260401 • TP7244