IEC 61869 Compliant Rogowski Coil for Volume Production

Wolfram Teppan
LEM Intellectual Property SA
Avenue Beauregard 1, 1700 Fribourg, Switzerland
WTe@lem.com

Pierre Turpin, Mathieu Beguin
LEM Switzerland SA, LEM International SA
Chemin des Aulx 8, 1228 Plan-les-Ouates, Switzerland
PTu@lem.com, MBn@lem.com

***Abstract*—International instrument transformer standardization efforts include alternative designs in their scope. Rogowski coils fall within the so-called "low power passive current transformers" category. The main disadvantage of easy-to-use split-core Rogowski coils can be overcome by adding a simple ferrite core at the clasp: short-circuiting the magnetic path by a soft magnetic part in the region where the winding density cannot be kept constant leads to a near perfect independence of the ratio error on the position of the primary conductor. A well-characterized winding support ensures an absolute error low enough to be acceptable for billing purposes.**

Keywords—Rogowski coil; IEC 61869; LPIT; LPPCT; position error; accuracy; type test; smart grid

I. INTRODUCTION

The idea to use a flexible coil with constant winding density to measure magnetic fields dates back to 1887 [1]. Since then, the concept has been applied to the measurement of currents with very high frequency contents like pulse currents in inverter stages or lightning currents, but also for currents at the common power frequencies of 50 Hz and 60 Hz. Rigid non-split Rogowski coils can reach accuracy classes down to 0.1 %, and many designs have been devised over the years [2]. Still, a flexible coil is much appreciated in retrofit applications where stringent space constraints apply. For power frequency applications, relatively high turn counts are used but still yield quite small output voltages in the range of tenths of millivolts per kiloampere. Therefore capacitive coupling to the primary conductor should be minimized.

II. STANDARDIZATION

A. Metrology

Efforts are on-going at the IEC to add so-called "low-power instrument transformers" (LPITs) to the list of instrument transformers of the former IEC 60044 series. The term "low-power" means that no significant power is meant to be drawn from the secondary terminals and no specifications for an apparent output power are asked for; the standard burden is a resistor of 2 MΩ in parallel with a capacitor of 50 pF.

The replacement of this series has begun in the 2000s: IEC 61869-1, ed. 1.0 ("General requirements") has been published in 2007 [3], part 2, ed. 1.0 ("Additional requirements for current transformers") in 2012 [4].

Since this year part 6, "Additional general requirements for low-power instrument transformers", is available [5]. This part of the series describes the measuring chain from what is called a "primary sensor", a device converting the primary current (or voltage) to a signal that can be transmitted over a "transmitting system" to a "secondary converter" that provides an output signal for further processing. Details of the signal transmission system are not given: a standardized digital communication scheme is defined in part 9 that replaces IEC 60044-8; it has been published in 2016, is based on IEC 61850-9-2 and includes time synchronization according to IEC 61588.

In part 6, the scope of medium and higher voltages including d.c. applications is mentioned, for a.c., nominal frequencies between 15 Hz and 100 Hz are specified. The standard defines parameters that are relevant for electronic digital systems, for example optical current transformers, including rated delay times and electromagnetic immunity requirements. Metrological specifications exceeding the "class accuracy" (input signal level depending maximum ratio errors and phase displacements) include a detailed requirement for the frequency response regarding the measurement of harmonics up to the 50^{th} order and – for special applications – up to 500 kHz (fig. 1). It replaces IEC 60044-7. Other details include the specification of an M12 connector including pin assignments for the connection of a LPIT; alternatively a modular 8P8C ("RJ-45") connector can be used if no sealed connection is needed. Two pins are reserved for the connection of a memory chip according to the "transducer electronic data-sheet" (TEDS) standard, ISO/IEC/IEEE 21451-4:2010.

In 2017, the IEC standard for "low-power passive current transformers" (LPPCTs) is planned to be published [6]. This part specifies current transformers with a magnetic core and low rated burden power as well as core-less sensors like Rogowski coils (fig. 2), but not including any electronics, for example an integrator. This is why no EMC requirements can be found in this part. Details are given to reach a good accuracy class without adjustments requiring additional components: a "ratio correction factor" can be specified for individual LPPCTs eliminating production tolerances from the error budget. The foreseen use of the TEDS will clearly be an important advantage to attain low installation costs.

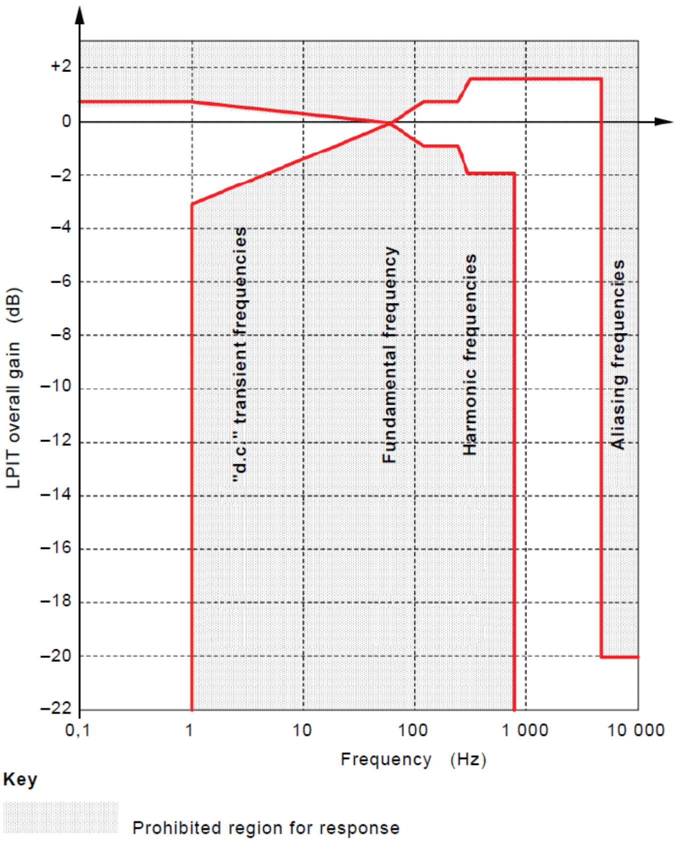


Fig. 1. Frequency response mask for metering accuracy class 1 (f_R = 60 Hz, f_s = 4 800 Hz) (from [5])

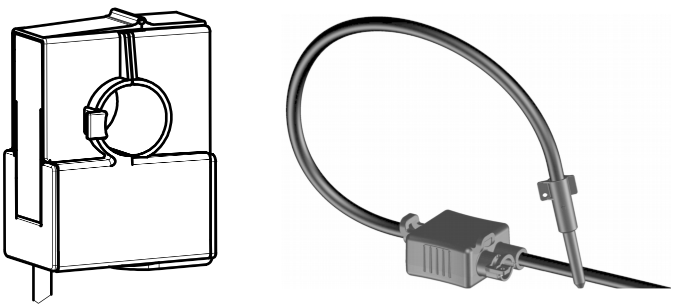


Fig. 2. LPPCT examples: clip-on CT (left), flexible Rogowski coil (right)

B. Safety

As no product specific safety requirements for fixed installed current transducers in low-voltage installations have been standardized yet, users tend to apply IEC 61010-2-032:2012 [7] although the LPPCTs are not "hand-held" during normal use. Still, the concept of measurement categories is considered useful and needed for compatibility with measurement instrument standards; 1000 V CAT III / 600 V CAT IV is a requirement covering most applications in low-voltage grids.

III. Applications

The so-called smart grid will allow more direct interactions between utilities and consumers who are often becoming "prosumers" integrating their own energy resources into the public electric grid. This trend changes the spatial and temporal load distribution in ways that were not anticipated at the time of design of the low-voltage distribution grids. Additional power electric and power electronic devices such as solid state transformers may be needed to guarantee the required power quality, in Europe defined by EN 50160.

Before expensive investments are made, the actual need for additional hardware in the grid has to be evaluated.

In the past, expensive measuring equipment has been installed at critical locations, mostly only after problems became evident. Some days or weeks later, the equipment needed to be removed again and the acquired data to be analyzed, requiring significant human interaction.

Distributed measuring nodes allow grid operators to exactly quantify the status of their installations. If the cost of a measuring node comes down to the cost of manually setting up and removing a measuring system, such fixed installed distributed measuring nodes become economically advantageous. Monitoring of distribution transformers is a good example for such a measuring system application – if designed with state-of-the-art components and software, not only transformer health, but also the load status of the LV grid as well as imminent violations of voltage and current limits can be detected and countermeasures be taken if remote control of distributed energy sources and loads is possible (fig. 3).

Energy measurement is another important application for Rogowski coils.

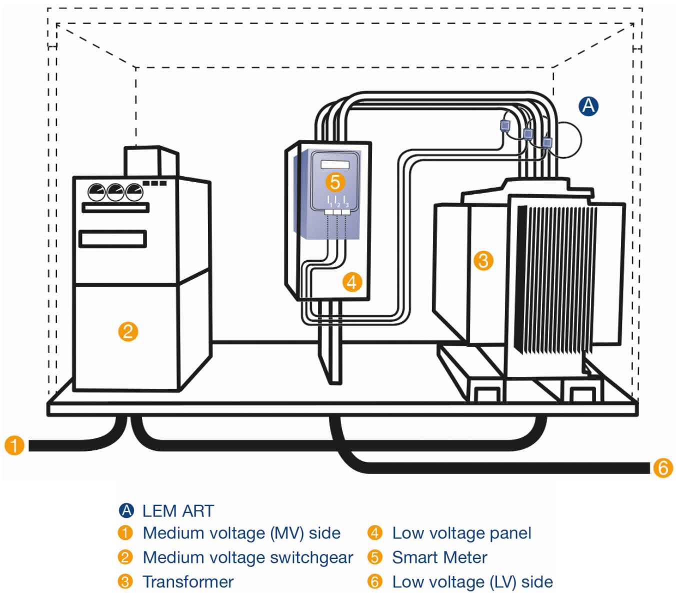


Fig. 3. Application of Rogowski coils and a smart meter in a MV/LV substation

The cost for the transducers, especially those to acquire the values of electrical current, can be significant compared to today's low-cost hardware for processing and communication. Therefore, simple transducers that can be manufactured with short production cycles are a prerequisite to reach wide-spread acceptance of distributed measuring systems.

If a.c. currents of more than some tenths of amperes are to be measured, thin and flexible split-core Rogowski coils are the transducers of choice because split-core instrument transformers tend to become bulky at higher currents.

IV. Design Trends

Flexibility and a small diameter are not the only important properties of a Rogowski coil. To reach low measurement errors, several parameters need to be optimized:

- the diameter of the flexible coil former must be constant all over its length,
- turn spacing must be as regular as possible and adapted to the wire diameter,
- the turns must be held in place after winding so that they do not move when the coil is bent,
- an electrostatic screen needs to be added to minimize capacitive coupling to the primary conductor leading to a high common mode rejection ratio.
- Special considerations are needed at the clasp location: as at the very ends of the coil no turns can be wound, a common measure is to add several turns close to the ends.

The last detail mentioned above reduces the overall sensitivity to the position of the primary conductor, but close to the clasp errors in the order of several percent are often unavoidable (fig. 4).

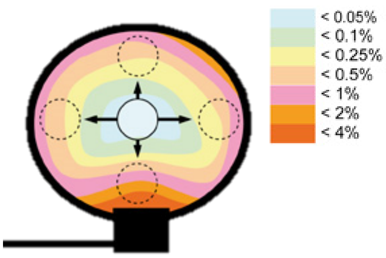


Fig. 4. Position sensitivity of commercially available Rogowski coils

The best way to reduce this effect that has been found is the addition of a soft magnetic part that short-circuits the magnetic field in this area (fig. 5, [8])

Fig. 6 shows the actually used ferrite core in its housing partially cut away.

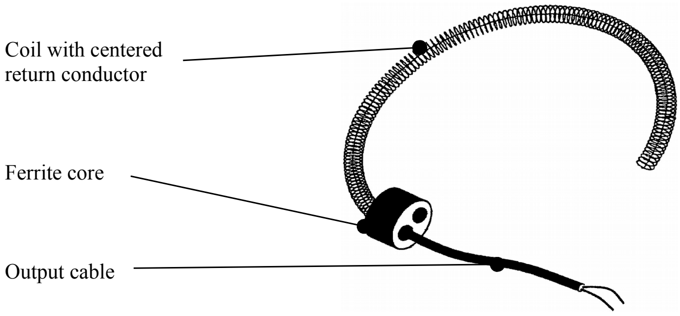


Fig. 5. Ferrite core to reduce the position dependent error close to the clasp

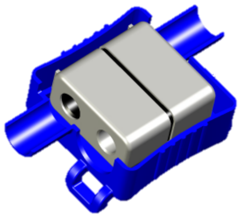


Fig. 6. Ferrite core of LEM Rogowski coils

V. Measurements

As a validation of very good measurement results obtained in the factory laboratory in Plan-les-Ouates, LEM had Rogowski coils with different coil lengths (including one as shown in fig. 7) tested by the Physikalisch-Technische Bundesanstalt in Braunschweig (PTB), Germany's national metrology institute.

Fig. 7. ART type Rogowski coil

A. *PTB test results*

A Rogowski coil with a diameter of 175 mm has been tested for linearity and sensitivity to the position of the primary conductor as well as for sensitivity to frequency variations.

Linearity: only for very low currents a small change of ratio error and phase displacement with respect to the other values can be detected, (fig. 8; the PTB equipment is specified with a measuring uncertainty of 0.25 % and 0.25 crad at 5 A).

Moving the primary conductor resulted in a maximum ratio error variation of 0.12 % (fig. 9).

The resonance frequency of the Rogowski coil depends on its cable length and can go down to values below 200 kHz (measured at LEM), but for power frequencies the influence is negligible (fig. 10).

Bürde 10 kΩ, 50 pF *Burden 10 kΩ, 50 pF*						
$I_{p,n}$ in A	M_n in nH	f in Hz	I_p / $I_{p,n}$ in %	I_p in A	ε_{iu} in %	δ_{iu} in crad
1000	71,619	60	600	6000	0,17	-0,02
			500	5000	0,17	-0,02
			200	2000	0,18	-0,01
			100	1000	0,18	-0,01
			50	500	0,18	-0,01
			25	250	0,18	-0,01
			20	200	0,18	-0,01
			12	120	0,17	0,00
			10	100	0,17	0,00
			2	20	0,16	0,03
			0,5	5	0,12	0,14

Fig. 8. Linearity – ratio error ε_{iu} and phase displacement δ_{iu} from 0.5 % to 600 % of I_{Pn}

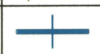
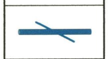
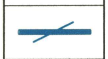
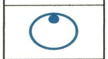
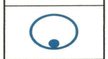
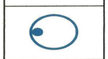
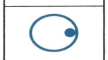
Bürde 10 kΩ, 50 pF *Burden 10 kΩ, 50 pF*						
$I_{p,n}$ in A	M_n in nH	f in Hz	I_p in A	Lage *position*	ε_{iu} in %	δ_{iu} in crad
1000	71,619	60	1000		0,16	-0,01
					0,18	-0,01
					0,13	-0,01
					0,23	-0,01
					0,25	-0,02
					0,14	-0,01
					0,15	-0,01

Fig. 9. Sensitivity to variations of the primary conductor position

Bürde 10 kΩ, 50 pF *Burden 10 kΩ, 50 pF*						
$I_{p,n}$ in A	M_n in nH	f in Hz	I_p / $I_{p,n}$ in %	I_p in A	ε_{iu} in %	δ_{iu} in crad
1000	71,619	50	100	1000	0,15	0,00
		60			0,15	-0,01

Fig. 10. Errors at 50 Hz and at 60 Hz

B. *LEM test results*

Measurements carried out at LEM during the development showed some residual position sensitivity in the range of 0.5 % (fig. 11). This error is mainly due to variations of the diameter of the flexible coil former and imperfections of the winding process.

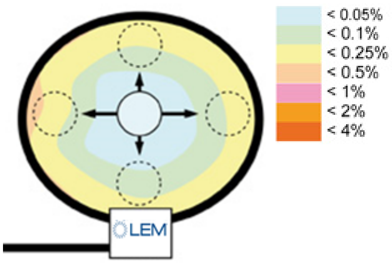


Fig. 11. Position sensitivity measured at LEM previously

To decrease the ratio error due to manufacturing uncertainties, often series resistors or voltage dividers are added to the output of Rogowski coils. Such an adjustment must be adapted to the input impedance of the subsequent integrator circuit.

Recent improvements in winding technology at LEM indicate that class 0.5 can be reached including positioning error without resistive dividers or series resistors.

Fig. 12 shows the change of the ratio error of 12 samples when moving a primary conductor with a diameter of 15 mm – touching the Rogowski coils around their inner perimeter – in steps of 6°, relative to their transfer ratio measured with a centric primary conductor.

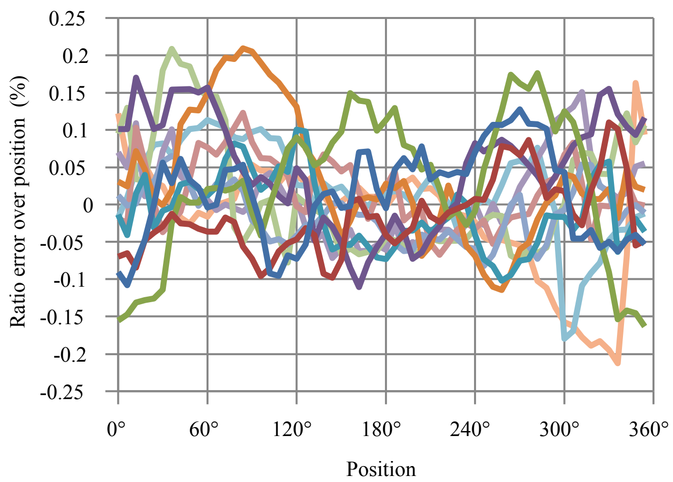


Fig. 12. Relative ratio error over primary conductor position

The absolute ratio error due to manufacturing tolerances (repeatability) could be decreased down to the region of 0.1 %, so the mentioned specification of class 0.5 seems feasible. Today, efforts continue to ramp up series production using the new winding technology.

VI. Conclusion

In recent years a rapid evolution of standards establishing the foundations of what is called the “smart grid” can be observed. The significant increase in performance of components in the signal processing chain of sensor data, starting for example with the Rogowski coil as current sensor over communication channels to the cloud based data centers storing and processing (big) data, shows a convergence and alignment of the interests of all smart grid stakeholders, getting a glimpse of the rapid transition to the “digital power grid”.

LEM supports this challenge by significant improvements of the performance of its current transducers, Rogowski coils being an optimum choice for many AC measurement applications by optimizing its design and manufacturing processes, making this technology very cost competitive.

By means of this new impoved technology, those split-core Rogowski coils achieve the same performance as current transformers in terms of accuracy. The absence of a magnetic core eliminating saturation effects even for the highest overcurrents and allowing the use of a single coil for a wide current range, LEM Rogowski coils provide an optimum choice in terms of technology and cost.

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