

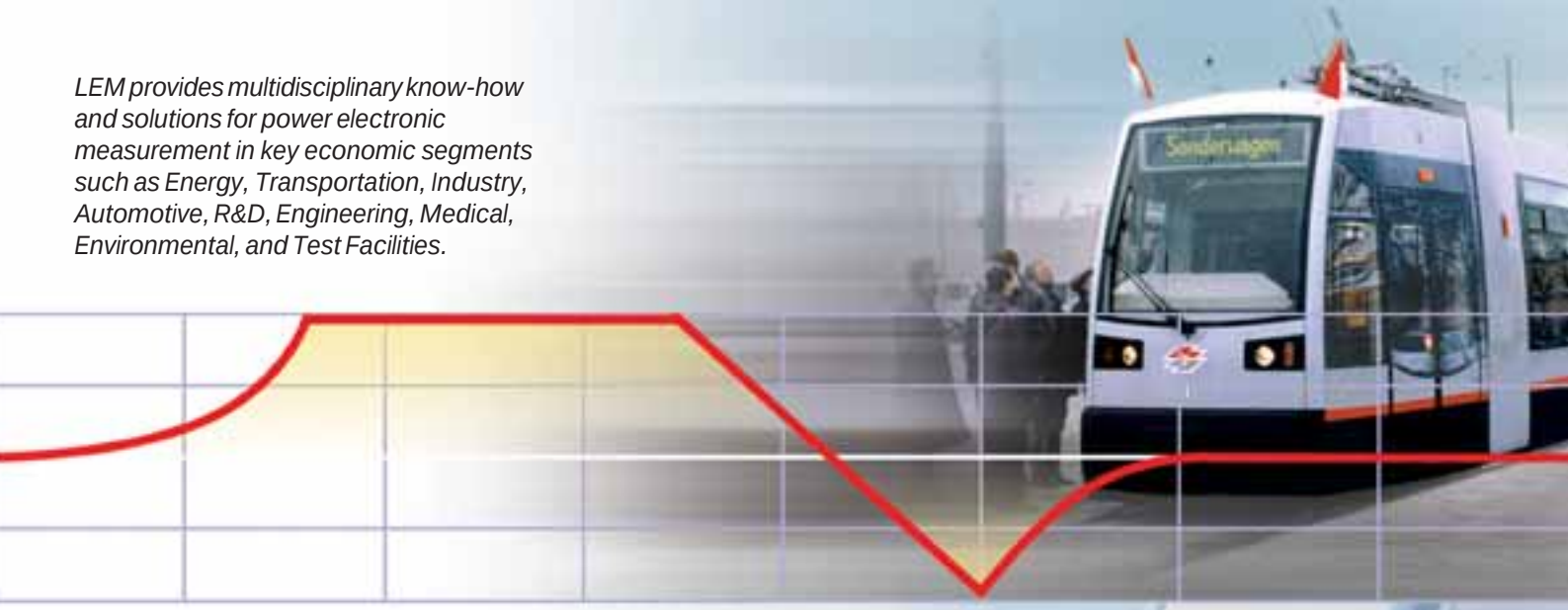
3rd Edition

Isolated current and voltage transducers

Characteristics - Applications - Calculations

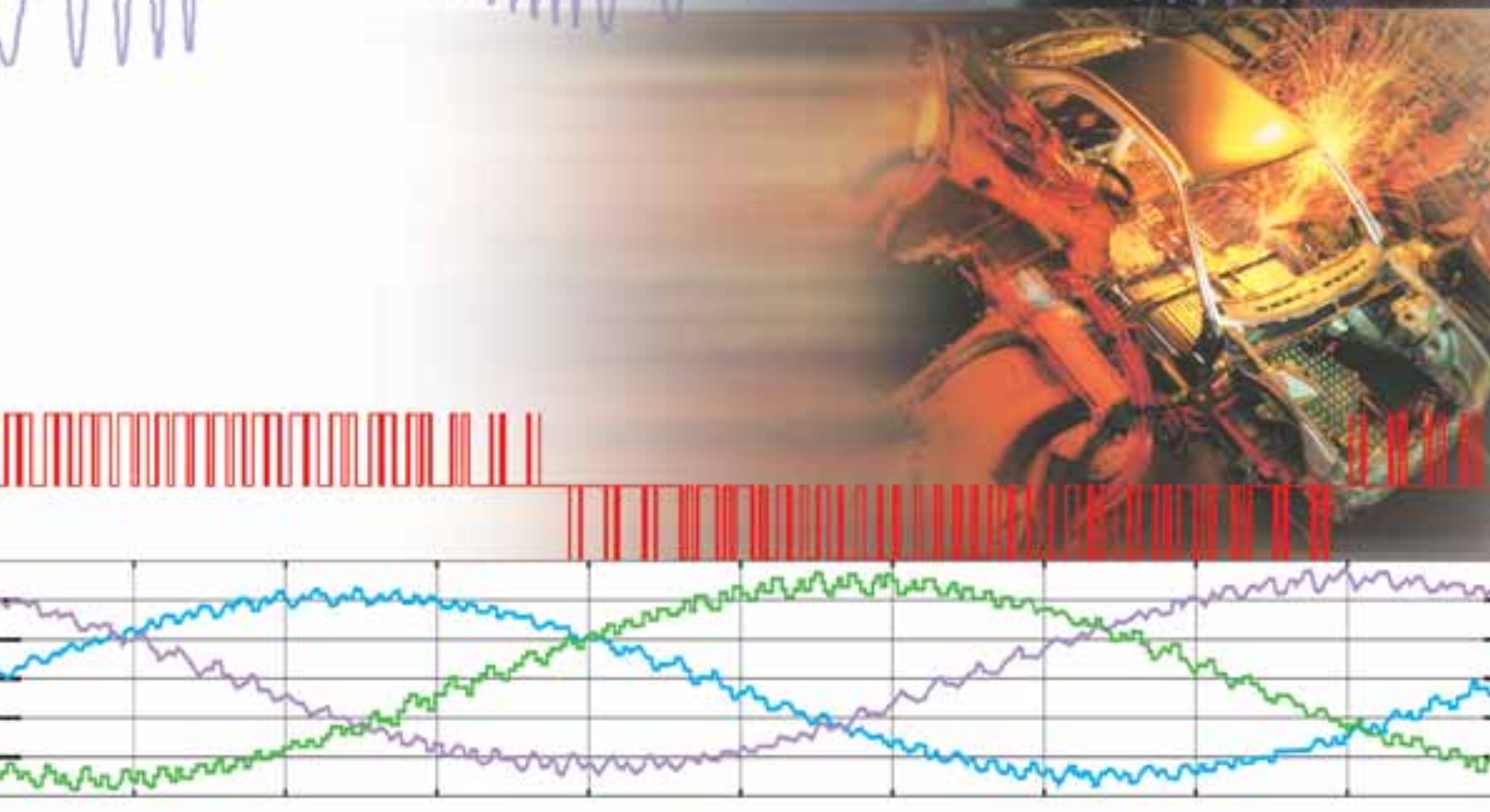
LEM

LEM provides multidisciplinary know-how and solutions for power electronic measurement in key economic segments such as Energy, Transportation, Industry, Automotive, R&D, Engineering, Medical, Environmental, and Test Facilities.



The top priority of LEM is a commitment to the quality of our products and services.
This, together with a combination of design, manufacturing, test, and customer service competencies, ensures the long-term success and satisfaction of our customers.





Isolated Current and Voltage Transducers
Characteristics - Applications - Calculations

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1 Optimal solutions with 6 different technologies of LEM transducers

Since 1972 LEM has been able to respond to customer demands, creating a wide range of galvanically isolated current and voltage transducers that have become standards in the measurement field. Our customers are offered a wide range of LEM transducers to meet their needs, based on the application requirements and transducer performance. This document is intended to provide our customers with a technical background to allow them to determine the best transducer to meet their needs.

We will begin by splitting the LEM transducer portfolio into four main categories covering six different technologies, discussed in detail later in this document:

- **Hall effect transducers**, which include closed loop, open loop, and Eta™ transducers
- **Fluxgate transducers**, which include „IT-types“, „C-types“, „standard types“, and „low frequency types“
- **Air-core transducers**, which include LEM~flex (Rogowski) and PRiME™ transducers
- **Various voltage transducers**, which include Hall effect, Fluxgate, the AV and OptiLEM™ products

The key attributes of these technologies are summarized in Table 1.

Finally, while most applications will find their best solution with a standard transducer selected from one of these technologies, LEM is fully capable of developing customized solutions to meet customer specific requirements. A review of this application note will allow the customer to better understand the critical aspects of transducer design, determine the closest standard device for the application, and better communicate the specific requirements of a custom device to LEM.

Table 1: Overview of the various LEM transducer technologies with their corresponding main characteristics

Current measurement		**Hall effect technologies ①**			**Fluxgate technologies ①**				**Air-core technologies ②**	
		Closed-Loop	'Eta' types	Open-Loop	IT-types	C-types	Low frequency types (CTS)	Standard type	LEM-flex	PRiME™
Measuring range	I_P	0 to 15 kA	25 to 150 A	0 to 15 kA	0 to 600 A	0 to 150 A	0 to 400 A	0 to 500 A	0 to 10 kA	0 to 10 kA
Bandwidth	f	0 to 200 kHz	0 to 100 kHz	0 to 25 kHz	0 to 100 kHz	0 to 500 kHz	0 to 100 Hz	0 to 200 kHz	10 Hz to 100 kHz	
Typ. response time (@ 90 %)	t_d	< 1 µs	< 1 µs	< 3-7 µs	< 1 µs	< 0.4 µs	< 5 ms	< 1 µs	10 to 50 µs	2 to 50 µs
Typ. accuracy at 25 °C, in % of I_{PN}	X	±0.5 %	±1.5 % (DC) ±0.5 % (AC)	±1.5 %	±0.0002 %	±0.1 %	±0.1 %	±0.2 %	±1.0 % ③	±0.5 % ③
Linearity	-	±0.1 %	±0.5 % (DC) ±0.1 % (AC)	±0.5 %	±0.0001 %	±0.05 %	±0.1 %	±0.1 %	±0.2 %	±0.2 %
Highlights	-	Accuracy Speed	Speed Low power Low voltage (5V)	Low power Small size Low cost	Best resolution Best accuracy Speed	High resolution High accuracy Best speed	Resolution Accuracy Low frequency Low cost	Resolution Accuracy Speed	Accuracy Bandwidth Light weight AC only	Accuracy Bandwidth Light weight AC only

① The Hall effect and Fluxgate attributes shown are based on a „solid core“ (non-opening) implementation. Split core (opening) versions are also available with reduced specifications.
② LEM~flex is a „split core“ device, implying that it can be opened to place around the conductor(s) to be measured. PRiME™ can also be designed for split-core operation which does not affect the performances.
③ The accuracy of air-core technologies is given in percent of reading (above 10% of nominal current) rather than percent of nominal current.

Voltage measurement		**Hall effect technologies** Closed loop	**Fluxgate technologies** C types	**Electronic Isolated** AV 100	**Optically isolated** OptiLEM
Measuring range	V_{PRMS}	0 to 9.5 kV	0 to 7 kV	50 V to 2 kV	100 V to 6 kV
Bandwidth	f	Several kHz	0 to 2/10/800 kHz ④	0 to 13 kHz	0 to 13 kHz
Typical response time (@ 90%)	t_d	10 to 100 µs	0.4µs	< 30 µs	< 30 µs
Typical accuracy at 25°C, in % of V_{PN}	X	±1 %	±0.2 %	±0.7 %	±0.9 %
Linearity	-	< 0.5 %	±0.05 %	±0.1 %	±0.1 %
Highlights	-	Standard performance	High accuracy Best speed Low speed	Small size Limited voltage Low speed	Excellent EMI immunity High common mode rejection High isolation capability Low speed

④ Design dependent

2 Determining parameters for transducer selection

The wide variety of available LEM transducers is the direct result of our know-how and many years of experience, enabling us to address the many variations of customer requirements within the greatly diversified field of power electronics. The application requirements create selection criteria, guiding the user to an appropriate product.

2.1 Which parameters need to be considered?

The selection of a transducer is the result of a technical and economic trade-off, considering the transducer as well as the associated sub-systems. All aspects of an application must therefore be taken into account during transducer selection and system design, with particular attention to the following:

- electrical requirements, including power supply requirements, peak measurement, response time, di/dt, dv/dt, etc.
- mechanical requirements, including aperture size, overall dimensions, mass, materials, mounting, etc.
- thermal conditions, including current profile versus time, maximum RMS measurement, thermal resistances, cooling, etc.
- environmental conditions, including vibration, temperature, proximity of other conductors or magnetic fields, etc.

The transducer development process includes a full regimen of tests that comprise the characterization report. These tests follow the scientific method, varying individual parameters to characterize the transducers response to each.

During production a quality plan indicates the tests to be carried out, on each product or batch of products, to verify compliance with specifications. Unless otherwise specified, performance is tested under nominal conditions of current, voltage, temperature, etc. in the production and laboratory environments.

In the actual application, several factors can act simultaneously and potentially provide unexpected results. It is essential to assess the transducer in those conditions to verify acceptable performance. Based on LEM experiences, this assessment is typically not difficult if the working conditions are known and defined.

The operating temperature range is based on the materials and construction of the selected transducer. The minimum temperatures are typically -40, -25, or -10 °C while the maximums are +50, +70, +85, or +105 °C.

2.2 Understanding the LEM documentation

The first step for transducer selection is a detailed understanding of the application, including parameters such as continuous RMS and repetitive peak measurement level, maximum possible peak or fault level, rate of change (e.g. di/dt and dv/dt) to be measured, allowable response time, etc. One must also consider external influences that will impact the application, such as temperature, shock, vibration, and external fields as well as any necessary compliance standards (EN, IEC, UL, CSA, etc.) that need to be met.

Using this information, refer to the general catalog of LEM transducers to locate the product line(s) that have the key characteristics to meet the requirements from the full range of available products. Then select the specific product(s) from those lines that meet the measurement requirements.

The individual datasheet (see the LEM website: http://www.lem.com) of the selected transducer(s) will then provide more details to determine if the transducer(s) match the requirements. The checklist provided in the following tables (§2.4 and §2.5) may help define critical concerns and assist in the transducer selection process.

2.3 Additional selection criteria

As previously discussed, some applications have a higher level of complexity and combine several potentially critical elements such as:

- electromagnetic interference
- significant common mode voltage transients (dv/dt)
- mechanical disturbances (vibration, shock, etc.)
- special isolation or partial discharge requirements
- compliance with specific standards, etc.

Obviously the best scenario is to perform tests in the specific application environment. If this is not reasonable or feasible, provide LEM with a diagram of your installation and a detailed description of the transducer operating conditions (e.g. description of the environmental conditions, graph of the waveform to be measured, nearby potentially disturbing elements such as inductors, current carrying conductors, the presence of magnetic materials or the desired location of other transducers).

2.4 Current transducers – selection check list

Electrical parameters	Selection criteria
Type of current to be measured	- DC, AC or complex waveform current - Selection of the adequate technology (Table 1)
Range of current to be measured	- Nominal current to be measured - Peak current to be measured - Transient current overloads to be measured - Maximum peak value and duration not measured
Required output signal	- Current or voltage output - Output value at nominal or peak current - For current output transducers, selection of the necessary or desired output load impedance
Measurement accuracy	- Required accuracy at 25 °C, taking into account the DC offset and non-linearity of the output signal - Global accuracy within the operating temperature range, adding the accuracy at 25 °C, the offset drift and, if applicable, the gain drift.
Available power supply	- Power supply voltage, including tolerances - Maximum allowable current consumption
Voltage	- Primary working voltage - Applicable standard for isolation (design or test) - Compliance to the relevant standards - Single or reinforced insulation - Dielectric withstand voltage (e.g. 4 kV_{RMS}, 60 Hz, 1 min.) - Pollution degree (e.g. class 2) - Over voltage category (e.g. 0V cat. 1) - Impulse withstand voltage (e.g. 8 kV with 1.2/50 µs) - Partial discharge extinction level and electric charge

Dynamic operating parameters	Selection criteria
Frequency range	- Frequency range to be measured - Fundamental operating frequency - Harmonic content (e.g. drive's switching frequency) - Current Harmonics not to be measured but likely to create transducer losses (e.g. drive's ringing current)
di/dt	- Match between the di/dt to be measured and the transducer's response and rise times (Figure 8) - Maximum possible di/dt overloads, to be withstood by the transducer, but not to be measured - Maximum transducer recovery time after a di/dt overload
dv/dt	- Maximum error allowed during dv/dt disturbance - Maximum transducer settling time after a dv/dt disturbance

Environmental parameters	Selection criteria
Temperatures	- Minimum and maximum working temperatures where the transducer performance is applicable - Extreme storage temperatures
Vibration & shock	- Standards and levels to be considered (when applicable)
Presence of external fields	- External current identical to the one being measured - Other currents of similar or greater amplitude - Fields from transformers or inductors - Fields from magnetized materials in the area
Mechanical Interfaces	**Selection criteria**
Primary electrical connection	- Printed wiring board (PWB/PCB) pins - Through-hole aperture size and shape - Busbar dimensions - Other connections (e.g. screw terminals)
Secondary electrical connection	- Printed wiring board pins - Connector - Faston tabs - Screw lugs - Other connections (e.g. screw terminals)
External dimensions	- Maximum specified dimensions - Aperture / primary location - Connector / secondary location - Required creepage / clearance distances
Package fastening	- Printed circuit mount - Panel mount - Aperture (cable or busbar) mount - DIN rail mount

2.5 Voltage transducers – selection check list

LEM produces a wide variety of galvanically isolated voltage transducers capable of measuring up to 9.5 kV. These are based on four different technologies, with different performances, as outlined in Table 1.

The selection criteria for a current transducer are also applicable to voltage transducers, especially when the voltage measurement is based on a 'current measurement principle', as described later in § 3.4. The main difference lies in the primary parameters which affect the link between the voltage to be measured and the current, I_{MES}, detected by the transducer (Figure 21), namely the effect of the series resistance R_1 and the parameters linked to the transducer primary impedance. This leads to the following additional selection criteria:

Electrical parameters	**Selection criteria**
Measurement accuracy	- The transducer's primary resistance and series resistance R_1 (built-in or external), taking into account the effect of the manufacturing tolerances and temperature variations
Power budget	- The total power lost from the primary circuit due to power dissipation in the primary measuring circuit - The selected series resistor, R_1, shall be capable of dissipating many times the nominal power
Dynamic operating parameters	**Selection criteria**
Bandwidth / response time	- Dependent on the L / R time constant of the primary circuit, the series combination of primary inductance (L_P), the primary resistance (R_P), and the series resistance (R_1)

2.6 Power transducers – selection check list

The combination of current and voltage transducer in a single device creates an instantaneous power transducer. The selection criteria for this device are identical to those previously listed for current and voltage transducers. There will be a limitation on bandwidth and response time to ensure proper multiplication of the signals.

2.7 Type of output

The output of a LEM transducer typically represents the instantaneous primary signal, providing both output scaling and isolation. Transducers may also provide average, peak, sine-wave RMS, or true RMS output(s).

The secondary signal can be a current, voltage, current loop (4-20mA), or digital output. This signal will have an offset level, the output with no primary signal, and a range, the output swing with a change in primary signal. These can be matched to a specific interface, such as the A/D converter of a DSP or microprocessor (Figure 1).

Devices can be ratiometric, implying that the offset level and/or output range are dependent on the power supply or a reference input voltage. This is ideal when driving an analog to digital converter (ADC) or other reference based electronic processing circuitry, allowing the output to track the external reference, minimizing drift between the transducer and this reference. Alternatively, the internal reference of the transducer may be provided to act as a reference source for other electronic processing circuitry, potentially eliminating a discrete reference source.

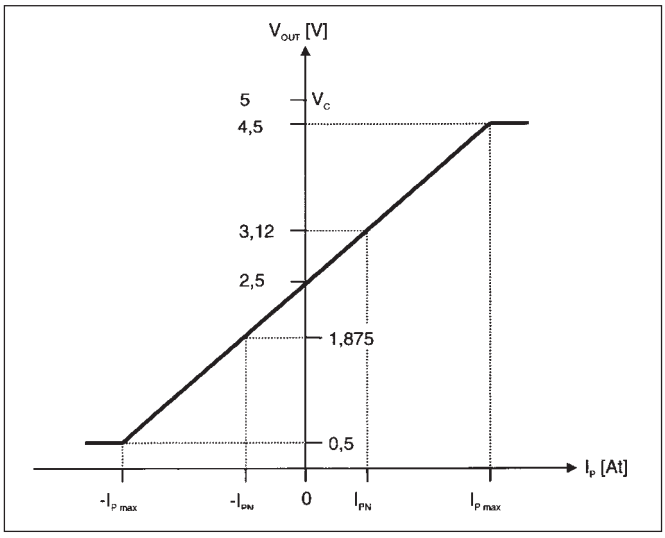


Figure 1: Output curve of the LTS and HTS product families

Loop powered devices are also available. These are two wire devices that obtain their power from a 4-20mA current loop and provide a variable current load to represent the output signal. These operate with a voltage drop across the transducer to power the internal circuitry, which must be taken into account when supplying the loop.

Conversion of a current output to a voltage is easily accomplished by the user with the addition of a measurement resistor, R_M, in series with the output. This allows the user to easily scale a single device to the desired output level. There is a range of acceptable R_M values dependent on the operating parameters of the application with the maximum value limited by available voltage and a minimum value required to limit the internal power dissipation. The transducer datasheet provides a range of values based on nominal parameters.

3 Hall effect technologies

Three of the LEM technologies (open loop, closed loop and Eta) are based on the Hall effect, discovered in 1879 by American physicist Edwin Herbert Hall at Johns Hopkins University in Baltimore. The Hall effect is created by Lorentz forces, $F_L = q \bullet (V \times B)$, which act on charges moving through a magnetic field.

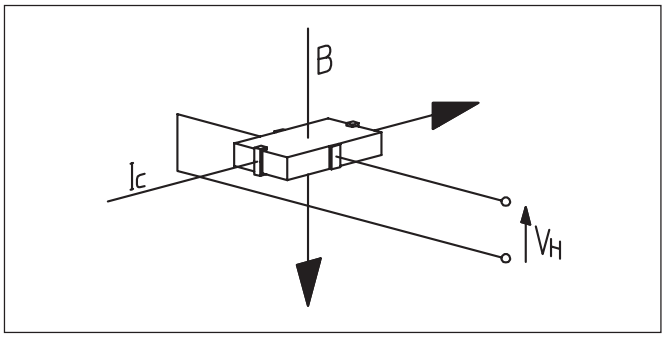


Figure 2: Representation of the electrical parameters of the Hall effect

A thin sheet of conducting material is traversed lengthwise by a control current, I_C (Fig. 2). The mobile charge carriers of this current are affected as the external magnetic flux, B, generates a Lorentz force, F_L, perpendicular to the direction of current flow. The resulting deflection of current causes more charge carriers to be located at one edge of the sheet, creating a potential difference referred to as the Hall voltage, V_H. For the arrangement described above, with the magnetic field, current, and sheet edges mutually perpendicular, we obtain:

$$V_H = K / d \bullet I_C \bullet B + V_{OH}$$

where 'K' is the Hall constant of the conducting material, 'd' is the thickness of the sheet, and 'V_{OH}' is the offset voltage of the Hall generator in the absence of an external field. Such an arrangement is referred to as a Hall generator and the product '$K / d \bullet I_C$' is generally referred to as the Hall generator sensitivity.

The sensitivity and offset voltage of Hall generators are temperature dependent. However, these effects can be greatly compensated by the biasing and amplification electronics driving and sensing the Hall generator.

3.1 Open loop Hall effect current transducers

Open loop transducers use the simplest implementation of the Hall effect. They provide the smallest, lightest, and most cost effective current measurement solution while also having very low power consumption.

3.1.1 Construction and principle of operation

A current carrying conductor creates a magnetic field. This field is concentrated by a magnetic core. The core has a gap cut through it and a hall generator is used to sense the magnetic flux density in the gap. The control current, I_C, and differential amplification are supplied by electronics (Fig. 3) built into the transducer.

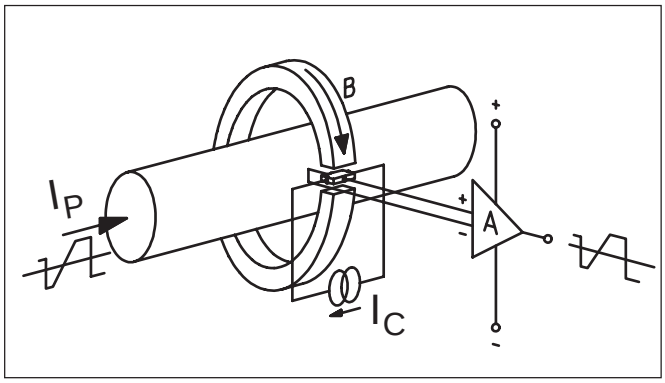


Figure 3: Conversion of the primary current into an output voltage

Within the linear region of the hysteresis loop of the material used for the magnetic circuit (Fig. 4), the magnetic flux density, B, is proportional to the primary current, I_P, and the Hall voltage, V_H, is proportional to the flux density. Therefore the output of the Hall generator is proportional to the primary current, plus the Hall offset voltage, V_{OH}.

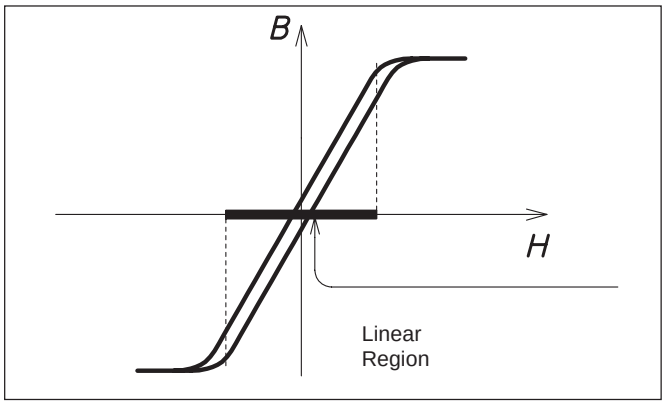


Figure 4: Magnetization curve

The measurement signal is then compensated to remove the offset component and address temperature effects and amplified to supply the user with the desired output.
In the case of low current measurement (< 50 A) multiple turns are recommended or implemented internally to achieve 50 Ampere-turns nominal providing reasonable flux density levels for measurement.

3.1.2 Advantages and limitations

Open loop transducers measure DC, AC and complex current waveforms while providing galvanic isolation. As mentioned earlier, the **advantages** include low cost, small size, light-weight, and low power consumption and are especially advantageous when measuring high (> 300 A) currents. As with most magnetic based measurement techniques, insertion losses are very low. Primary current overloads can be easily handled although it may result in some magnetization of the core creating an offset shift, called remanence or magnetic offset (§ 3.1.6).

Compared to other technologies the **limitations** of open loop transducers are moderate bandwidth and response time, a larger gain drift with temperature, and a limitation on the current frequency product (power bandwidth).

In many applications the advantages outweigh the limitations and an open loop solution is advised.

3.1.3 Nominal and extreme currents

LEM open loop transducers are made for nominal currents, I_{PN}, from several amperes to 10 kA, with a peak current rating up to 30 kA. This wide range of products addresses virtually all of the industrial requirements.

The maximum current an open loop transducer can measure is dependent on the design and material used for the magnetic circuit and on the design of the processing electronics. In general, LEM open loop transducers are designed such that the maximum measurable current is 200 % to 300 % of the nominal RMS current rating.

Even so, open loop transducers can withstand current overloads significantly beyond the maximum measurable value, for example 10 times the nominal current. However, as described earlier, this can create a magnetic offset resulting in an additional measurement error, to be removed by applying a dedicated demagnetization procedure.

3.1.4 Output signals

The output of an open loop transducer is generally a voltage directly proportional to the measured current. This voltage is typically equal to 0V without primary current and 4V at the nominal current, I_{PN}. Variations are possible, including different offset, and/or nominal values or a current output.

3.1.5 Measurement accuracy

The typical open loop transducer has an overall accuracy of a few percent. There are a number of error terms that combine to create this error, at nominal temperature (25°C) and across the temperature range.

The accuracy is limited by the combination of:

- DC offset at zero current (hall generator, electronics)
- DC magnetic offset (remanent magnetization of core material)
- gain error (current source, hall generator, core gap)
- linearity (core material, hall generator, electronics)
- output noise floor (hall generator, electronics)
- bandwidth limitation (attenuation, phase shift, current frequency)

Temperature changes also create drift in:

- DC offset
- gain

LEM transducers are factory calibrated at nominal temperature and nominal current, leading to the „accuracy at 25 °C“ given in the LEM datasheets. The datasheet also provides the temperature drift specifications.

The location of the primary conductor through the aperture as well as the positioning of the return conductor can affect dynamic performance of the transducer. LEM generally recommends an optimal routing / position for the primary and return conductors. In addition, high frequency disturbances can affect the transducer output due to capacitive coupling, so the routing and layout of the transducer output must be considered (e.g. twisted and shielded cables, appropriate routing of the output PWB tracks).

3.1.6 Magnetic offset considerations

Depending on the type of transducer and the magnetic material used, the residual flux (B_R or remanence) of the magnetic core induces an additional measurement offset referred to as ‘magnetic offset’. The value depends on the previous core magnetization and is at a maximum after the magnetic circuit has been saturated. This might occur after a high overload current.

As an example, measurements carried out on the HAL and HTA types of open loop transducers give the following results: after a cycle of current varying from 0 to 300 % of I_{PN} and then back to zero, the magnetic offset is 2.5 mV for HAL transducers and 3 mV for HTA transducers, less than 0.1 % of the nominal output, V_{SN}.

In the case of a higher current overload (e.g. 1000 % of I_{PN}), a larger magnetic offset error may occur. Recovering from this condition requires demagnetization, either by appropriate reversal of the primary current or a dedicated degauss cycle. This process will return the transducer to the initial, pre-overload, performance.

3.1.6.1 Demagnetization to eliminate magnetic offset

The elimination of magnetic offset requires demagnetization. A degauss cycle requires driving the core through the entire B-H loop with a low frequency AC source, then gradually decreasing the excitation returning the B-H operating point to the origin (Fig. 5). As a minimum, provide 5 cycles at full amplitude and then decrease the excitation smoothly no faster than 4 % per cycle, requiring 30 cycles or 500 ms at 60 Hz. For closed-loop devices, additional care must be taken to be sure the compensation coil does not negate the demagnetization effort (see § 3.2.6).

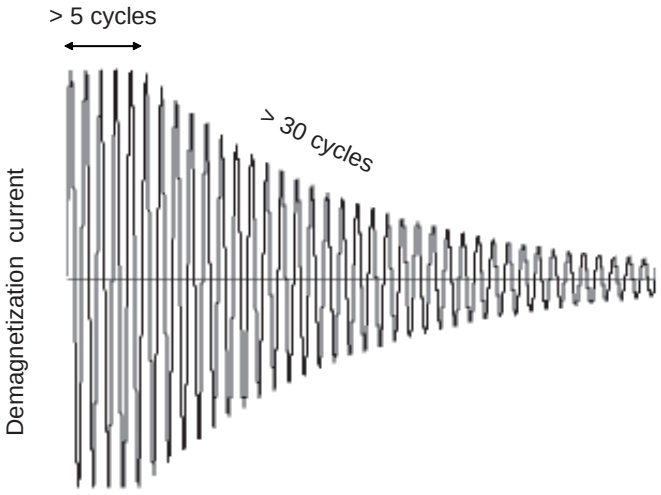


Figure 5: Degauss cycle current

Alternatively, a partial demagnetization of the core is possible by providing an appropriate signal in the opposite polarity of the magnetization. The difficulty is determining the exact amplitude and duration to obtain a satisfactory result. With a well-defined application it may be feasible to determine the required value empirically and apply this correction as necessary.

3.1.7 Bandwidth and core losses

The bandwidth limitation of open loop transducers is mainly due to two factors:

- limitations of the processing electronics
- magnetic core heating due to core losses, a combination of eddy current and hysteresis losses

3.1.7.1 Core losses

The magnetic material and core design as well as the current amplitude versus frequency spectra define the level of core losses:

- eddy current losses are proportional to the square of three different parameters: the peak flux density in the core, the frequency of induction and the lamination sheet thickness of the core
- hysteresis losses are proportional to frequency, core volume and the square of peak flux density

For LEM transducers, this leads to the following conclusions:

- these losses are directly proportional to the square of the flux density, which is directly related to the primary ampere-turns, implying core losses are theoretically proportional to the square of primary ampere-turns if no magnetic saturation occurs. When increasing sensitivity by using multiple primary turns, core losses are increased by the square of the turns
- core losses become significant at high frequencies and it is essential to limit the current amplitude at these frequencies to acceptable levels (dependent on ambient and maximum transducer temperatures); this implies not only limiting the maximum frequency of the fundamental current, but also harmonic content, since even a low amplitude signal may create unacceptable losses at high frequencies.

3.1.7.2 Core loss rule-of-thumbs

Iron losses calculation are complex and, as a „rule-of-thumb“ judgment, it is possible to consider that the iron losses are minimized if the product "N • I • f" is kept as small as possible, where:

N = number of internal or external primary turns
I = primary current or amplitude of a current harmonic
f = frequency of the primary current or current harmonic

As a result, when one of the three factors is increased (i.e. the current), the iron losses are increased unless at least one of the two other factor is decreased (i.e. the frequency of the measured current and/or the number of primary turns).

While this formula implies that the core losses will increase with an increase of any of these parameters, it is not intended to say that acceptable core losses are realized if the product of the three parameters is kept constant. For example, it is wrong to say that one can operate at twice the frequency if the Ampere-turns are cut in half.

At a given frequency, it is nevertheless correct to assume that keeping constant the "N • I" product implies similar iron losses, even the probable change on the primary conductor magnetic coupling may affect the iron losses value.

To conclude, trouble-free operation of a current transducer requires limiting the temperature rise to avoid overheating the internal components. Parameters affecting temperature rise go beyond core losses and include the primary busbar resistive losses, the losses of the electronics and the various thermal resistances. In particular, to keep losses constant requires to decrease the transducer primary current while the working frequency increases.

3.1.7.3 A core loss example

Considering the LEM open loop HY 10-P transducer, where the primary is integrated into the transducer and the number of primary turns cannot be changed, tests show the following maximum working conditions:

At an ambient temperature of 25 °C		
I_P	f_{max}	N • I • f
10 A	13 kHz	130,000
6 A	33 kHz	198,000
2 A	340 kHz	680,000

At an ambient temperature of 70 °C		
I_P	f_{max}	N • I • f
10 A	6 kHz	59,000
6 A	12 kHz	72,000
2 A	90 kHz	180,000

Obviously these values are far from constant, but they can be considered as limits for acceptable operation. Even so, this transducer cannot operate above 50 kHz as limited by the maximum bandwidth (3dB) of the electronics.

3.1.7.4 Addressing core losses

Often the adverse effects of core losses are not considered or cannot be predicted accurately during the initial design stages. Therefore many designers find themselves in a difficult situation when a design, or a specific application of that design, causes overheating of the transducer due to core losses. There are solutions to this problem, but a careful analysis of the tradeoff between reducing core losses and maintaining acceptable response time of the transducer is required.

Although the insertion loss of a transducer is extremely low this impedance is, in fact, a combination of the resistance and inductance of the primary. Placing a series resistor-capacitor in parallel with the primary (Fig. 6) diverts the high frequency components of the current around the primary, significantly reducing core losses. This also removes these frequencies from the measurement path increasing the response time. An example is shown in Fig. 7 where the V_{OUT} response of the HX 15-NP transducer is given, with and without parallel resistor R (C = 0).

3.1.8 Response time, delay time, and di/dt behavior

Three different criteria are used to characterize the dynamic behavior of a transducer: bandwidth, response time, and step

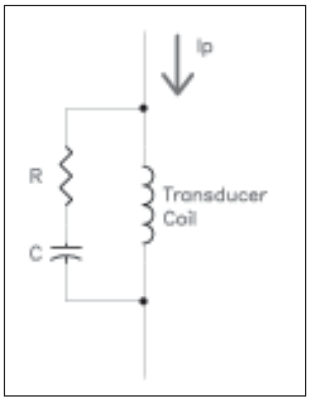


Figure 6: Schematic of high frequency bypass

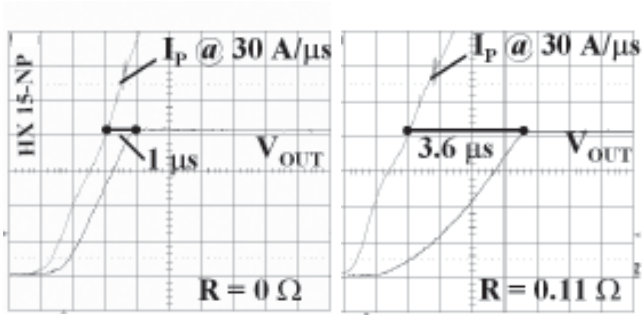


Figure 7: HX 15-NP transducer response

response, also called di/dt following (the transducers ability to follow a fast change in primary current).

LEM defines the response time t_r as the delay between the primary current reaching 90 % of its final value and the transducer reaching 90 % of its final amplitude (Fig. 8). The primary current shall appoximately behave as a current step, with an amplitude close the nominal current value.

This is actually the combination of three effects: the input rise time (from 10 % input to 90 % input, also called di/dt), the

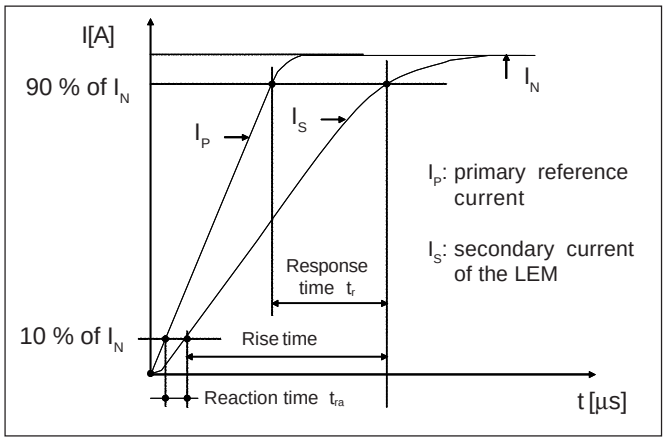


Figure 8: Definition of the transient response parameters

reaction time t_{ra} (from 10 % input to 10 % output), and the output rise time (from 10 % output to 90 % output, also called slew rate).

Open loop transducer response is dependent on the transducer design and the magnetic coupling of the signal to be measured, as well as those not to be measured. The latter places some responsibility on the user to investigate the coupling effects and determine the appropriate placement of the primary and other conductors to optimize the response of the transducer in the application. Careful consideration of the cabling in and around the transducer usually resolves response time and di/dt performance problems.

Fig. 9 shows the response of a HAL 600-S transducer, where a slight difference between the input and output currents can be noticed at the corners. In this case, the response time is less than 3 µs with a di/dt of 50 A/µs.

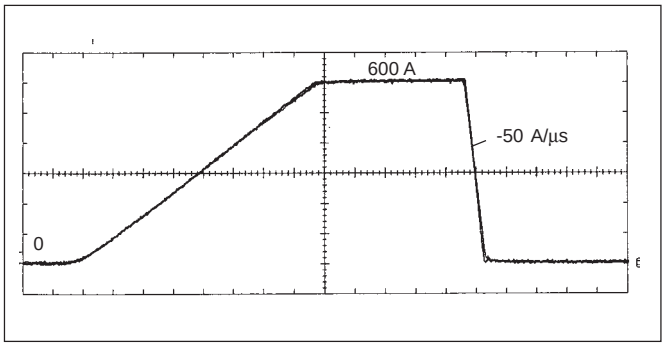


Figure 9: Dynamic behavior of an HAL 600-S transducer at 600 A

3.1.9 Typical applications

Open loop current transducers are used in numerous industrial applications as the key element of a regulation loop (e.g. current, torque, force, speed, position) or simply to drive a current display.

Typical applications include:

- frequency inverters and 3-phase drives, for the control of the output phase and DC bus currents
- power factor correction converters, for monitoring of the mains current(s)
- electric welding equipment, for the control of the welding current
- uninterruptible power supply (UPS) or other battery operated equipment, for the control of charge and discharge currents
- electric vehicles, for motor drives and battery current control
- electric traction systems, trackside circuit breaker and rectifier protection, rolling stock traction converters and auxiliaries
- energy management systems, switching power supplies, electrolysis equipment, and other applications

3.1.10 Calculation of the measurement accuracy

As indicated previously, the accuracy indicated in the datasheets applies at the nominal current at an ambient temperature of 25 °C. The total error at any specific current includes the effects of offset, gain, non-linearity, temperature effects and possibly remanence. The LEM datasheet provides the worst-case value of each of these factors individually. The theoretical maximum total error corresponds to the combination of the individual worst-case errors, but in practice this will never occur.

Example: Current transducer HAL 200-S (see datasheet)
In this example it is assumed the power supplies are accurate and stabilized and magnetic offset is negligible. A current of 200A is measured at an ambient temperature of 85 °C.

The datasheet indicates the output voltage is 4 V at the 200 A nominal current. The worst-case accuracy at I_{PN}, 25 °C and with ±15 V supplies is 1 %, or 40 mV. In addition there is a maximum offset voltage at Ip = 0 and 25 °C of 10 mV. These two values are independent because the accuracy (40 mV) is confirmed with an AC signal while the offset (10 mV) is a DC measurement. Therefore, when measuring a 200A DC current at 25 °C the output could be in error by as much as 50 mV, which is 1.25 % of the 4 V output.

Operating at a different temperature causes both offset and gain drift. The maximum offset drift is specified as 1 mV/K and the maximum gain drift is 0.05 %/K. When we operate the transducer at 85 °C there can be an additional 1 mV/K • (85 – 25) °C = 60 mV of offset voltage and 0.05%/K • 4 V • (85 – 25) °C = 120 mV of gain drift. The total error from all of these effects is 230 mV, or 5.75 % of the nominal 4 V output.

3.2 Closed loop Hall effect current transducers

Compared to the open loop transducer just discussed, Hall effect closed loop transducers (also called Hall effect 'compensated' or 'zero flux' transducers) have a compensation circuit that dramatically improves performance.

3.2.1 Construction and principle of operation

While open loop current transducers amplify the Hall generator voltage to provide an output voltage, closed loop transducers use the Hall generator voltage to create a compensation current (Fig. 10) in a secondary coil to create a total flux, as measured by the Hall generator, equal to zero. In other words, the secondary current, I_S, creates a flux equal in amplitude, but opposite in direction, to the flux created by the primary current.

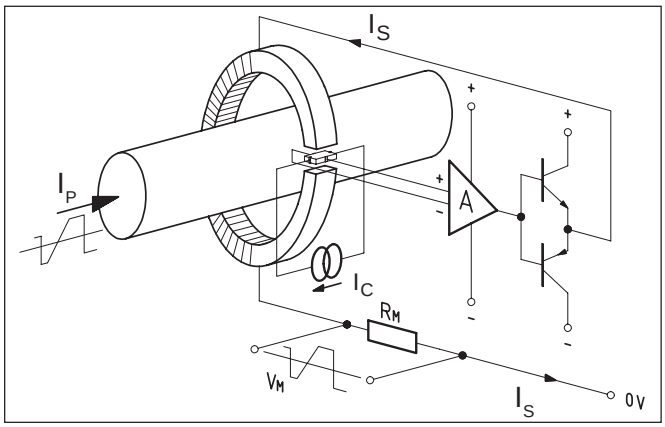


Figure 10: Operating principle of the closed loop transducer

Operating the Hall generator in a zero flux condition eliminates the drift of gain with temperature. An additional advantage to this configuration is that the secondary winding will act as a current transformer at higher frequencies, significantly extending the bandwidth and reducing the response time of the transducer.

When the magnetic flux is fully compensated (zero), the magnetic potential (ampere-turns) of the two coils are identical. Hence:
$N_P \bullet I_P = N_S \bullet I_S$ which can also be written as $I_S = I_P \bullet N_P / N_S$

Consequently, the secondary current, I_S, is the exact image of the primary current, I_P, being measured. Inserting a „measurement resistor“, R_M, in series with the secondary coil (Fig. 10) creates an output voltage that is an exact image of the measured current.

To give an order of magnitude, the typical number of secondary turns is N_S = 1000…5000 and the secondary current is usually between I_S = 25…300 mA, although it could be as high as 2 A. For higher output currents an output power stage is needed to produce the transducer output current.

At low frequencies the transducer operates using the Hall generator. At higher frequencies the secondary coil operates as a current transformer, providing a secondary output current again defined by the turns ratio and converted to a voltage by the measuring resistor. These effects are illustrated in Fig. 11.

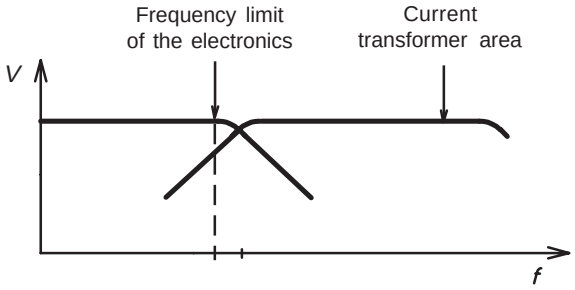


Figure 11: Bandwidth of the „Hall generator“ and „current transformer“

The unique design of closed loop transducers provides an excellent bandwidth, typically from DC to 200 kHz. The challenge is to ensure a flat frequency response across the entire range, especially where the two response curves cross, to provide excellent dynamic response and accuracy for all possible signals.

Finally, while closed loop transducers work theoretically at zero flux, various magnetic imperfections (leakage flux, non perfect coupling) imply a residual flux into the core which results in iron losses at high frequencies. Consequently, the heating phenomena described in § 3.1.7 for open-loop transducer also applied in this case, even if much less significantly.

3.2.2 Advantages and limitations

Closed loop transducers are capable of measuring DC, AC and complex current waveforms while ensuring galvanic isolation. The **advantages** of this design include very good accuracy and linearity, low gain drift, wide bandwidth, and fast response time. Another advantage is the output current signal that is easily scalable and well suited to high noise environments; nevertheless, closed loop transducers are available in voltage output configurations. Again, as with most magnetic based measurement techniques, insertion losses are very low.

The main **limitations** of the closed loop technology are the high current consumption from the secondary supply (which must provide the compensation as well as bias current), the larger dimensions (more noticeable on high current transducers), a more expensive construction compared with the simpler open loop designs and a limited output voltage due to the internal voltage drops across the output stage and secondary coil resistance.

Again, depending on the application requirements, the advantages often outweigh the limitations and the accuracy and response of a closed loop solution is desirable over other alternatives.

3.2.3 Nominal and extreme currents

LEM closed loop current transducers are available in models with nominal currents from 2 A to more than 20 kA. Specific designs even allow current measurements up to 500 kA. With closed loop technology the maximum measurable peak current is typically 150 to 300 % of the nominal current rating. For a given closed loop transducer, the maximum peak current which can be measured can be defined in three different ways:

- from DC to mid-frequencies (in the closed loop compensation mode, § 3.2.1), the maximum measurable current is limited by the ability of the electronics to drive compensation current, I_S, in the secondary coil; this limit is based on the available supply voltage, internal voltage drops, and current through the total series resistance and exceeding this limit at low frequency will result in „electronic saturation“
- also, each transducer is designed for a specific measurable current range and exceeding the transducer ratings will result in non nominal magnetic effects (excessive fringing) that does not allow the electronics to properly compensate the loop resulting in „magnetic saturation“
- for transient currents at higher frequencies the transducer operates as a current transformer and the current can reach higher values, limited by magnetic (pulse duration in ampere seconds) and thermal (core losses related to ampere-hertz) constraints; the transducer user should consult LEM when considering working in the transformer mode, beyond the limits set in LEM datasheets.

In some specific LEM transducer types (e.g. the LTS family), primary currents exceeding the peak measuring range can create abnormal, though non-destructive, results due to the unique electronic configurations.

In case of current overload, a too long overload duration (e.g. > 1 ms) may in some case start to overheat the snubber which protects the transducer against short time overloads.

3.2.4 Output signal – Measurement resistance

The majority of closed loop transducers have a current output that can be easily converted to a voltage for measurement by adding a measurement resistor in series with the output. Refer to § 2.7 for more details.

3.2.5 Measurement accuracy

Due to the closed loop working principle, operating at nearly zero flux (some flux remains due to system loop gain and magnetic leakage phenomena), LEM closed loop current transducers have excellent linearity and minimal gain drift over a wide measuring and temperature range, with total accuracy typically remaining below 1 %.

At ambient temperature, the accuracy is given by the combination of:

- output offset at zero primary current ($I_P = 0$)
- non-linearity of the Hall generator, electronics, and magnetics
- gain tolerance (tolerance of the number of secondary coil turns)
- tolerance of the measuring resistor, R_M (internal or external)

And temperature changes imply:

- offset drift (or with respect to the reference voltage, if appropriate)
- drift of the measuring resistor value, R_M

While those factors may be simple to assess for DC current, AC signals and complex waveforms may have their total accuracy affected by transducer bandwidth limitations (Fig. 11), possibly introducing frequency attenuations and phase shifts.

To make the best use of the transducer, the mounting conditions must be such that it optimizes the primary to secondary magnetic coupling, specifically for AC signals where the transducer works as a current transformer. The designer must consider both the primary conductor (wire or busbar being measured) and other conductors in close proximity, such as the return conductor or the conductors of other phases.

Additionally, the routing of the transducer output wires, or paths of the PWB tracks, at the transducer output should limit high frequency disturbances created by external conductors. The output wiring should have minimal loop area, to minimize di/dt effects, and long runs parallel to power wires must be avoided, to limit capacitive coupling and minimize dv/dt effects.

3.2.6 Observations regarding magnetic offset

In standard working conditions, a closed loop transducer is always working near zero flux, either when the low frequency Hall based closed loop is effective or when the high frequency current transformer is working (§ 3.2.1). However, this does not imply that closed loop transducers are not at risk of having a permanent magnetic offset. As discussed for open loop transducers:

- if a low or medium frequency primary current exceeds the measuring range (based on supply voltage, transducer parameters, and measuring resistor value) the electronics can no longer drive sufficient secondary coil current to maintain the zero flux condition
- if one or both of the secondary supply voltages are missing, disabling the electronic compensation process, there will no longer be zero flux compensation
- when an external conductor creates localized core saturation, not totally detected by the Hall generator and compensated by the electronics, the total flux in different areas of the core will be non-zero

If any of these conditions occur the result could be magnetic offset, resulting in an additional measurement error. This can be corrected with demagnetization (§ 3.1.6.1).

With compensated devices care must be taken to ensure the compensation does not negate the demagnetization effort. Ideally the output can be disconnected to open the compensation loop. If this is not possible, disabling the power supplies accomplishes the same goal if a low frequency is used for excitation, to avoid the current transformer effect.

3.2.7 Bandwidth and core losses

Closed loop transducers demonstrate excellent bandwidth characteristics. Typically the bandwidth is from DC to 200 kHz, while a LEM patented design (the LB family) achieves a bandwidth better than DC to 300 kHz.

Nominal current can not be considered over the full frequency range. To keep constant the transducer losses, current value shall be decreased while working frequency increases.

While the current transformer effect of closed loop transducers provides excellent high frequency performance they are still subject to core losses due to hysteresis and eddy current losses. As with open loop transducers (§ 3.1.7), care must be used when attempting long term measurement of high currents at high frequencies.

3.2.8 Response time and di/dt behavior

The response time of a transducer characterizes how it will respond to a step current with a controlled rate of change, called di/dt following. It is defined by several parameters such as the delay time, rise time and reaction time (§ 3.1.8, Fig. 8). Closed loop transducers show fast reaction times, typically better than 1 µs.

The correct following of di/dt depends on the intrinsic construction of each product and, as mentioned in § 3.2.5, the mounting conditions of the transducer within the circuit to be measured.

Dependent on the closed loop transducer model, it is possible to measure a di/dt of 50 to 400 A/µs or more. This makes them well suited for the short-circuit protection of semiconductors in power equipment.

3.2.9 Typical applications

Closed loop transducers are particularly well suited for industrial applications that require high accuracy, wide bandwidth and fast response time. They are often used as the key element of a regulation loop for the control of current,

torque, force, speed and/or position as well as for the protection of semiconductor devices.

Applications are identical to those for open loop transducers, except higher performance results can be expected:

- frequency inverters and 3-phase drives, for the control of the output phase and DC bus currents as well as protection of the power semiconductors from fault conditions such as output short-circuits
- converters for servo-motors frequently used in robotics, for high performance speed and position control
- special wide bandwidth power supplies for special equipment, such as radar

Other applications include energy management systems, switching power supplies, electrolysis equipment, lasers, rectifiers for electrolysis and, finally, many applications for laboratories or test and control benches.

In the specific case of the LTS family, with a through-hole and several U-shaped primary conductors, series-parallel connections combined with wire sensing offers a multitude of possibilities, such as the measurement of differential currents or performing phase current mathematic calculation (Iu – Iv or Iu + Iv + Iw) with a single device.

3.2.10 Transducer parameter examples

The following examples are intended to help the user estimate the limits of the operating values for a closed loop current transducer based on operating parameters and the measurement resistor. Two approaches can be used to determine the appropriate measuring resistance; based on the range provided on the datasheet or based on acceptable operating values outside those listed on the datasheet. In some cases it is also possible to measure beyond the maximum current given on the datasheet and two examples are provided for this case.

Example 1: LA 55-P operating within nominal datasheet parameters (see datasheet)

a) What maximum measuring voltage can be obtained with the following parameters ?
I_P = 70 A, T_A = 70 °C, V_C = ±15 V

The number of secondary turns, 1000, determines the secondary current, $I_S = I_P \bullet N_P / N_S$ = 70 mA

The LEM datasheet indicates R_{Mmax} = 90 Ω for these conditions leading to a maximum measuring voltage of:
$V_M = R_M \bullet I_S$ = 90 Ω • 70 mA = 6.3 V

b) Using the following parameters, which measurement resistance must be selected to achieve a measuring voltage of 3.3 V at the nominal primary current?
I_{PN} = 50 A, T_A = 85 °C, V_C = ±12 V, and $I_{SN} = I_{PN} \bullet N_P / N_S$ = 50 mA

We have $R_M = V_M/I_S$ = 3.3 V / 50 mA = 66 Ω and, for the given parameters, the datasheet recommends a measuring resistance between R_{Mmin} = 60 Ω and R_{Mmax} = 95 Ω; therefore a 66 Ω resistor can be used.

c) For the same parameters, is it possible to have a 6 V measuring voltage?
$R_M = V_M/I_S$ = 6 V/50 mA = 120 Ω
The 50 A current will not be measured with this resistance since it exceeds the specified R_{Mmax} value of 95 Ω. The maximum measuring voltage is obtained with the R_{Mmax} resistance and is equal to 50 mA • 95 Ω = 4.75 V.

If a 120 Ω resistor is used, the measurement will only be correct for primary currents less than 50 A (actually up to 43.9 A and 5.25 V). In this case the calculation of the maximum current value is not straightforward and is described in the following paragraphs.

Example 2: LA 55-P operating outside of nominal datasheet parameters

When operating at lower measurement currents it is possible to get more output voltage by selecting a larger measurement resistor than specified on the datasheet. Alternatively, when operating at power supply voltages other than those specified on the datasheet the measurement range may be limited.

a) What is the maximum voltage available at the amplifier output?
Fig. 12 shows the schematic diagram of the output of a typical closed loop current transducer. The output voltage is limited by the voltage drops across each of the circuit elements: the maximum output stage driving voltage (V_A), the transistor drop (V_{CE}), the secondary coil resistance (R_S), and the measuring resistance (R_M). Knowing the maximum possible value of the voltage at the output of the amplifier stage (V_A) will allow the determination of the measurable current range. The worst-case situation will be considered, with the maximum temperature and the minimum supply voltage, but other situations can be evaluated with this same method.

Using datasheet values for peak current (70 A), coil resistance (80 Ω @ 70 °C), and maximum measurement resistance (90 Ω @ 70 °C with ±15 V supplies) we have:
$V_A = I_S \bullet (R_S + R_M)$ = 0.07 A • (80 Ω + 90 Ω) = 11.9 V

b) What is the maximum output voltage with I_P = 60 A, T_A = 70 °C, and V_C = ±15 V ± 5 %, I_S = 60 mA?

Using the results from a) above, the maximum level for V_A under similar circumstances with a min 14.25 V supply is 11.9 V. We can determine the maximum value of V_M and then R_M.

$V_M = V_A - \Delta V_C - R_S \bullet I_S$ = 11.9 V - 80 Ω • 60 mA = 7.1 V
$R_{Mmax} = V_M/I_S$ = 7.1 V/60 mA = 118 Ω

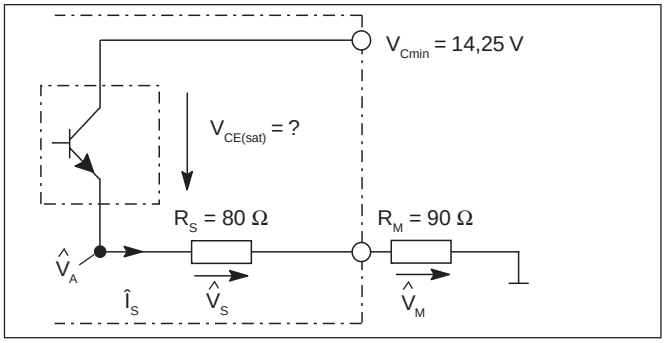


Figure 12: Diagram for calculation of the available voltage, V_A, at the output stage

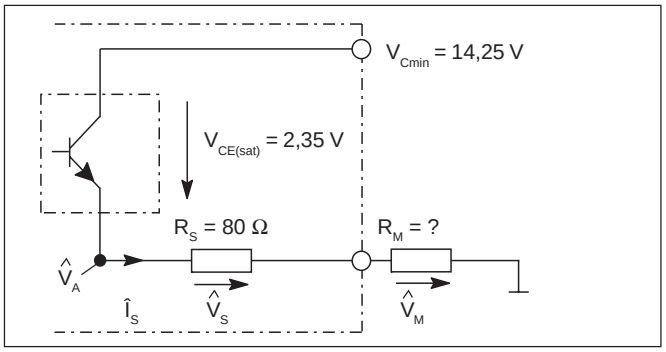


Figure 13: Equivalent diagram to calculate the measuring resistance, R_M

Example 3: Measuring current higher than the maximum value given in the datasheet

LEM datasheets indicate the transducer operating conditions, with a measuring range that is generally limited to 150 to 200 % of the nominal current (I_{PN}). However, it is possible to measure currents exceeding this range if the following two parameters are considered:

- the measurement resistance must not be smaller than the R_{Mmin} value given in the datasheet; this minimum value is required to limit the power dissipated in the transducer output stage; depending on the selected transducer R_{Mmin} can be very small, in some cases equal to zero
- the primary conductor temperature must not exceed the value specified in the datasheet (e.g. 90 °C), to keep the transducer within acceptable operating temperature levels

The following examples demonstrate the calculation of the maximum measurable current. Various scenarios are examined to address different types of LEM transducers.

a) The datasheet requires an R_{Mmin} value greater than zero.

For example, the following parameters are defined for the LA 55-P transducer: V_C = 15 V ± 5 %, T_A = 70 °C, R_S = 80 Ω, R_{Mmin} = 50 Ω, V_A = 11.9 V (as calculated in example 2a). The maximum value of the measurable secondary current is:
$I_S = V_A / (R_S + R_{Mmin})$ = 11.9 V / (80 + 50)Ω = 91.5 mA
The corresponding maximum measurable primary current is 91.5 A.

b) The datasheet allows an R_{Mmin} value equal to zero.

For example, the following parameters are defined for an LA 305-S transducer: V_C = 15 V ± 5 %, T_A = 70 °C, I_P = 300 A, R_S = 35 Ω (at 70 °C), R_{Mmin} = 0 Ω, N_P:N_S = 1:2500. The minimum measurement resistance R_M can be zero and it is up to the user to select the most suitable value. The smaller the value the larger the maximum measurable current, but the smaller the available output voltage signal. The available voltage at the amplifier output (V_A) is determined as follows:

R_{Mmax} = 75 Ω at 300 A for V_C = 15 V, I_S = 300 A/2500 = 120 mA
So:

$V_A = (R_S + R_{Mmax}) \bullet I_S = (35 + 75)\Omega \bullet 0.12\ A = 13.2\ V$

The maximum value of the measurable secondary current depends on the selected measurement resistance.
For example, with R_M = 5 Ω, we have:
$I_S = (V_A - \Delta V_C)/(R_S + R_M)$ = (13.2 V) / (35 + 5)Ω = 330 mA

The maximum measurable primary current is consequently equal to 330 mA • 2500 = 825 A, corresponding to 2.75 • I_{PN}. The voltage measured on the measurement resistance is V_M = 330 mA • 5 Ω = 1.65 V.

With R_M = 2 Ω, we have I_S = 357 mA, a maximum measurable primary current of 3 • I_{PN} (892 A) with a smaller output voltage of 0.71 V.

If a zero ohm measurement resistor is considered, the transducer can provide I_S = 377 mA, which represents 3.14 • I_{PN} (943 A). This arrangement provides no output voltage, so a virtual ground referenced current to voltage converter will be required to obtain a usable output signal. It is up to the user to decide exactly what is needed.

Under these higher current conditions it is especially important to keep the temperature of the primary conductor below the maximum allowable temperature to avoid permanent damage.

Example 4: Measuring transient current higher than the maximum value given in the datasheet

In some cases higher currents can be measured using the current transformer effect, provided the frequency and/or the di/dt are high enough. This can be useful for short circuit detection, as this is typically a high di/dt event, but care must be exercised when attempting to use this capability for standard or continuous measurement. See § 3.2.3 for more details.

It is important to note that some transducers (e.g. LTS) have an internal measurement resistor value that cannot be adjusted and, in these circumstances, the measuring range cannot be adjusted.

Example 5: Periodic transient current overload

The following measurement sequence is considered, illustrated for the LTS 25-NP transducer:

- The transducer is measuring the nominal current of 25 A
- During the time t_1 a current overload occurs (I_{Pt1}), exceeding the 25 A nominal value
- During the time t_2 the current returns to the initial value (I_{Pt2}) of 25 A, allowing the transducer to cool after the overload
- In the worst-case, the sequence is continuously repeated

Fig. 14 shows DC current levels, but these can also represent the RMS value of the primary current over time. The following examples use DC values, but total RMS (using AC and DC values) has an equivalent effect.

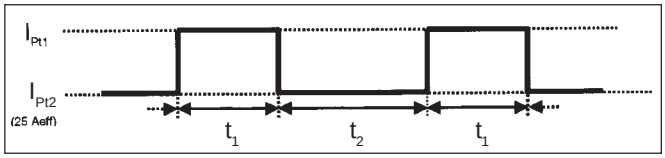


Figure 14: Periodic overload with a standby current of 25 A at 85 °C

The maximum environmental temperature of 85 °C is considered and, in this specific example of an LTS 25-NP transducer, the three configurable primary terminals must be connected in parallel to allow the long-term measurement of 25 A.

What is the acceptable limit for t_1 and t_2 based on the magnitude of I_{Pt1}?

For given overload duration (t_1) and amplitude (I_{Pt1}), Fig. 15 and Fig. 16 give the minimum time (t_2) required for the transducer to cool when the continuous current, I_{Pt2}, is the nominal 25 A value with a maximum ambient temperature of 85 °C. Fig. 16 is a close-up view of the linear zone shown in the lower left corner of Fig. 15 for short overload duration. In this case the curves are linearized, allowing to define a simple duty cycle relation:

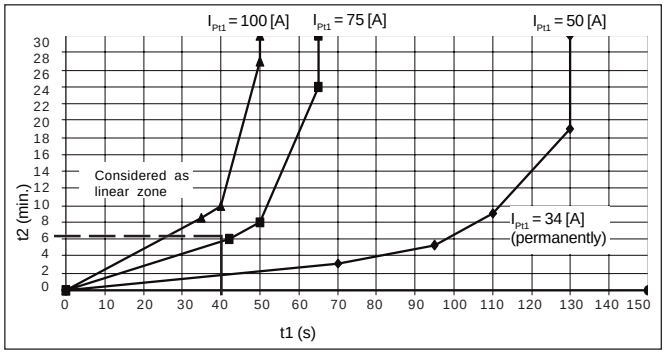


Figure 15: Overload diagram of the LTS 25-NP with a standby current of 25 A

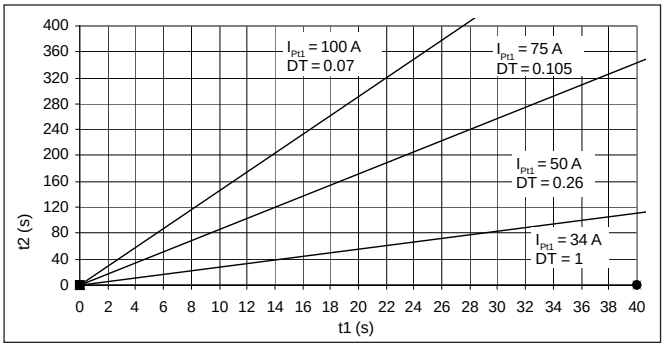


Fig. 16 Overload diagram of the LTS 25-NP for a rest current of 25 A_{rms}, linear zone

Duty cycle = DT = $t_1 / (t_1 + t_2)$

Giving:

$t_2 = (1 – DT) \bullet t_1 / DT$

Example

For a current overload of $50A_{RMS}$ applied during t_1 = 14 s, the recovery time shall be at least t_2 = 40 s. This value can either be taken from Fig. 15 or Fig. 16, or calculated according to the duty cycle relation, considering a 26 % duty cycle in this case:

$t_2 = (1 - 0.26) \bullet 14 / 0.26 = 40$ s.

At 85 °C, 34A can be measured continuously by the LTS 25-NP transducer. In this condition the various parts of the transducer (the ASIC, coil, and primary pins) remain at or below their maximum critical temperatures.

Unfortunately the failure rate of a transducer increases significantly as the temperature increases. Therefore these overload conditions will reduce the transducer reliability. This overload capability is considered a key element of the safety factor inherent in all LEM designs and, while temporary excursions are anticipated, long term operation at levels beyond those specified in the datasheet must not be allowed.

Important! The maximum operating temperature defined in the transducer datasheet must always be observed. If not, abnormal and possibly destructive behavior may result. Always consult LEM when actual operating or storage conditions fall outside of those specified on the datasheet.

To conclude, Fig. 17 and Fig. 18 give the maximum overload conditions for a rest current of I_{Pt2} = 0A.

3.2.11 Calculation of the measurement accuracy

For closed loop transducers, examples of the maximum error calculations are provided below. It is important to note that there are four regions of operation that exist:

- the region at or near zero primary input, which is characterized by the offset specification

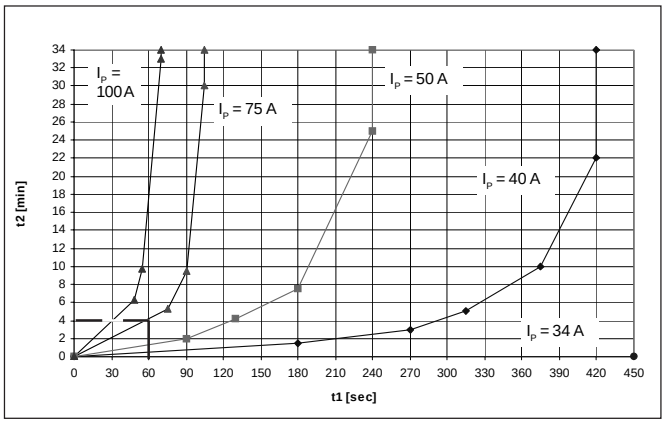


Figure 17: Overload diagram of the LTS 25-NP for a standby current of 0A

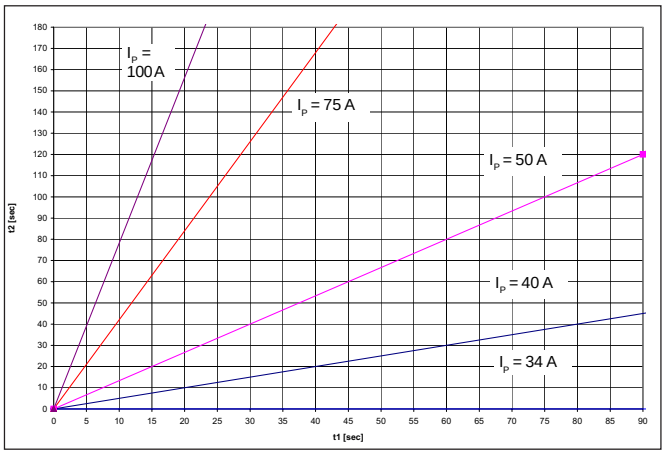


Fig. 18 Overload diagram of the LTS 25-NP for a rest current of 0 A, linear zone

- the region at or near the nominal primary level, which is characterized by the accuracy specification
- the region between these two, characterized by the linearity specification
- and the region near the limit of the measuring range, where saturation effects may begin

Maximum error takes all factors into account using the worst-case parameters. Because of the statistical distribution of each parameter it is highly unlikely that all will be at worst-case values in a single device. Nonetheless, this is the basis of worst-case design analysis.

Current transducer LA 55-P (see datasheet)

In this example, a DC current is measured with the LA 55-P current transducer with a ±15 V supply.

The datasheet provides the following information: I_{PN} = 50 A, I_{SN} = 50 mA, accuracy (@ 25 °C and ±15 V) is 0.65 % of I_{PN}. The accuracy is breakdown in several parameters, including linearity < 0.15 %, offset error I_O = 0.2 mA, and offset drift I_{OT} = 0.6 mA for 25…85 °C.

When a 50 A current is measured (one primary turn) the output current is 50 mA and the errors are:

Accuracy at 25 °C	±0.65 % of I_{PN}	±0.65 %
Offset drift with temperature	±0.6 mA / 50 mA	±1.20 %
Worst-case error (+85 °C)		**±1.85 %**

The worst-case error when measuring a 50 A current is consequently equal to ±1.85 % • 50 A = ±0.93 A.

When a 40 A current is measured the output current is 40 mA and the errors are:

Accuracy at 25 °C	±0.65 % of I_{PN}	±0.81 %
Offset drift with temperature	±0.6 mA / 40 mA	±1.50 %
Worst-case error (+85 °C)		**±2.31 %**

The worst-case error when measuring a 40 A current is consequently equal to ±2.31 % • 40 A = ±0.93 A.

The errors when measuring lower currents are larger as a percentage of reading due to the offset currents becoming significantly larger with respect to the output signal current. The initial offset current, I_O, of ±0.2 mA and the residual current, I_{OM}, (magnetic offset) of ±0.3 mA after a current overload, are also given in the data sheet. It shall be read as follows: When measuring a 0 A current the output can be ±0.2 mA, or ±0.4 % of I_{PN} = ±0.2 A. In addition, after experiencing an accidental 300 % overload (150 A) there can be an additional ±0.3 mA of offset for a total of ±0.5 mA, or 1.0 % of I_{PN} = ±0.5 A.

Current transducer LTS 25-NP (see datasheet)

For the LTS 25-NP transducer, the accuracy at 25 °C is given as ±0.7 % of I_{PN}. This breaks down as follows:

Number of secondary turns	±0.1 % of I_{PN}
Non-linearity	±0.1 % of I_{PN}
Tolerance on R_{IM}	±0.5 % of I_{PN}
Worst-case error	**±0.7 % of I_{PN}**

The internal measurement resistance, R_{IM}, has a value of 50 Ω and a thermal drift specified as 50 ppm/K. Considering a -10…85 °C temperature range, the maximum variation is ±0.15 Ω and the corresponding error due to the R_M drift is equal to 50 ppm/K • (85 - 25)°C = ±0.3 % of I_{PN}.

In addition, the voltage output of the LTS 25-NP transducer uses a 2.5V 'reference voltage' corresponding to a zero primary current (Fig. 1). The offset on this reference voltage (given in the datasheet) is ±25 mV at 25 °C. Considering a -10…85 °C temperature range, the worst-case offset value goes up an additional 100 ppm/K • (85 - 25)°C = 0.6 % to a total of ±40 mV at 85 °C, corresponding to 1 % initial offset plus 0.6 % drift.

Because a primary nominal current (I_{PN}) generates an output voltage of 625 mV at 25 °C, the error introduced by the offset on the reference voltage is:

- error due to the standard offset ±25 / 625 = ±4.0 % of I_{PN}
- maximum error due to the drift ±15 / 625 = ±2.4 % of I_{PN}

The worst-case measurement error throughout the temperature range is: 0.7 + 0.3 + 2.4 = ±3.4 % of I_{PN}

The error due to the standard offset (4%) is not taken into account because it represents a constant deviation which can easily be eliminated by an adequate electronic design.

3.2.12 Unipolar power supply

The vast majority of LEM closed loop transducers are specified for use with bipolar supply voltages (e.g. ±15 V). Even so, most transducers can also be operated from a single, unipolar, supply for the measurement of unidirectional currents. In these cases the following must be taken into account:

- the supply voltage should be equal to the sum of the positive and negative voltages indicated in the datasheet (e.g. a ±15 V product should be powered with +30 V)
- selection of the measurement resistance and the maximum current must not imply excessive power dissipation in the transducer output stage; assessment of the worst-case condition is not straightforward
- the output stage is designed for use with a bipolar power supply and diodes must be inserted in series with the output (Fig. 19) to allow a minimum output bias voltage without creating a measurement offset

The LEM portfolio also includes standard transducers dedicated to unipolar operation and use of these is advised as the electronic design and specifications are based directly on expected operating conditions.

Applications that only require a second supply voltage for the transducers, with the associated cost, complexity, space and reliability concerns of this additional circuitry, would justify the use of a unipolar transducer.

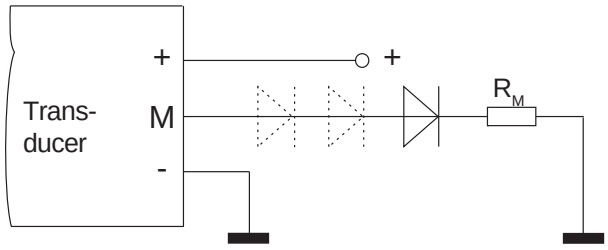


Figure 19: Addition of series diode(s) when operating with a unipolar power supply

3.3 Eta Technology Hall effect current transducers

Eta is the name of the Greek symbol 'η', representing efficiency. This product family has been given this name because of its very low secondary power requirements while also providing exceptional performance. In terms of performance, Eta falls between open loop and closed loop technologies. Because the construction is similar to closed loop, this technology offers no price advantage.

3.3.1 Construction and principle of operation

Hall effect Eta transducers are similar in construction to closed loop transducers (Figure 20), with the same magnetic circuit geometry, a Hall generator and secondary winding. Differences lie in the details of the magnetic core and processing electronics designs, leading to the Eta specific features. A Hall effect Eta transducer is a mix of open loop and current transformer technologies providing the following characteristics:

- it works as an open loop transducer at low frequencies (up to 2…10 kHz depending on the specific transducer design), with the Hall generator providing a signal proportional to the primary current to be measured (§ 3.1.1)
- it works as a current transformer at higher frequencies, where the output current is proportional to the AC primary current (§ 3.2.1)

Both the Hall effect and transformer signals are electronically added to form a common output signal.

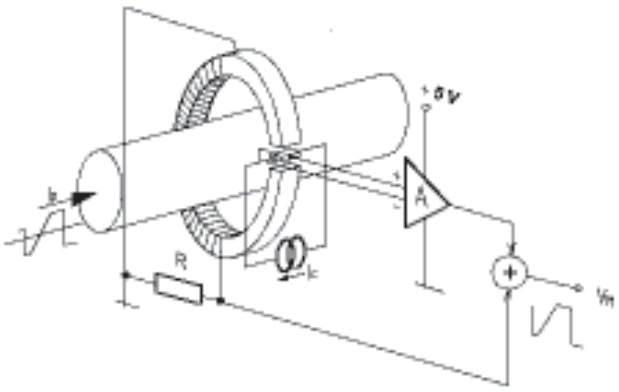


Figure 20: Hall effect Eta principle

Eta technology is better suited than others when the following performance is expected:

- wide bandwidth – DC to 100 kHz or more
- low power consumption
- use of a low voltage secondary supply (e.g. +5 V)

Power consumption is minimal because the power supply is not required to drive the secondary coil with compensation current, which also makes them suitable for use with a low voltage secondary supply, as they do not require the voltage 'headroom' of a closed loop device (§ 3.2.1).

Indeed, it is very difficult to design closed loop transducers that will operate from low voltage secondary supplies (less than or equal to 5 V) with primary currents exceeding 25 A. This design issue is due to the fact that there is very limited voltage 'headroom' to drive a suitable secondary coil and measuring resistance. It is this combination of requirements that are best address with Eta technology.

3.3.2 Advantages and limitations

Eta transducers are capable of measuring DC, AC and complex current waveforms while ensuring galvanic isolation and low insertion loss. Their significant **advantages** are the low power consumption and suitability for small secondary supply voltages, such as a unipolar 5 V supply, as with open loop transducers along with the high bandwidth and fast response time of a current transformer.

These characteristics also lead to the **limitations** of an open loop transducer at low frequencies; offset and gain drift with temperature and moderate accuracy. With higher frequencies (> 2…10 kHz) the current transformer effect provides very good accuracy and negligible temperature drift. In addition, the flux canceling nature of a current transformer reduces the concern of core losses with high frequency currents.

With Eta technology the major inconveniences are the size of the magnetic circuit, with a large core sized for low frequencies as with open loop transducers, and the need for a large secondary coil for detecting high frequencies, as compared to closed loop transducers. This typically results in a more expensive construction than is required for a similarly rated closed loop transducer.

3.3.3 Nominal and extreme currents

The LEM Eta transducer range is made for nominal currents I_{PN} from 25 to 150 A. This rather narrow range is not limited by technical issues, but rather by the market itself: for currents less than or equal to 25 A it is possible to work with the higher performance closed loop technology, while for currents greater than 150 A secondary voltage supplies with a greater amplitude (e.g. ±15 V) are generally available, again allowing the use of closed loop transducers. The reduced secondary power consumption of the Eta technology is often not a sufficient asset to promote Eta technology beyond this current range, although there are always exceptions.

For a given Eta transducer, the maximum current which can be measured depends on the limitations set by the open loop (§ 3.1.3) or current transformer (§ 3.2.3) behavior, at low and high frequencies respectively. This leads to a maximum measurable current of typically 150 to 200 % of the nominal current at low frequencies, and a capability going significantly beyond that at higher frequencies.

The risk of magnetic offset after an unexpected current overload is similar to that of open loop and closed loop transducers (§ 3.1.6 and § 3.2.6), again at the expected frequency of disturbance.

3.3.4 Output signal

By design an Eta transducer has a voltage output, although the internal design could be modified or voltage signal post-processed to provide other output types. Refer to § 2.7 for more details.

3.3.5 Measurement accuracy

The accuracy of an Eta transducer is dependent on the working frequency:

- for low frequencies (< 2…10 kHz), the overall accuracy is a few percent, as with open loop designs
- for higher frequencies, the overall accuracy is typically below one percent

Refer to the related open loop Hall effect (§ 3.1.5 and § 3.1.10) and closed loop (§ 3.2.5 and § 3.2.10) sections for more details on the factors affecting the accuracy and to review calculation examples.

3.3.6 Dynamic behavior

The bandwidth, response time and di/dt behavior of Eta transducers is very close to those of the closed loop technology (§ 3.2.7 and § 3.2.8), although slight performance reductions may come from the use of a less efficient magnetic circuit (material, design) for high frequency operations.

Measurements carried out on Eta transducers show a typical bandwidth range of DC to 100 kHz or more.

The response to a current step demonstrates the ability to correctly reproduce a transient. It is defined by several parameters such as the delay time, rise time, reaction time (§ 3.1.8) with a particular waveform. Eta transducers show fast reaction time, better than 1 µs, similar to closed loop designs.

The correct following of di/dt depends on the intrinsic construction of each product and, as mentioned previously, the mounting conditions of the transducer in the circuit to be measured. Depending on the selected Eta transducer model, it is possible to measure di/dt from approximately 50 A/µs to 400 A/µs or more. This feature makes them well suited for the protection of semiconductor devices.

3.3.7 Typical applications

Eta current transducers are used in numerous industrial applications, generally as an important element of a regulation loop (for current, torque, force, speed, position feedback), but also for current monitoring and display. Examples of applications are similar to the ones of open loop (§ 3.1.9) and closed loop (§ 3.2.9) transducers.

3.4 Closed loop Hall effect voltage transducers

Previous sections address the measurement of current with galvanic isolation, but it is also possible to measure a primary voltage with galvanic isolation using the same LEM technology. These voltage transducers are based on the more sensitive and accurate current measurement technologies, such as closed loop Hall effect designs. The main difference from a current transducer is the addition of an internal primary winding with a large number of turns,

allowing the transducer to create the necessary ampere•turns to measure the small primary current.

3.4.1 Construction and principle of operation

The operating principle of closed loop Hall effect voltage transducers is to measure a small current that is directly proportional to the voltage of interest. Dividing the voltage to be measured by a large resistance, R_1, creates a small current, I_{mes}, that can be measured by an 'optimized' transducer (Fig. 21), enabling it to accurately measure the small Imes current, while also having controlled insertion impedance to maintain suitable accuracy and measurement bandwidth. The R_1 resistance is added in series with the transducer primary coil to obtain the optimal I_{mes} current value for the nominal voltage level. This resistance is often split into two resistors, placed on both sides of the primary coil, to improve common mode rejection.

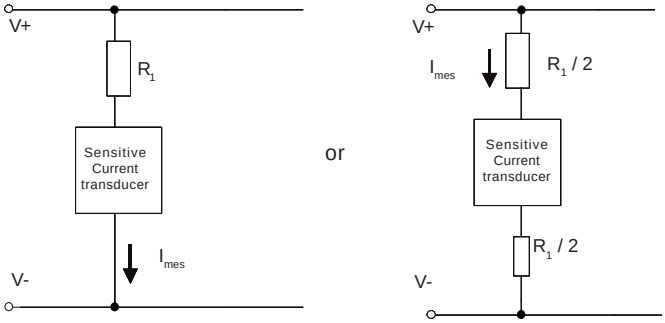


Figure 21: A basic principle for voltage measurement

Two situations exist with the LEM voltage transducer portfolio:

- the series resistance, R_1, is built into the LEM voltage transducer providing optimal performance when used at or near the product ratings, as with the LEM LV 100-100
- the series resistance, R_1, is external, allowing the customer to tune the transducer working voltage range and/or response time, as with the LEM LV 100 and LV 200

The equivalent electric diagram of a voltage transducer primary part is show on Fig. 22, including the serial resistance R_1, the primary coil resistance R_P and the primary coil inductance L_P. The latter generally creates a negligeable insertion reactance (ωL_P), in most cases neglected.

3.4.2 Voltage transducer with internal resistor

For the „LV 100-[voltage]" transducers (e.g. LV 100-100) the series resistance, R_1, is built into the transducer and cannot be changed by the user. This design has a 10 W input power at nominal voltage. The internal series resistor allows factory calibration of the transducer at the specified nominal voltage, implying better accuracy.

The measuring range is limited to 150 % of the nominal value, except for transient measurements where the RMS transducer input power remains below the specified 10 W.

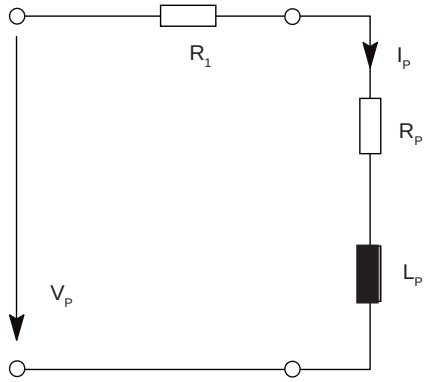


Figure 22: Equivalent diagram for the R1 primary series resistance calculation

3.4.3 Voltage transducer without internal resistor

Example 1: LV 100 closed loop voltage transducer with external R1 resistor (see datasheet)

a) What external resistance, R_1, is required to measure a nominal voltage of V_{PN} = 230 V_{AC}?

The LV 100 datasheet provides the following information: nominal current, I_{PN} = 10 mA, measuring range, I_P = 20 mA, primary coil resistance, R_P = 1900 Ω at T_A = 70 °C. We have:

$R_1 = V_{PN} / I_{PN} - R_P = (230 / 0.01) - 1900 = 21.1$ kΩ
We select the nearest standard resistance value of 21.0 kΩ

The total resistance of the primary circuit is consequently equal to 22.9 kΩ at 70 °C.

The nominal power P_N dissipated in R_1 is:

$$P_N = I_{PN}^2 \bullet R_1 = \left(\frac{V_{PN}}{R_1 + R_P}\right)^2 \bullet R_1 = 0.012 \bullet 21000 = 2.1 \text{ W}$$

In order to avoid excessive thermal drift of the resistor, and to improve reliability, the user would preferably select a resistor with a power rating of 300 to 400 % of the calculated nominal power. In this example, a 21.0 kΩ, 8 W resistor should be considered.

b) With this resistor, can we measure a maximum voltage of 500 V ?

The measurement of a voltage higher than the nominal value is possible during transient operation, depending on the following two conditions:

- the RMS value of the primary voltage shall be such that it keeps the transducer current below nominal value (10 mA for the LV 100); in our example, if this rule is not fulfilled at 500 V with the selected 21.0 kΩ resistance, a higher resistance value must be considered
- the primary current at the higher voltage should normally be lower than the transducer specified 'measuring range', 20 mA for the LV 100; we have: $I_P = (V_P/R_{Ptot}) = 500/22900 = 21.8$ mA and are therefore beyond the

specified measuring range; a check on the transducer secondary side is required to see if this transient measurement is nevertheless possible

For the latter point, as discussed in § 3.2.10 – example 2, it is sometimes possible to measure a current beyond that specified in the transducer datasheet, more precisely when the measurement resistor is not exceeding a maximum R_{Mmax} value. In this example, we have:

- the conversion ratio of the transducer is 10000 / 2000, giving a secondary current of $I_S = 5 \bullet 21.8 = 109$ mA
- the voltage available at the amplifier output is (Fig. 12) $V_A = (R_S + R_{Mmax}) \bullet I_S = (60 + 150)\Omega \bullet 50$ mA = 10.5 V
- the maximum measurement value is $R_{Mmax} = (V_A / I_S) - R_S = (10.5 / 0.109) – 60 = 36.3\Omega$

In conclusion, measuring a 500 V transient is possible if a measurement resistance lower than 36.1 Ω is used.

c) Measurement accuracy: influence of the serial resistance R_1 and primary resistance R_P

The measurement principle discussed in § 3.4.1 is based on the measurement of a current I_{mes} (Fig. 21) proportional to the voltage to be measured. The two main factors affecting the measurement accuracy are:

- The accuracy of the measurement of the collected current I_{mes}
- Unexpected changes of the ratio between the collected I_{mes} current and the voltage to be measured.

Thus, changes of the resistances R_1 and R_P will affect the measurement accuracy, since it will change the value of the I_{mes} current.

The example below calculates the impact on accuracy of a change in resistances, due to both resistance tolerances and temperature effects. A LV 100 voltage transducer is considered, with a +20°C to +70°C worst case working temperatures.

Reference case

The reference value of the current to be measured, I_{mes}, is defined as the value obtained at +70°C when both resistors R_1 and R_P have their nominal value. These values are R_1 = 21.0 kΩ (as calculated in point a), at +70°C) and R_P = 1.9 kΩ (data-sheet, measured value).

The collected I_{mes} current is then equal to 230 V / (21 + 1.9) kΩ = 10 mA

Maximum error

The value of the resistances are smaller at +20 °C when compared to +70 °C. The worst case shall additionally consider the tolerance on the resistances' value when at their minimum.

For the resistance R_1, typical values for the temperature drift and tolerance are 50ppm/°C and ± 0.5% respectively. The minimum value becomes:

$R_1 = 21'000 \bullet (1 - 50 \bullet 50 \bullet 10^{-6}) \bullet (1 – 0.005) = 20'942\ \Omega$

The primary resistance R_P is made of copper and exhibits a resistance change with temperature as follows:

$R_{PF} = R_{P20} (1 + \alpha \bullet \Delta T)$ where
R_{PF} : resistance at Final temperature (e.g. +70 °C)
R_{P20} : resistance at +20 °C
α : copper temperature coefficient = 0.004 K^{-1}
ΔT : change in temperature (Final – 20 °C), positive when above +20 °C

Note that the temperature of the R_P copper is likely to be higher than the maximum ambient temperature due to internal transducer heatings.

In our case:

$R_{P20} = 1'900 / (1 + 0.004 \bullet 50) = 1'538\ \Omega$

Collected current become equal to I_{mes} = 230 V / (20'942 + 1'538) = 10.21 mA, corresponding to a +2.1 % error compared to the reference value.

The measurement accuracy of the I_{mes} current has still to be added to this 2.1 % error.

d) What is the accuracy of the transducer, converting the primary current into an isolated output signal ?

In this case, we assume that the resistor R_1 has been selected in order to have a 10 mA primary current I_{PN}. According to the LV 100 datasheet, the accuracy of the current measurement at 25 °C is ±0.7 % of I_{PN}. The thermal drift of the offset current is ±0.3 mA max. With a conversion ratio of 10000:2000, the input current of 10 mA generates an output current of 50 mA. The values of the errors are:

Accuracy at 25 °C	±0.7 % of I_{PN}	±0.7 %
Temperature offset drift	±0.3 mA/50 mA	±0.6 %
Maximum error of the current measurement:		**±1.3 %**

e) What is the total measurement error?

The effects listed in c) and d) above provide the total measurement error of the output current of the transducer. Typical applications include a measuring resistance, R_M, to convert this output into a voltage for measurement.

Assuming typical parameters for R_M, we have an intial tolerance of ±0.5 % and a 50 ppm/K temperature drift, giving a 0.225 % variation for a 20 °C to 70 °C temperature range. The total R_M error becomes 0.5 + 0.225 = 0.725 %.

For the LV 100 transducer, the total measurement error at the 230 V nominal, considering a temperature range of 20 to 70°C, is the combination of the effects in c) and d) and R_M above:

total measurement error =
2.1 % + 1.30 % + 0.725 % = 4.125 %

Example 2: Design for continuous measurement of 1000 V nominal

Select the value of the external primary resistance R_1 to continuously measure a voltage of V_{PN} = 1000 V nominal and determine the corresponding measurement accuracy.

a) Calculation of the primary resistance

Again using the LV 100 datasheet values: nominal current, I_{PN} = 10 mA, measuring range, I_P = 20 mA, primary coil resistance, R_P = 1900 Ω at 70 °C or R_P = 1615 Ω at 25 °C. We have: $R_1 = (V_{PN}/I_{PN}) - R_P = (1000/0.01) - 1615 = 98\,385\ \Omega$.

The nominal power, P_{1N}, dissipated in R_1 is:

$P_{1N} = I_{PN}^2 \bullet R_1 = 0.01^2 \bullet 98385 = 9.8$ W and, as already discussed, it is suggested to use a resistor with 300 to 400 % of this power rating: a 40 W resistor.

The total resistance, R_{Ptot}, of the primary circuit is:
$R_{Ptot} = R_P + R_1 = 100.3\ k\Omega$

b) Voltage measurement accuracy: effects of the series resistance, R_1, and coil resistance, R_P

Following the same methodology as in example 1c above, we have a maximum R_1 value of:

$R_{1max} = 98\,385\ \Omega \bullet 1.005 \bullet 1.00225 = 99\,099\ \Omega$

and a minimum value of:

$R_{1min} = 97.6\ k\Omega \bullet 0.995 \bullet 0.99875 = 97\,771\ \Omega$

The maximum value of R_P at 70 °C is 1.9 kΩ while the minimum value, at 20 °C, is equal to:

$$R_{Pmin} = \frac{R_{P70\ °C}}{(1 + 0.004 \bullet 50)}\ 1583\ \Omega$$

The primary resistance calculations are the same so the value of the total resistance, R_{TOT}, is between

97 771 + 1583 = 99 354 Ω and
99 099 + 1900 = 100 999 Ω

The range of primary current collected at nominal voltage is:

1000 V / 100 999 Ω = 9.90 mA to
1000 V / 99 354 Ω = 10.07 mA

This can be interpreted as a value of 9.985 mA ± 0.085 mA, corresponding to a ± 0.85 % tolerance.

c) The current measurement accuracy is identical to the calculation in example 1d before, namely 1.3 %.

d) For the LV 100 transducer, the total measurement error for a 1000 V nominal voltage over the temperature range 20 to 70 °C, making the same R_M assumptions as in example 1e is 0.85 % + 1.3 % + 0.725 % = 2.875 %.

Conclusions based on these two examples

The use of the LV 100 transducer for the measurement of a 230 V or a 1000 V nominal voltage leads to a worst-case measurement accuracy of 3.84 % or 2.97 %, respectively. The measurement accuracy is significantly better for larger voltages because the variation of the primary coil resistance is less significant in comparison to the primary total resistance ($R_1 + R_P$) due to the larger series resistor value. To obtain better accuracies when measuring low voltages one must select transducers with a larger conversion ratio. This will, however, require higher power dissipation in the primary circuit and thus increase the power taken from the source being measured. A second benefit of considering a larger conversion ratio (smaller number of primary turns) is the resulting larger bandwidth (reduced inductance value L in R / L time constant limitation).

Finally, if needed, the calibration of the output signal of a voltage transducer can be made by either tuning the external resistor value, R_1, or, as with current transducers, by adjusting the measuring resistor, R_M.

3.4.4 Transducer Output

The output of a closed loop voltage transducer is identical to that of a closed loop current transducer. Therefore, the methodology previously described in § 3.2.4 and § 2.7 for the selection of the transducer measuring resistor and output voltage also applies to these devices.

3.4.5 Typical applications

Closed loop Hall effect voltage transducers are used in many industrial applications to detect, monitor and regulate voltages. A typical application is the monitoring of input, output and DC filter voltages of frequency inverters, where accuracy and isolation are of primary importance.

3.5 Other Hall effect voltage transducers

Actually, most current transducers technologies can be modified into a voltage transducer by ensuring the small measurement current (proportional to primary voltage) is applied to a large number of primary turns to create the Ampere-turns necessary for measurement. This is commonly made with Fluxgate technologies (§4.4.4) but less typical with open loop and Eta Hall based transducers.

4 Fluxgate technologies

The Fluxgate technologies discussed in this chapter cover several types of isolated current and voltage transducers based on the same basic measurement principle: the magnetic field created by the primary current to be measured is detected by a specific sensing element. The latter is driven through its B-H loop by a dedicated electronic and the resulting magnetic effects are used for primary current detection. There are a wide variety of methods for concentrating the field, driving the magnetic core, and sensing the field intensity, but in all cases the underlying working principle is the same.

4.1 Working principle of Fluxgate technologies

To start, the 'standard' Fluxgate design will be investigated as this has a construction similar to the closed loop Hall effect current transducer already described (§ 3.2.1). After this the Fluxgate principle should be understood and other topologies can be covered, highlighting their specific characteristics and performances.

4.1.1 „Standard" Fluxgate – working principle

An isolated Fluxgate current transducer (Fig. 23) can be designed in the same manner as a Hall effect based closed loop transducer (§ 3.2.1), using the same magnetic circuit including a gap and secondary winding. The secondary winding is driven to provide zero flux in the gap as sensed by the Fluxgate element, rather than a Hall generator.

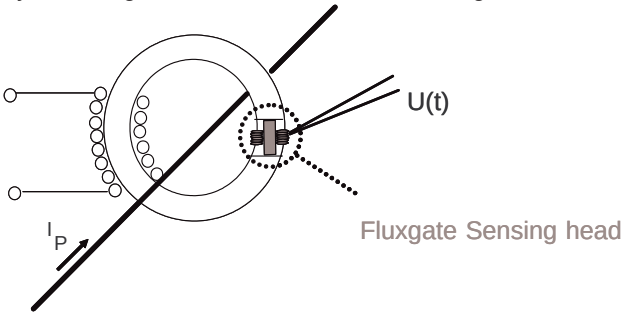


Figure 23: Structure of the „standard Fluxgate"

The main difference between the closed loop Hall technology and the Fluxgate is on the way the airgap field is detected: by a Hall cell in the first case, and by a so-called „saturable inductor" (Fig. 24) in the second. This implies a drastic change of the transducer electronics, to drive the sensing element and to process the resulting signal.

The Fluxgate sensing element is intentionally a „saturable inductor" (Fig. 24) made of a small, thin magnetic core with a coil wound around it. It is generally made of discrete pieces of material (lamination sheet & copper wires), but various designs can be considered, including advanced concepts based on MEMS technologies (not yet commercially viable).

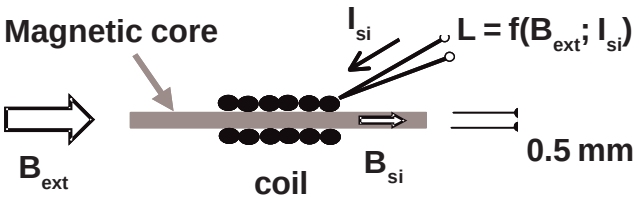


Figure 24: Fluxgate magnetic sensing head (saturable inductor)

As with any inductor, the value of inductance of the „saturable inductor" depends on the magnetic permeability of the core. When the flux density is high, the core is saturated, its permeability low, and the inductance high. At low field density, the inductance is high.

The „saturable inductor" is purposely designed so that any change in the external field, B_{EXT} (Fig. 24), affects its saturtion level, changing its core's permeability and consequently its inductance. Thus, the presence of an external field change the inductance value of the field sensing element. This change can be very pronounced if the saturable inductor is adequately designed. The second factor affecting this inductance is the current, I_{SI}, injected into the coil of the saturable inductor (Fig. 24). This current produces a flux, channeled into the magnetic core, resulting in an additional magnetic field components, B_{SI}. The saturable inductor is generally designed in a way that B_{EXT} and B_{SI} have the same order of magnitude, both affecting the inductance value.

With the „standard Fluxgate" design (Fig. 25), the primary current creates an airgap flux, Φ_P (corresponding to B_{EXT}), added to the flux Φ_{SI} created by the saturable inductor current I_{SI}. The addition of these two flux creates an over saturation of the saturable inductor's core and its inductance drops. When the polarity of the I_{SI} current is reversed, the flux Φ_P and Φ_{SI} are substracted, giving a lower total flux when Φ_{SI} is smaller than Φ_p, a zero total flux when Φ_P and Φ_{SI} are equals, or a reverse total flux when Φ_{SI} is larger. The latter case lead to a strong core saturation when Φ_{SI} is much larger than Φ_P. The design of the saturable inductor shall provide high inductance near zero total flux and low inductance under saturation.

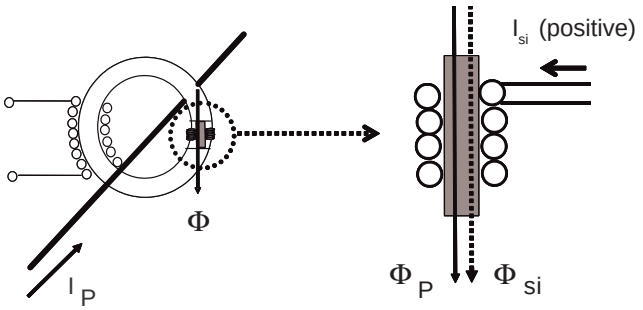


Figure 25: Standard Fluxgate - gap flux distribution – additive flux

In conclusion, changes in the magnetic saturation of the Fluxgate sensing head leads to inductance variations to be detected by the processing electronics (Fig. 26). The closed loop principle is then used, where variations in inductance

created by the primary current, I_P, can be detected and compensated using the closed loop principle, feeding a current into the transducer's secondary coil, I_S, to return the gap field to zero and thus inductance back to a reference case. The relation between primary and secondary current is then simply given by the primary to secondary turns ratio (§ 3.2.1). The next paragraphs details the methodology followed to detect inductance variations.

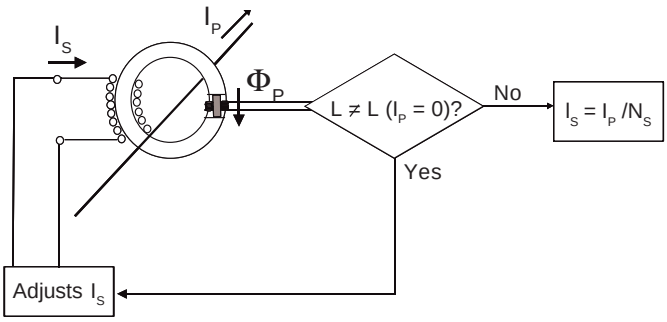


Figure 26: Principle of the „standard Fluxgate"

4.1.2 Sensing head – a current response to a voltage step

Since the Fluxgate working principle is based on the detection of an inductance change, it is necessary to first have a good understanding of the electric behavior of the saturable inductor. Thus, before analyzing the way inductance changes are detected (§ 4.1.3), lets first see what is the current response of the saturable inductor when a voltage step is applied.

The electric diagram of the saturable inductor is given in Fig. 27. The resistance represents the copper resistance of the inductor coil, constant at a given temperature, while the inductance is variable, depending on both the external field applied on the saturable inductor and the injected i(t) current .

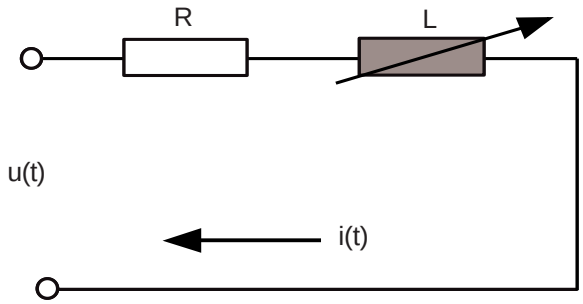


Figure 27: Electric diagram of the sensing head inductor

If the inductance of the sensing head were constant, the current response to a voltage step would be as shown in Fig. 28, given for three different inductance values: small, medium and large. The initial slope is defined by di/dt = V / L for t=0, giving lower slopes, or slower current responses, with higher inductances, while the final value is always the same and is defined by i = V / R.

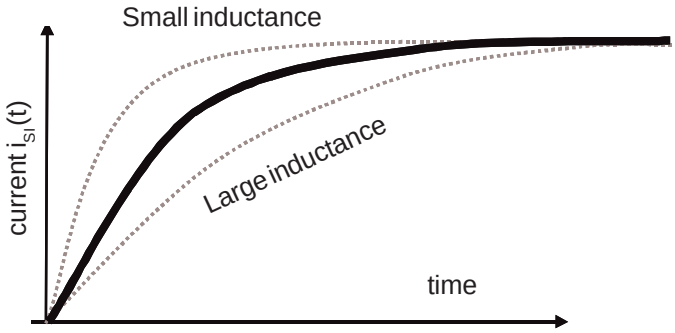


Figure 28: Current response to a voltage step – constant inductance

Figure 29 again shows the current response to a voltage step, but in this case with a saturable inductor, where the I_{SI} current increase lead to an increase or decrease of the inductance value, depending if the field B_{SI} (created by the same I_{SI} current) is added or substracted from the external B_{EXT} airgap field. When those fields are for example added, an I_{SI} current increase leads to an increase of the saturation level, implying a decrease of the inductance value and thus a faster current variation.

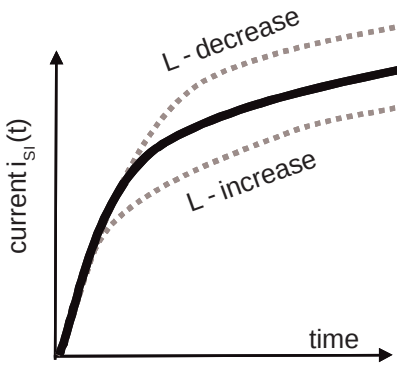


Figure 29: Current response to a voltage step – saturable inductance

In practice, Fluxgate sensing heads are designed so that the current response to a voltage step is very „sharp", as shown in Figure 30 (B_{EXT} = 0), where the current behaves in three different stages: (1a) For small current values, the current variation is slow, the saturable inductor being designed with a very high inductance when non-saturated; (2a) When the current exceeds a pre-defined level, its variation becomes very fast due to a sudden drop of the inductance value (use of magnetic materials with a sharp magnetic characteristic); (3a) The current reaches the asymptotic level defined by the excitation voltage and coil resistance.

This sharp profile is desired because it acts as a „closed" or „open" gate for the current, restraining or allowing the current flow depending on the saturation level of the core. This behavior, of the core flux controlling the current „gate", is the origin of the name Fluxgate.

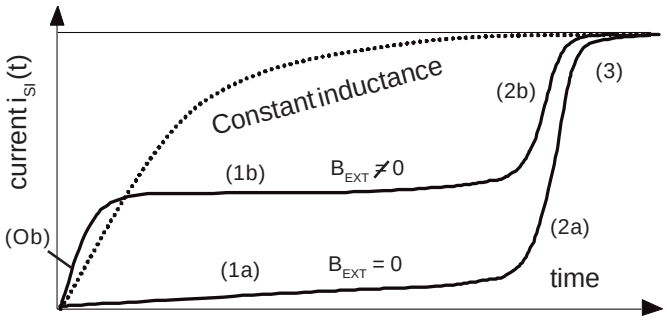


Figure 30: Current response to a voltage step – Fluxgate sensing head (B_{EXT} set at a parameter)

In the case where the external field B_{EXT} is non-zero, the current response appears as in Fig. 30, where the current behaves in four different ways: (0b) For small I_{SI} current values, the external field B_{EXT} is pre-dominant and drives the core into saturation, leading to a low inductance and a fast current change; (1b) As the inductor current I_{SI} reaches a level where it creates a B_{SI} field equal and opposite to the B_{EXT} field (total core flux equal to zero), the saturation level is low, the inductance high and the resulting current variation slow; (2b) As the inductor I_{SI} current continues to grow, the B_{SI} field becomes pre-dominant and drives again the inductor core into opposite saturation, resulting in an inductance drop and a fast current variation; (3) the current reaches the asymptotic level defined by the excitation voltage and coil resistance.

4.1.3 Detecting the sensing head inductance variation

As mentioned before (Fig. 26), the Fluxgate working principle is based on the detection of an inductance change. This change can be detected in different ways, the most common being described here.

Looking at Fig. 31, the saturable inductor is driven with a square wave voltage, u(t), leading to the sensing head current, i(t), when no primary current I_P (or no external field B_{EXT}) is applied. This current shape is directly related to the behavior shown in Figure 30, with the applied voltage changing polarity prior to reaching the asymptotic current level.

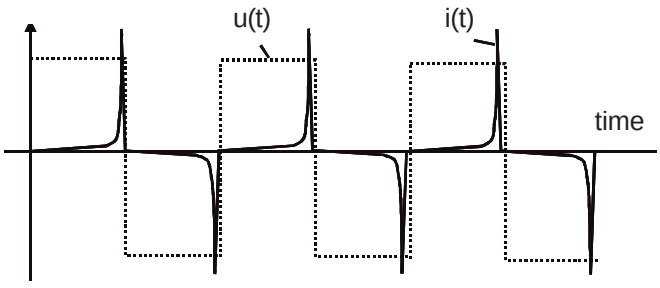


Figure 31: Voltage steps and current response ($I_P = 0$)

Assuming the loop is not closed, and compensating secondary current is not available, Fig. 32 shows the current behavior when a primary current (or external field B_{EXT}) is present, as described in Fig. 30. The current almost immediately goes to a non-zero positive value, then stays relatively stable until the core saturates in the other direction. Again, the voltage polarity changes prior to reaching the asymptotic current level. Compared to the Figure 31 current, the main differences are on the peaks amplitude (comparing the peaks above and below the DC value of the signal) and the appearance of a DC current component.

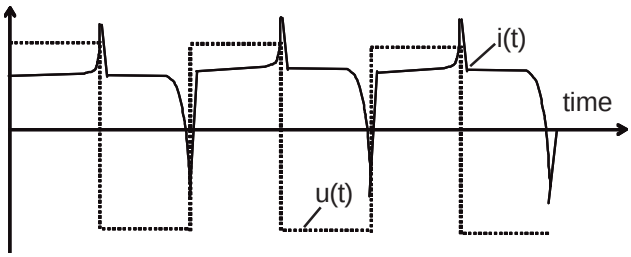


Figure 32: Voltage steps and current response ($I_P \neq 0$)

The polarity of the applied voltage can be triggered to change by different parameters (e.g. when the current reaches pre-defined trigger levels) or by having a fixed frequency.

Different techniques are then used to sense the change of inductance (Fig. 26), leading to various complexities and performances. The most common are (1) to measure the DC current component of Fig. 32; (2) to perform a spectral analysis of the Fig. 32 current and measure the amplitude of a selected current harmonic, the one which is the most sensitive to current shapes changes (generally the second harmonic order), or (3) to measure the duty-cycle of the Fig. 32 voltage. Once the changes of these signals are detected, the closed loop principle of Fig. 26 is used to compensate the flux in the gap.

4.1.4 Current transformer effects

As with a closed loop Hall effect transducer (§ 3.2.1), the secondary coil of Fig. 26 acts as a current transformer to measure high frequency currents. Depending on the type of Fluxgate considered, this is not always possible and, in those cases, the result is a reduced bandwidth and limited response time.

4.2 Existing types of Fluxgate transducers

The main types of Fluxgate transducers are shown in Figure 33 and briefly described here:

(1) The „standard“ Fluxgate (§ 4.1), similar to a closed loop Hall effect design

(2) The „C-type“ Fluxgate (§ 4.4), where the performance is significantly improved by:
- Making the field sensing element with the entire toroidal core, without a gap
- Ensuring high frequency performance by using a separate core for the transformer effect

(3) The „IT-type“ Fluxgate (§ 4.5), where the performance is improved a step further by:
- Duplicating the field sensing element, using two toroidal cores with opposing excitation coils
- Improving the design of the high frequency current transformer and processing electronics

(4) the „Low frequency“ Fluxgate, using only the low frequency part of the „C-type“ Fluxgate transducer, not considering the current transformer, to have a cost effective and efficient transducer for low frequencies

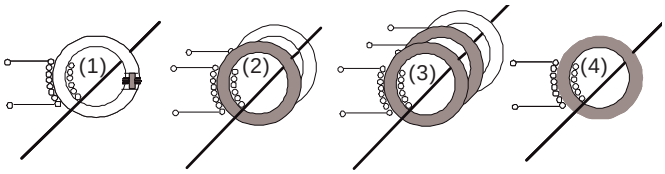


Figure 33: Main types of Fluxgate transducers - field sensing element in dark color

4.3 General performance of Fluxgate technologies

In general, Fluxgate technologies offer the following **advantages**:

- Low offset & offset drift, because the magnetic core is cycled throughout its B-H loop suppressing any magnetic offset in the Fluxgate core (not avoiding offset or offset drift of the processing electronics or, for the „standard“ Fluxgate, the magnetic offset created by the main toroid).
- Excellent accuracy due to the quasi absence of offset. Compared Hall based technologies, this advantage is more noticeable for small currents measurements, where the relative effect of the offset is more significant
- Excellent over-current recovery, again because any permanent magnetization of the field sensing element is reset with subsequent B-H cycles (and again, not affecting the main toroid of the „standard“ Fluxgate)
- Much higher sensitivity than other technologies, allowing the measurement of very low Ampere-turns (determined by design and dependent on the required magnitudes of B_{EXT} and B_{SI})
- A large dynamic range, allowing measurement of both small and large currents with the same transducer
- Very high resolution, provided by the low offset. See comment on the noise hereunder.
- Large temperature range, the low offset drift make Fluxgate technologies suitable for broader operating temperature ranges (still limited by the transducer materials and component limits)
- High bandwidth – fast response time, provided by the current transformer effect (when relevant) which is further enhanced on C-type and IT-type Fluxgates.

The technology has in general the following **limitations**:

- Limited bandwidth for the simpler designs
- A large noise level at the excitation frequency, present at the output and possibly coupled into the primary
- Voltage noise injection into the primary lines (acceptable for the vast majority of applications)
- Relatively high secondary power consumption, similar to that of closed loop Hall effect transducers
- More efficient designs are more complex and thus more expensive to produce
- The design of Fluxgate transducers is relatively complex and makes for more difficult customization

More details are given in the following sections outlining the details of specific Fluxgate designs.

4.4 „C-type“ Fluxgate transducers

„C-type“ closed loop Fluxgate transducers are a significant part of the LEM current and voltage product portfolio. This technology was developed in co-operation with the University of Auckland - New Zealand (Prof. Dan Otto) and provides very high performance in terms of accuracy, temperature drift, bandwidth and response time. This high performance is the result of a patented design used for the compensation of Ampere-turns.

4.4.1 Construction and principle of operation

The basic working principle and performance of a „standard“ Fluxgate has been discussed in § 4.2 and § 4.1. An understanding of this device is the foundation for a complete description of „C-type“ operation, provided here.

A „C-type“ Fluxgate transducer (Fig. 34) is made with two identical magnetic cores (T1 and T2), each wound with an equal number of secondary turns, N_S. The primary winding, N_P, is common to both cores. The two secondary windings are connected in series and the shared center point is also connected to the electronics.

One core, T1, uses the Fluxgate principle to measure the lower frequencies (T1 being the so called Fluxgate sensing head), while the other, T2, acts as a current transformer for

higher frequencies. Both secondary windings of T1 and T2 also acts as the zero flux compensation winding, ensuring the transducer works in a closed loop mode.

This design has the ability to supply a single coil (secondary of T1) with the „Fluxgate“ current (Fig. 32 and I_μ in Fig. 34) as well as the secondary current (I_S in Fig. 34) required for flux compensation. The processing electronics then removes the Fluxgate current in a „filter“ (ref. 2 in Fig. 34) to prevent noise at the transducer output. The output current (point C of Figure 34) is then equal to $I_S = I_P \bullet N_P/N_S$. Finally, for a wide operating temperature range, the electronics are designed to automatically compensate the electronic offsets and voltage drops, eliminating the need for adjustments.

„C-type“ transducers internally control the loading of the secondary current and therefore have a voltage output.

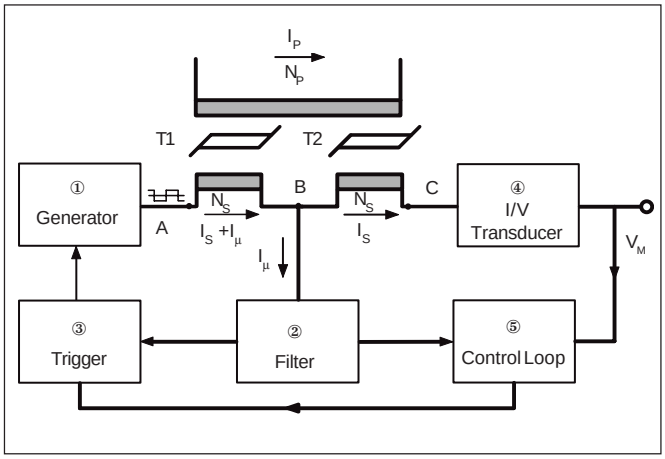


Figure 34: Block diagram of the C-type Fluxgate transducers

4.4.2 „CT-type“ current transducers

Please note that „CT“ is a LEM product designation and is not used as an abbreviation for current transformer.

The LEM „CT“ current transducers measure currents up to a maximum of 150 A. They typically have an accuracy of 0.1 % and a remarkable 0 to 500 kHz bandwidth.

The main **advantages** are:

- Excellent accuracy across the entire operating temperature range
- Wide bandwidth
- Extremely short response time
- Excellent immunity to surrounding magnetic fields
- High overload current capability (e.g. a CT 1-S transducer, with a 1 A nominal current, can withstand a overload above 15 kA for 150 ms)
- Output short circuit protection
- Very high isolation levels and excellent resistance to partial discharge (e.g. CT 5-T/SP3 transducers have 50 kVrms isolation with a partial discharge extinction level of 14.5 kV with < 20 pC)

The **limitation** of the CT transducer is the injection of a rectangular voltage ripple on the primary line. This is caused by the Fluxgate excitation voltage, typically at a frequency of 500 Hz, and is a function of the primary to secondary turns ratio. This primary voltage ripple induces a current noise, with an amplitude dependent on the primary circuit impedance; the lower the impedance the higher the current noise (see calculation examples in § 4.4.6b). While this current noise is generally not a problem, it is measured by the transducer and will be seen as an additional measurement error.

4.4.3 „CD-type“ differential current transducers

A LEM „CD“ transducer is designed to measure differential currents, the difference between two primary currents flowing in opposite directions. This application takes advantage of the very high sensitivity of this topology, allowing measurement of a differential current that is only 0.1 % of the main current flowing in each primary conductor. For example, a differential current of 1 A can be measured with a main current of 1000 A, or 0.1 A with a main current of 100A. The measurement accuracy is about 5 to 10 % within the specified operating temperature range.

The main **advantages** are:

- Very good differential resolution (able to measure low differential currents with high main currents)
- Possibility to have an external adjustment by the user of the level of the differential current to be measured (a special design provides external terminals in the housing, where an adjustment resistor is connected)
- Special designs allow the adjustment of the time constant of the measured differential current, which is convenient when the output signal of the transducer is used as a trigger in a safety system
- Options to define several levels of differential currents to be measured (the transducer is then designed with a separate individual output for each current level)
- Protection against primary current overloads

The main **limitations** are:

- Limited frequency bandwidth, typically DC to 2kHz
- A differential current measurement should theoretically be independent of the main current value, but the main current must never exceed the transducer rated value to avoid permanent local saturation affects, due to both internal and external magnetic effects, which will reduce the accuracy of the transducer

4.4.4 „CV-type“ voltage transducers

The „CV“ family of transducers measure voltages up to 7 kV. The typical accuracy is 0.2 % and 1 % for the CV3 and CV4 series respectively. The bandwidth is from DC to a maximum frequency ranged between 10 kHz and 800 kHz, depending on the selected transducer reference. CV voltage transducers generally include the primary resistor as this value is tuned for optimum performance. Because of the high sensitivity of the „C-type“ design the required primary ampere-turns is small, leading to a lower primary inductance and resistance, improving accuracy, bandwidth, and response time.

Their main **advantages** are:

- Excellent accuracy over a broad operating temperature range
- Low primary power consumption
- Wide frequency bandwidth and fast response time
- Excellent fast dv/dt measurement capability
- Very good immunity against surrounding magnetic fields
- Very good immunity against common mode voltage variations

The **limitation** of most of the CV transducers is the dielectric withstand voltage of 6 kV_{RMS}, with a partial discharge extinction level of 2 kV_{RMS} with < 10 pC. The CV4 transducer has been designed with an extended isolation capability.

4.4.5 „C-type“ transducers - typical applications

„C-type“ transducers are used in industrial applications requiring very high accuracy, for example calibration units, diagnosis systems, test platforms and laboratory equipment. It is also appropriate when the application needs an absolute robustness of performance with temperature changes.

CT current transducers

- Current measurement in transmitters.
- Measuring the magnetizing current and DC current in power transformers, avoiding unexpected magnetic saturation (industrial equipment and electric traction).
- Current measurement in induction heating systems.
- Measurement of charge and discharge currents for battery testers.
- Calibration benches for power converters and motors.
- Current measurement in the electric energy distribution simulators and substations.
- Current measurement in photovoltaic plants (precise measurement of the maximum power point).
- Laboratory instruments: isolated current measurement for use with an oscilloscope or a digital multi-meter; power measurement for inverters, as an interface with a power analyzer, etc…
- Measurement of the heating current in the cathode of a KLYSTRON accelerator.

CD differential current transducers

- Measurement and detection of earth leakage currents.
- Replacement of the classic differential relays, with a better accuracy and the detection of much smaller currents.
- Measurement of differential currents, as a safety function in electric traction equipment.

CV voltage transducers

- Measurement of AC voltages in high power industrial inverters.
- Voltage measurement in electric traction converters (DC and AC).
- Voltage measurement between phases of power cyclo-converters.
- Calibration benches for power converters and motors.
- Voltage measurement in photovoltaic plants (precise measurement of the maximum power point).
- Laboratory measurement instruments: isolated voltage measurement, power measurement for inverters, as an interface with a power analyzer, etc.

4.4.6 Calculation of the measurement accuracy & noise rejection

The following examples show the high performance of the „C-type“ transducers.

Example 1: Accuracy of the CT 100-S current transducer (see datasheet)

In this example a 100 A DC current is measured and, according to the transducer datasheet, the output voltage will be 5 V. Using this part within its operating temperature range of 25 to 70 °C the indicated accuracy is ±0.15 %, including an initial offset of maximum ±0.4 mV, and the temperature drift of the offset voltage can be ±0.6 mV.

Accuracy	±0.15 % of I_{PN}	±0.15 %
Offset drift with temperature	±0.6 mV/5 V	±0.012 %
Worst-case error		±0.162 %

This worst-case error is expressed as a percentage of the nominal value

Example 2: Ripple rejection and the CT 5-T current transducer (see datasheet)

This example demonstrates the ripple rejection in the primary circuit of a CT 5-T transducer. We have:

- The internal square-wave generator (Fig. 34 - ref. 1) provides a voltage of U_{SW} = ± 6.8 V
- Number of primary turns is N_P = 10

- Number of secondary turns is N_S = 1000
- I / V converter resistance (Fig. 34 - ref. 4) is R_C = 100 Ω

If the primary circuit impedance is Z_P = 100 Ω, the induced primary current becomes:

$I_{Pind} = V_{SW} \bullet N_P / (N_S \bullet Z_P) = 6.8 \bullet 10 / (1000 \bullet 100) = 0.68$ mA

The voltage induced in the secondary by this parasitic current is:

$V_{Sind} = I_{Pind} \bullet (N_P/N_S) \bullet R_C = 0.68\,\text{mA} \bullet (10/1000) \bullet 100 = 0.68\,\text{mV}$

For a primary current giving a 5 V output signal, the corresponding measurement error is 0.68 mV/5 V = 0.014 %.

If, on the other hand, the primary impedance is small, for example Z_P = 1 Ω the measurement error becomes much more significant, 1.4 % in this case.

Example 3: CV voltage transducer – Accuracy calculation

	T_A +25 °C	$T_{A\,max}$ +70 °C
Typical accuracy of the primary resistances	0.05 %	0.05 %
Variation with temperature (typical coefficient 20 ppm/°C)	-	0.10 %
Typical resistance accuracy of the converter	0.05 %	0.05 %
Variation with temperature (typical coefficient 20 ppm/°C)	-	0.10 %
Secondary offset voltage:		
- nominal is 5 mV	0.10 %	-
- Maximum with temperature is 10 mV	-	0.20 %
Maximum total error	**0.20 %**	**0.5 %**

Example 4: Accuracy of the CV 1-1500 voltage transducer (see datasheet)

The CV 1-1500 voltage transducer is designed to measure a 1500V peak voltage. According to the transducer datasheet, the output voltage will then be 10 V peak. Using this part within its operating temperature range of 25 to 70 °C the indicated accuracy is ±3. 0% including an initial offset of max ±100 mV. This worst-case error is expressed as a percentage of the peak value.

4.5 „IT-type“ Fluxgate transducers

LEM „IT-type“ closed loop Fluxgate transducers allow AC and DC current measurement with very high accuracy, linearity and stability, while eliminating the injection of noise into the primary.

4.5.1 Construction and principle of operation

The „IT-type“ transducer consists of a current measuring head made of three magnetic cores, C1, C2, and C3, with primary (w_{P1}) and secondary (w_{S1} to w_{S4}) windings as shown in Fig. 35. Closed loop compensation is obtained by a secondary current, I_C, fed into one of the secondary coils (w_{S2}). The latter coil, magnetic coupled to the three magnetic cores, is connected in series with the measuring resistor to obtain an output voltage of typically 1 V with secondary currents of 200 or 400 mA.

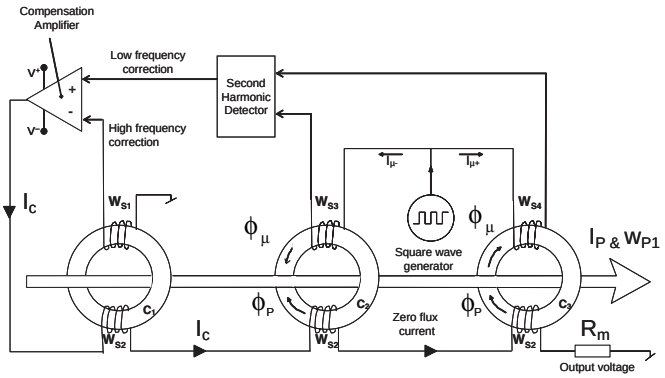


Figure 35: Principle of the IT transducer

For the upper frequency range, the secondary current results from a transformer effect in two secondary coils (w_{s1} and w_{s2}). For lower frequencies, including DC, the design functions as a closed loop Fluxgate transducer (§ 4.1), with the winding w_{S3} and w_{S4} being the Fluxgate sensing coils. These features are described in details hereunder.

4.5.1.1 Transformer effect – high frequencies

The current transformer is made with a primary (w_{P1}) and two secondary coils (w_{S1} and w_{S2}), wound around the same magnetic core (C1). The secondary coils are connected to a compensation amplifier in order to improve the overall performances. This system works as follow:

- The coils w_{P1} and w_{S2} work as a classical current transformer, where a current I_C is induced into the secondary coil, proportional to the primary current to be measured, leading theoretically to a zero total flux into the magnetic core.
- In practice, a residual flux remains, reflecting the imperfect coupling between the primary (w_{P1}) and secondary (w_{S2}) coils as well as the transformer burden. For a current transformer, this residual flux is an image of the measurement imperfections.
- The coil w_{S1}, connected on a high impedance, collects a non zero voltage when an AC residual flux occurs: a signal is then sent into the correction amplifier, adjusting the secondary current I_S until the total flux is equal to zero.

The resulting current transformer performances are remarkable.

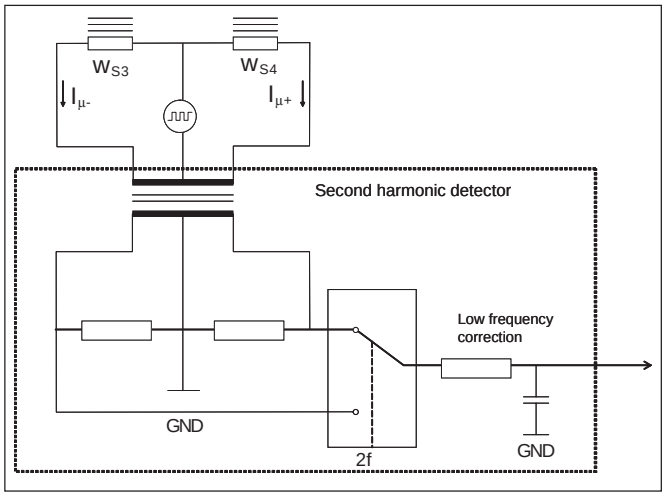


Figure 36: Block diagram of the symmetrical zero flux detector

4.5.1.2 Fluxgate detector – low frequencies

The Fluxgate sensor (Fig. 35) is made of two magnetically symmetric parts (two saturable inductors), each of them made with one magnetic core (C2 or C3), one primary winding (w_{P1}), one compensation winding (w_{s2}) and one secondary winding (w_{S3} or w_{S4}).

Close-loop not active

At low frequency, assuming in first instance that the zero flux compensation created by w_{S2} is inactive, the flux Φ_P created by the primary current is identical in both C2 and C3 cores (Fig. 35), with the same magnetic polarity.

The secondary windings are connected to a square-wave generator that supplies the I_μ currents (Fig. 36), bringing the core C2 and C3 into saturation. The resulting Iμ currents have a shape as shown on Fig. 31 and Fig. 32.

Due to the magnetic construction and electric connections of w_{S3} or w_{S4} windings, the fluxes created by the I_μ currents into the C2 and C3 cores have an opposite magnetic polarity ($\pm\Phi_\mu$). The total flux in the C2 and C3 core are consequently different, since at a given time the flux Φ_μ and Φ_P are additive in C3 and subtractive in C2 (Fig. 35). The level of saturation in the two cores being different, the shape of the $I_{\mu+}$ and $I_{\mu-}$ currents will be at any time different, including differences on the DC value and when the current 'peaks' (or saturation) occur. Assuming a frequency of the I_μ currents significantly larger than the primary current frequency, the $I_{\mu+}$ and $I_{\mu-}$ currents have typically the shape shown on Fig. 37.

In term of noise, the fact that the switched currents ($I_{\mu+}$ and $I_{\mu-}$) create fluxes with an opposite polarity ($\pm\ \Phi_\mu$) explains why the conducted noise created by the IT transducer is very limited.

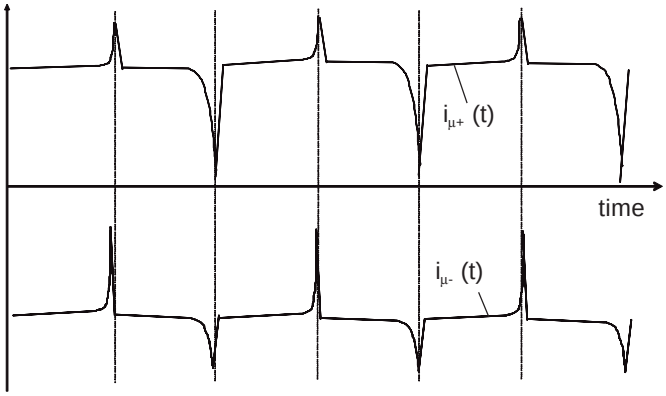


Figure 37: I_μ+ and I_μ- currents

IT transducer working principle

In normal working conditions, the close-loop coil w_{S2} is active and the principle can be further described as follow : When there is no primary current, the system is magnetically symmetric and the I_μ currents are identical, with a shape looking like that shown in Fig. 31.

An increase of the primary current has the following consequences (Fig. 37):

- It creates a DC current component on the $I_{\mu+}$ and $I_{\mu-}$ currents, positive or negative respectively.
- The „AC" behavior of the two I_μ currents different, with peaks with large and small amplitudes not occurring at the same time.

The IT transducer only monitors the differences in the I_μ currents shapes, reflecting a change in the primary current. When a change is noticed, the compensating I_s current in the secondary coil w_{S2} is adjusted in order to be back to the initial magnetic stage. This is identical to the general closed loop principle described before.

The shape change is detected by a „second harmonic detector" (Fig. 36), described hereunder, which detects changes in the harmonic content of the I_μ current waveform. The second harmonic order is selected because it is the most sensitive.

Due to the targeted very high resolution and accuracy, preference is given to this harmonic detection principle rather than a monitoring of the changes in the Iμ current's DC offset. Indeed, while the latter principle is regularly considered for less efficient Fluxgate designs, it suffers from offset errors introduced by the processing electronic.

A key element of this detector is the center-tapped transformer, which naturally sort out the second harmonics of its I_μ primary currents. The transformer primary coil is made in two parts, connected in a way that the $I_{\mu+}$ and $I_{\mu-}$ currents create flux with an opposite polarity:

- When the two I_μ currents are identical (I_P = 0), the flux cancellation is such that there is no signal induced into the secondary of the center-tapped transformer
- When the two I_μ currents are different (I_P different from zero), only their AC differences create a signal. In this case, where the I_μ currents have the Fig. 37 shapes, all the I_μ currents uneven harmonics (1, 3, 5…) create a zero total flux, while the even harmonics (2, 4…) create an AC flux and thus a signal into the secondary winding of the center-tapped transformer.

Finally, among the harmonic content of the transformer output signal, only the second harmonic is detected by the dedicated processing electronics (Fig. 36), using an analog switch driven at twice the excitation frequency, ensuring „synchronous rectification“ of the second harmonic signal. The output of the synchronous rectifier is then filtered using a low-pass filter, before controlling the amplifier that drives flux compensation coil, w_{S2} (Fig. 35).

This W_{S2} coil is consequently compensating both the low frequencies, using the Fluxgate principle, and the high frequencies, through current transformer effects.

4.5.2 „IT-type“ transducers – advantages & limitations

The main **advantages** are:

- Very high accuracy and stability
- Very low initial offset and drift with temperature
- Excellent linearity (< 1 ppm)
- Very good temperature stability (< 0.3 ppm/K)
- Large bandwidth (DC to 100 kHz)
- Very low distortion for AC current measurement
- Very low noise on the output signal

The **limitations** are:

- Operating temperature presently limited to laboratory or clean environment usage (basically 10 °C to 50 °C)
- High power supply current consumption
- Relatively large dimensions

4.5.3 „IT-type“ transducers - typical applications

- Feedback measurement in precision current regulated power supplies.
- Precision current control in gradient amplifiers for medical imaging.
- Current measurement for power analysis.
- Calibration device for test benches.
- Battery charging equipment requiring high-resolution measurement.
- Laboratory/metrology equipment requiring high accuracy measurement.

4.5.4 Calculation of the measurement accuracy

Set an IT 600-S transducer to measure nominal current and check accuracy at 100 % and 10 % of this level.

Example 1: Accuracy of the IT 600-S at 600A (see datasheet)

When measuring a 600 A DC current, an IT 600-S can only provide a 1 V output. With a current transfer ratio of 1500:1, the secondary current is 400 mA and therefore the measurement resistance must be 2.5 Ω. We will assume the worst-case rated operating temperature of 50 °C for the analysis. This amounts to a 25 °C deviation which creates a 0.1 µA/°C • 25 °C = 2.5 µA offset drift. The error is given in both mA and ppm of reading.

At 25 °C ambient

DC offset on secondary current at I_P = 0	< 4 mA	10 ppm
Non-linearity: <1 ppm of full scale	< 0.4 mA	1 ppm
Measuring ratio stability of < 2ppm of reading	< 0.8 mA	2 ppm
Total error at 25 °C	**< 5.2 mA**	**13 ppm**

Drift with temperature (from 25 °C to 50 °C)

DC offset drift: 0.1 mA/K	2.5 mA	6.25 ppm
Measuring ratio stability of 0.3 ppm of reading/K	3 mA	7.5 ppm
Maximum global error at 50 °C	**< 10.7 mA**	**26.75 ppm**

Example 2: Accuracy of the IT 600-S at 60 A

With the same configuration, capable of measuring 600 A, the IT 600-S will only give 40 mA and 0.1 V at 60 A. The error is given in both mA and ppm of reading.

At 25 °C ambient

DC offset on secondary current at I_P = 0	< 4 mA	100 ppm
Non-linearity : <1 ppm of full scale	< 0.4 mA	10 ppm
Measuring ratio stability of < 2ppm of reading	< 0.08 mA	2ppm
Total error at 25°C	< 4.48 mA	112ppm

Drift with temperature (from 25 °C to 50 °C)

DC offset drift: 0.1 mA/K	2.5 mA	62.5 ppm
Measuring ratio stability of 0.3 ppm of reading/K	0.3 mA	7.5 ppm
Maximum global error at 50°C	**< 7.28 mA**	**182 ppm**

5 Air-core technologies

The performance of current and voltage transducers are often limited by the characteristics of the magnetic core material itself (e.g. remanence, hysteresis, non-linearity, losses, saturation) so the design of an air-core, or coreless, transducer is often considered.

In this case the following issues have to be taken into account:

- the measurement of DC current requires the use of a field sensing element; due to the absence of a field focused area (e.g. gap), a highly sensitive field sensing device must be considered (e.g. GMR, Hall cell) ideally in an array around the conductor.
- when available, a magnetic circuit can be used as a shield to external magnetic field disturbances (e.g. earth's field, external conductors); with air-core technologies the sensitivity to external disturbances must be managed in a different way, for example an array of field sensors instead of a single sensor or, when coils are considered, special design execution such as the Rogowski method of routing the return wire; the ability to accurately measure the desired current while also rejecting external fields is a significant challenge for air-core technologies.

Two efficient air-core transducer technologies are presented in this chapter, both related to AC measurements: the LEM~flex and PRiME™(1) technologies.

(1) patented and licensed to LEM by Suparule Ltd.

5.1 Basic working principle and sensitivity

LEM~flex and PRiME™ technologies both work on the same basic principle; a pick-up coil is magnetically coupled with the flux created by the current to be measured. A voltage is induced on the pick-up coil proportional to the derivative of flux and thus proportional to the derivative of the current to be measured. Because the derivative of DC is zero these technologies are only useful for the measurement of AC or pulsed currents.

The instantaneous voltage induced in the pick-up coil is typically:

$$E_{OUT}(t) = L_{12} \bullet di(t)/dt \quad [V]$$

where i(t) is the primary current [A] and L_{12} is the mutual inductance [H] between the primary and pick-up coil.

For a sinusoidal current, we have:

$$i(t) = I_{PEAK} \bullet \sin(2 \bullet \pi \bullet f \bullet t) \quad [A]$$

Hence:

$$E_{OUT}(t) = L_{12} \bullet I_{PEAK} \bullet 2 \bullet \pi \bullet f \bullet \cos(2 \bullet \pi \bullet f \bullet t)$$
$$= E_{PEAK} \bullet \cos(2 \bullet \pi \bullet f \bullet t) \quad [V]$$

As shown in this example, where a sinusoidal current i(t) creates a phase delayed (cosine) voltage $E_{OUT}(t)$, reproducing the waveform of the measured current requires the integration of the induced voltage. Therefore, the current transducer includes an integration function in the processing electronics.

In the LEM~flex and PRiME™ transducer datasheets the value of sensitivity (S_{12}) is provided, linking the amplitude of a sinusoidal current to the amplitude of the transducer output voltage at a specific frequency. The same sensitivity parameter can also be used to link the RMS values of a sine wave primary current and the corresponding sine wave output voltage, namely:

$E_{PEAK} = S_{12} \bullet f \bullet I_{PEAK}$ and $E_{RMS} = S_{12} \bullet f \bullet I_{RMS}$

To give an order of magnitude, the typical sensitivity is:

- LEM~flex probe $S_{12} = 2.0$ [µVs/A]
- PRiME™ $S_{12} = 1.0$ [µVs/A]

5.2 LEM~flex - the flexible AC current transducer

LEM~flex is a transducer based on the Rogowski coil principle (Fig. 38), providing a flexible air-core sensor that can be opened, allowing it to be installed on a primary conductor without interrupting the circuit.

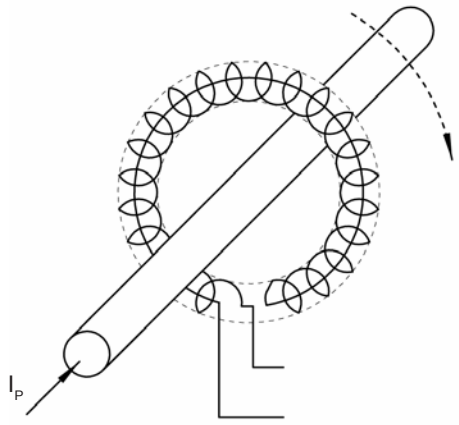


Figure 38: Rogowski AC current measurement

5.2.1 Construction and principle of operation

The key element of the LEM~flex transducer is the flexible measuring head (Figure 39), which is a coil uniformly wound around a flexible former of insulating material. The end of the coil wire is returned to the same end as the start by returning it co-axially through the coil former (Fig. 38). This construction technique minimizes the sensitivity to external field disturbances.

To make a measurement, it is not necessary to have the LEM~flex transducer formed as a circle or to have the primary conductor(s) centered within the perimeter. In practice, the flexible measuring head is wrapped around the conductor(s) carrying the current to be measured and the two ends are brought together and mechanically connected by a coupling latch (Fig. 40) to form a closed path.



Fig. 39 LEM-flex transducers



Fig. 40 Typical LEM-flex use, surrounding conductor(s) and latched.

The sensitivity (§ 5.1) of a LEM~flex transducer can be detailed as follows:

$S_{12} = 8 \bullet 10^{-7} \bullet \pi^2 \bullet N \bullet A$

where N is the density of the coil turns made around the flexible insulating cylinder [turns/m] and A is the cross-sectional area of the coil [m^2].

To design a Rogowski coil with a high sensitivity requires either a large number of turns per meter or a large cross-sectional area. Note that changing the length of a Rogowski coil does not affect the sensitivity.

5.2.2 Characteristics and features

The LEM~flex family of transducers has been designed to conveniently measure single and 3-phase AC currents, as well as pulsed DC currents. Standard ranges include 30/300/3 kA_{RMS} and 60/600/6 kA_{RMS}, but scaling is easily designed for other currents. Theoretically the size of the measuring head and/or measurement range is unlimited.

The standard LEM~flex current transducer provides a sensitivity of 50 or 100 mV/A at 50 Hz and at the output of the processing electronic. The analog output voltage, galvanically isolated from the measured current, is 0 to 3 V_{RMS}, or to be precise 4.25 V_{PEAK}.

Due to the flexibility of the measuring heads, it is possible to position them around one or more irregularly shaped or difficult to access conductors or busbars. The transducer can be quickly and easily installed as well as removed. Installation and measurement is performed without mechanical or electrical interruption of the current carrying conductor, while also ensuring galvanic isolation. LEM~flex transducers are also very lightweight.

In terms of bandwidth, the performance of the LEM~flex transducer is similar in concept to a band-pass circuit, exhibiting both high and low cut-off frequencies. As the integrator gain can be very high, shielding and appropriate filtering prior to the integrator must be used to minimize the influences from low frequency influences. For high frequency performance, the upper cut-off frequency is determined by the coil inductance and capacitance. It should also be noted that the integrator includes compensation circuits that limit the thermal drift. The typical bandwidth targeted by the LEM~flex portfolio is 10 to 100 kHz, with possible extension to 1 MHz.

As the LEM~flex measuring head is fundamentally an air-core coil, there is no magnetic hysteresis, no saturation phenomena or non-linearity, as is present with magnetic cores. The main factors that affect the accuracy of this technology are:

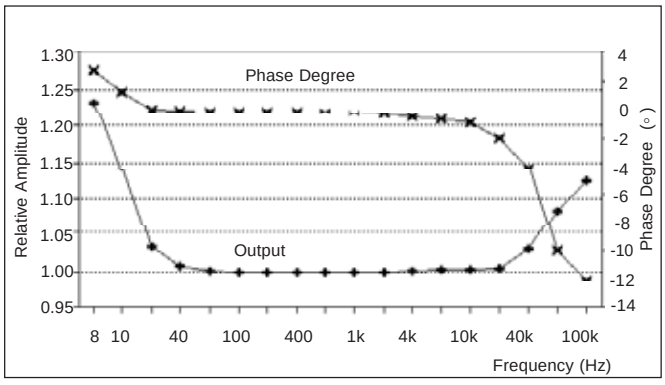


Figure 41: Integrator circuit & bandwidth

- the manufacturing tolerances of the wound coil (consistent turns/m and m^2)
- the fact this is a mechanically open structure, leading to a slight gap in the coil perimeter where the two ends are brought together
- the error introduced by the processing electronics, such as the integrator circuit phase angle error and relative amplitude as shown in Fig. 41.

These factors lead to slight errors based on the position of the current conductor inside the LEM~flex and sensitivity to fields from conductors just outside the perimeter of the LEM~flex. These errors are typically below 1 %, with a maximum of 2 %, and can be avoided entirely by proper positioning of the LEM~flex.

5.2.3 Typical applications

LEM~flex is a lightweight measuring head combined with remote electronics (distance between head and electronics can be as great as 4 meters, or 12 feet). This, along with all of the previous described attributes, lead to a device suitable for use in a wide range of applications.

- Measuring currents in busbar sets, in particular in induction heating equipment.
- Frequency converters, variable speed drives and generators.
- Control of power semiconductors.
- Analysis of the current distribution in mains networks.
- Analysis of harmonics, power measurements, measurement of the peak load in the mains, and in UPS.
- Switched mode power supplies.
- Low or medium voltage distribution installations.
- Power electronics installations.
- Sensing devices for watt meters and network analyzers installed by electric power distribution companies.
- Electrical maintenance, repair and machine installation and start-up applications.
- Connection to most measuring instruments including multimeters, oscilloscopes, recording devices, data loggers, etc.

5.2.4 Calculation of the measurement accuracy

An example of a total error calculation is given for the LEM~flex RR 3020, (see datasheet) having three selectionable working ranges of 30/300/3000 A nominal current. Considering a 280 A_{RMS} current giving a 2.8 V_{RMS} output signal (10 mV/A), what is the measurement accuracy at an ambient temperature of 50 °C? According to the datasheet, the error values are:

Linearity error	±0.2 % of reading	±0.56 A
Accuracy at 25 °C	±1 % of range	±3 A
Accuracy drift	±0.08 %/K • 25°C • 280	±5.6 A
Position error	±2.0 % of reading	±5.6 A
Worst-case error		**±14.76 A ⇔** ±5.3 % of reading

Care must be exercised in properly identifying errors based on reading and those based on range.

5.3 PRiME™ Transducers

PRiME™ has been developed to measure AC and pulsed DC currents with minimal effect from external sources, achieved by the application of a novel compensation technique. PRiME™ is an air-core technology based on planar magnetic sensors, constructed using no ferromagnetic material. It is similar to the LEM~flex technique, but uses discrete coils at regular intervals around a fixed perimeter rather than a continuous uniform coil. A specific coils arrangement gives the robustness to external field perturbations.

5.3.1 Construction and Principle of Operation

The transducer head comprises two parts, a number of sensor printed wiring boards (PWBs), and a base-PWB (Fig. 42). The sensor PWB consists of two separate coils constructed on a multi-layer PWB (Fig. 43). Several sensors are mounted onto the base-PWB, at right angles to it, and connected in series to form two concentric inner and outer loops (Fig. 44). A larger number of sensor PWBs provides higher accuracy, lower sensitivity to conductor position and improved external field rejection performance.

To make measurements, the current carrying conductor needs to be positioned within the aperture of the transducer head, within both loops (Fig. 42). This creates an AC magnetic flux, which is coupled into the sensors and induces a voltage proportional to the rate of change of the current (di/dt) in both the inner and outer loops (Fig. 44). As a result, a

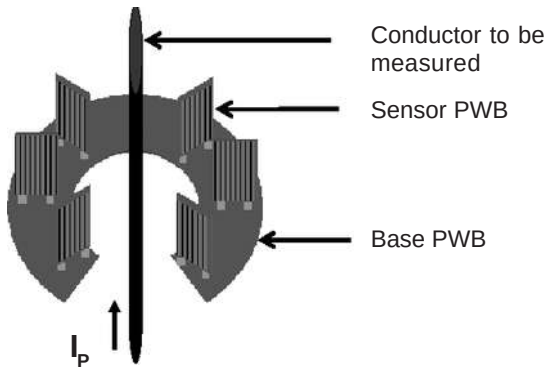


Figure 42: PRiME™ current transducer



Figure 43: PRiME™ sensor multi-layers printed wiring board

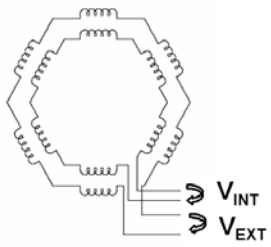


Figure 44: PRiME™ – two coils concentric loops

constant DC current will not produce a voltage and therefore cannot be measured. However, as with LEM~flex, it will respond to pulsed currents.

The output signal V_{TOTAL} (Fig. 45), used for the current measurement is:

$$V_{TOTAL} = V_{INNER} - V_{OUTER} / \lambda = V_{INNER} \bullet [1 - (V_{OUTER} / V_{INNER}) / \lambda]$$

For an external current source, the essence of the technology is that the ratio of the induced voltage in each loop of sensor PWBs (V_{OUTER} / V_{INNER}) is almost constant, irrespective of the magnitude or position of this external source. As a result, the external field effects are cancelled if the correct proportion of the voltage induced in the outer loop (V_{OUTER}) is substracted from that in the inner loop (V_{INNER}). Making $\lambda = V_{OUTER} / V_{INNER}$ will force $V_{TOTAL} = 0$ or, in other words, an external current source will not produce any signal at the output.

To measure the current from the conductor placed within the aperture, an optimized transducer design leads to a typical V_{OUTER} / V_{INNER} ratio of $\lambda / 2$, again irrespective of the conductor position. As a result, the usable signal for the measurement is close to $V_{TOTAL} = V_{INNER} / 2$, meaning that approximately half of the signal collected by the inner concentric chain of sensing PWB coils is used for the measurement.

In short, this novel arrangement provides one-half of the total possible signal for measurement while effectively canceling the unwanted influence of signals from external current sources.

As with the LEM~flex, the collected signal is proportional to the derivative of the current and it is necessary to integrate the voltage induced in the transducer head to obtain both amplitude and phase information for the current being measured. The integrator circuit (Fig. 45) is kept as close to the transducer head as possible to reduce stray inductive pickup that would give rise to errors.

Finally, the comments made previously (§ 5.1) regarding the instantaneous voltage collected by the coils of an air-core technology are again applicable.

5.3.2 Characteristics and Features

Since PRiME™ utilizes an air-core coil as the sensing element, there is no magnetic hysteresis, saturation, or non-linearity, as is present in a current transformer with a magnetic core.

There is no theoretical maximum limit to the measuring range, but the typical dynamic range is 1000:1, corresponding to the ratio of the maximum to minimum measurable current with a given transducer. The accuracy is typically specified as a percentage of reading, above 10 % of the nominal rated current, leading to a highly accurate solution when the current is only a fraction of the nominal current. The accuracy is generally better than 0.8 % of reading and the gain variation due to temperature is low, typically 0.01 %/K.

The output voltage is directly proportional to the measured current and provides accurate phase information. The level of sensitivity depends on the required measuring range and supply voltage.

The aperture sizes for existing transducers range from 20 mm to 160 mm in diameter, in both ring and split format. There is no theoretical limit to the size of the aperture. With split versions, installation and measurement can be performed without mechanical or electrical interruption of the current carrying conductor, while also ensuring galvanic isolation.

The bandwidth of PRiME™ has both a high frequency and a low frequency cut off. The high frequency limit is dependent on the resonant frequency of the sensors while the low frequency limit is a function of the integrator design. Products are designed for a given bandwidth, typically 5 to 100 kHz, but an upper limit in the MHz range appears to be feasible.

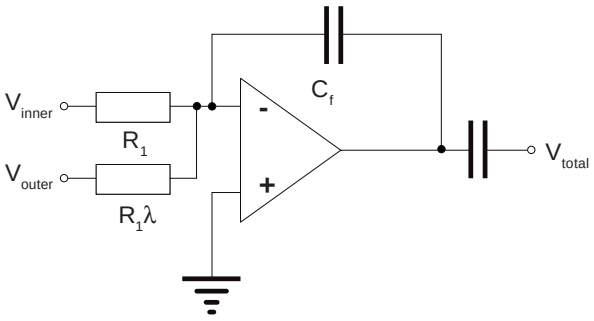


Figure 45: PRiME™ – processing of the coil signals

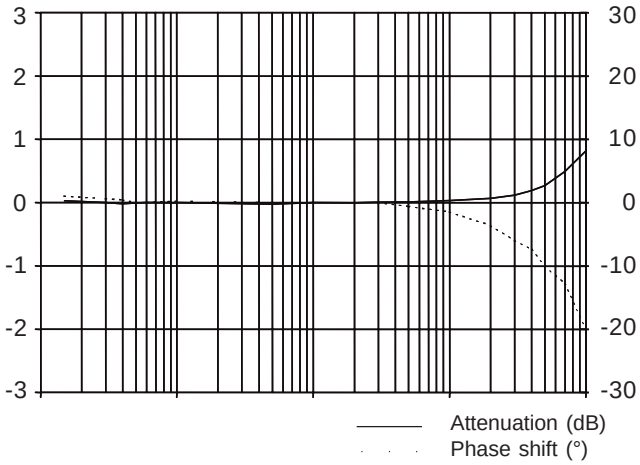


Figure 46: PRiME™ – typical bandwidth 5 to 100 kHz

5.3.3 Advantages and Limitations of PRiME™ Technology

- Capable of measuring AC and pulsed DC currents.
- Wide current measuring range, capable of withstanding high overload.
- Accuracy given in percent of reading; high accuracy over a wide measuring range.
- Large bandwidth, not including DC.
- Lightweight in comparison with current transformers or transducers.
- On-board electronics that can potentially be merged with the users electronics.
- Provides an isolated output signal (e.g. 4-20 mA, 0-10 V) usable with PLCs without conditioning.
- Requires a power supply, but has low current consumption requirements.

This makes them suitable for portable applications and power quality monitoring where weight and battery life are a concern. This performance also make them suitable replacements for current transformers.

6 Other types of voltage transducer technologies

Two additional voltage measurement technologies have been developed by LEM to achieve differentiated measurement performance compared to Hall (§ 3.4) or Fluxgate (§ 4.4.4) based voltage transducers. The first technology, OptiLEM, uses fiber optics for the transmission of the voltage measurement information, providing a high level of dielectric isolation. The second technology is the AV-type of voltage transducer based on electronic isolation circuitry that also provides galvanic isolation, but at the component level rather than using discrete fiber optics.

6.1 OptiLEM voltage transducers

The OptiLEM voltage transducer has been developed to provide an optimal solution for higher isolation voltages. The result is an interesting product containing numerous patented concepts.

The following key attributes are reached with the first voltage transducer model:

- isolated voltage measurements up to 12 kV_{RMS}
- 100 V to 6 kV measuring range
- overall accuracy better than 1.5 %
- bandwidth from DC to 12 kHz
- low stray capacitance between primary and secondary (less than 10 pF)
- low partial discharge extinction level of 5 kV with < 10 pC

The working principle of the OptiLEM voltage transducers is shown in Fig. 47. The primary voltage is directly applied to the transducer primary connections, ±U. An internal resistor divider network and differential amplifier measure the primary voltage signal. This output is converted to a serial data string and transmitted to the secondary side through an optical link. The same is done with the required data synchronization signals.

On the secondary side the data stream is converted back into an analog signal and converted into an output current for high noise immunity and easy scaling. A very critical function of the transducer is to provide a low voltage supply for the components on the primary side, requiring a very high level of voltage isolation and very low capacitive coupling from primary to secondary. A sine wave signal is used to minimize noise levels.



Figure 48: OptiLEM voltage transducer

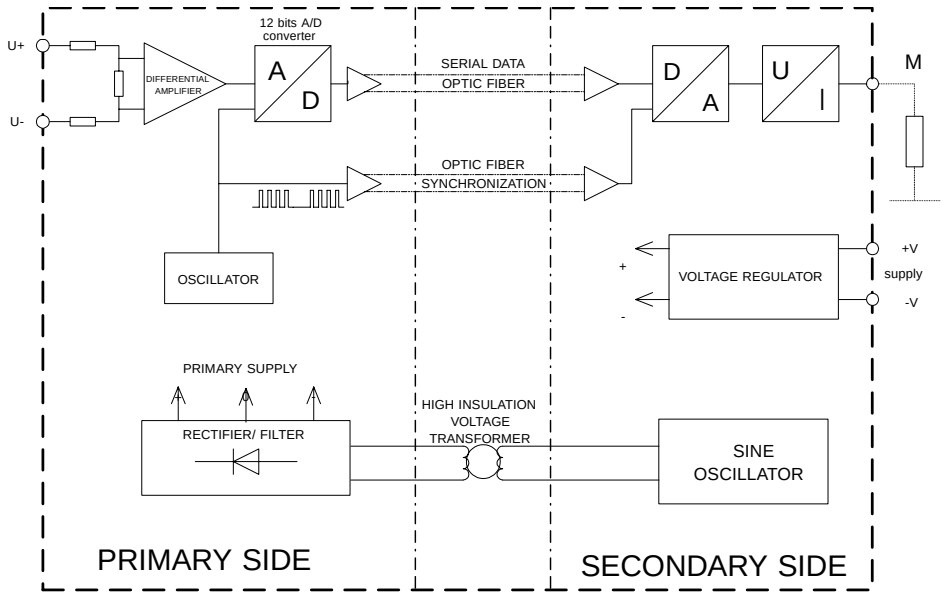


Figure 47: OptiLEM working principle

6.2 „AV type“ voltage transducers

6.2.1 Construction and Principle of Operation

The working principle of the AV-type voltage transducers is shown in Fig. 49. The primary voltage (V_{PN}) is applied directly to the transducer primary connections (±HT). An internal resistor network and amplifier perform the voltage measurement and drive an isolation amplifier. The latter ensures an accurate and isolated transfer of the measured information from the primary to the secondary side of the transducer, based on a capacitive isolation principle. Another important function of the transducer is to provide a low voltage supply for the components on the primary side, which requires the use of an efficient, well isolated, voltage transformer capable of withstanding the specified primary to secondary insulation levels.

At the output, the transmitted signal is recovered and then conditioned to supply a current at the transducer output that is an exact representation of the primary voltage. While the AV-type transducer is a new LEM product, it utilizes only well-known electronic components and techniques to ensure quality and reliability.

6.2.2 Characteristics and Features

The AV-type is a galvanically isolated voltage transducer made for measurements from 50 V to 1.5 kV_{RMS}. The peak voltage measurement capability is 150 % of the nominal voltage value. Any kind of signal can be measured: DC, AC, or complex waveforms. The output current is always a true image of the primary voltage.

The measurement bandwidth ranges from DC to 13 kHz. The delay time is less than 13 µs while the response time is less than 33 µs. Compared to magnetically isolated voltage transducers, the frequency bandwidth is not linked to the model chosen, as there is no appreciable primary inductance to create an L / R rolloff.

The linearity errors are within 0.1 % while the overall accuracy is 1.7 % of V_{PN} between –40 and 85 °C.

The main advantage of the AV technology is the small size and lightweight, with a common compact design for each model from 50 V to 1.5 k V_{RMS} nominal. Compared to Hall based voltage transducers, the large heat sink often used for power dissipation of the integrated primary resistors is not needed. This is a significant space and weight reduction. As a comparison, the AV 100 family has approximately one-half the volume ($3 \cdot 10^{-4} m^3$) of the LV 100 family. The limitations are a lower accuracy and limited insulation capability compared to some of the other available voltage transducers.

The AV 100 family delivers an output current of 50 mA at V_{PN}.

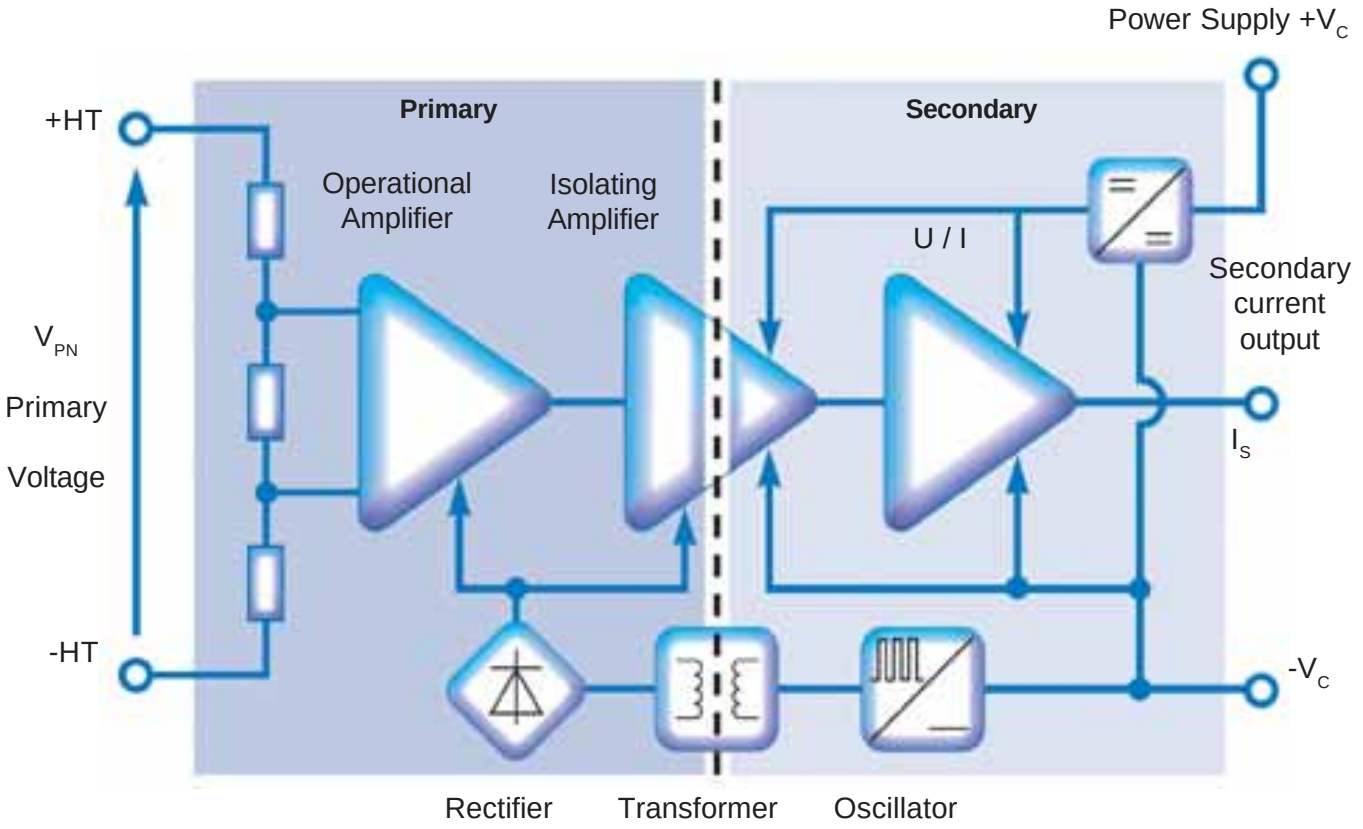


Figure 49: AV type voltage transducers

6.2.3 Typical applications

Presently, the main market for the AV 100 is in traction inverters, but they can also be used in or adapted for any industrial application.

- Auxiliary and main converters (input voltage, DC link, output phase voltages).
- Chopper and power factor correction circuits.
- Battery chargers.
- Sub-Stations and others.

6.2.4 Calculations & Properties

Calculation of the measuring resistor RM

The AV 100 family provides a current output. This current can be transformed into a voltage with the addition of a measuring resistor, R_M, at the output which cannot exceed a defined R_{Mmax} value, based on the available voltage at the transducer supply and the maximum voltage measured. For the AV 100 family, R_{Mmax} can be easily calculated using the following formula:

R_{Mmax} = $((V_{Cmin} - 5.1) \bullet V_{PN} / (V_{Pmax} \bullet I_{SN}) - 31) \bullet 0.9$ [Ω]

With:

V_{Cmin} = Minimum value of the secondary power supply [V]

5.1 = Internal voltage drop of the electronics [V]

V_{PN} = Nominal measurable primary voltage [V]

V_{Pmax} = Maximum measurable primary voltage [V]

I_{SN} = Secondary output current at V_{PN} [A]

31 = Secondary internal resistance [Ω]

0.9 = Safety factor [-]

The R_{Mmax} values indicated in the datasheets are the values calculated using V_{Pmax}.

Unipolar Power Supply

For unipolar voltage measurements the AV 100 family can operate from a unipolar secondary supply. A positive supply allows positive voltage measurements while a negative supply allows negative voltage measurements.

Positive unipolar power supply

In this case, a zener diode must be inserted as shown in Figure 50 and the zener voltage, V_Z, must be greater than 2.0 V. The maximum measuring resistance becomes:
$R_{M\,max} = [(V_{Cmin} - 5.1 - V_Z) \bullet V_{PN} / (V_{Pmax} \bullet I_{SN}) - 31] \bullet 0.9$

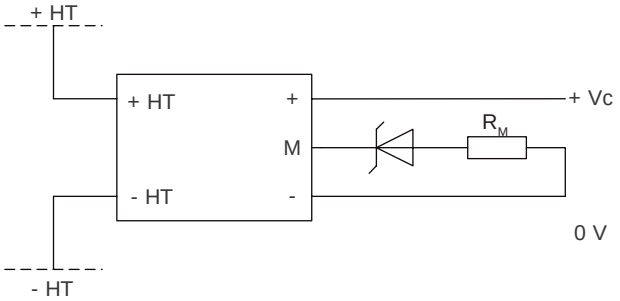


Figure 50: Electric connection – AV 100 with positive unipolar power supply

Negative unipolar power supply

In this case, the zener diode must be inserted as shown in Figure 51 and the zener voltage, V_Z, must be greater than 5.1 volts. The maximum measuring resistance becomes:
$R_{Mmax} = [(abs(V_{Cmin}) - 2.0 - V_Z) \bullet V_{PN} / (V_{Pmax} \bullet I_{SN}) - 31] \bullet 0.9$
with abs (V_{Cmin}) corresponding to the absolute value of the V_{Cmin} voltage.

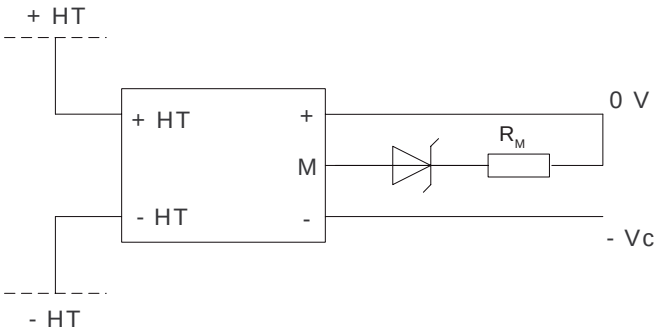


Figure 51: Electric connection – AV 100 with negative unipolar power supply

7 Current probes

A comprehensive range of LEM clamp-on current probes (Figure 52) allows current measurements from 5mA to 6kA. The technologies used for the probes have been presented before, including Hall effect, Fluxgate and air-core technologies. Probe performance depends on the selected sensing technology with bandwidths from DC up to 50MHz and accuracies as low as 0.1% - 1%.



Figure 52: Clamp-on current probes

Compared to current transducers, additional issues need to be considered when specifying a probe, linked to the way an end-user handles a probe. For example, the effect of the position of the conductors in the head, the manner in which the jaw opens, the need for the head to fit into tight areas, and safety concerns, such as „tactile barrier“ (indicating a safe working distance from the operator’s hand to the live conductor) and a reinforced or double-isolated output cable with safety connectors.

In term of applications, clamp-on current probes open many opportunities: in maintenance, repair-shops, and for the installation and commissioning of industrial machines and equipment. Applications include automobile diagnostics in the factory and in garages, electroplating plants, telecommunication and computer equipment, drives controlled by frequency inverters, industrial controllers and electrical vehicles. In Hi-Fi amplifiers, the different loudspeaker currents can be easily measured. Earth-leakage measurements in single or 3-phase AC networks are also possible, by inserting two or three conductors in a single probe head. Finally, current probes are also frequently used in process control applications, for measuring the status of 4 to 20mA current loops.

8 Miscellaneous

Here are additional concerns when using the types of measurement devices described in this document.

8.1 Power supply polarity inversion

A LEM transducer may be damaged by an inversion of the power supply voltage or connection of supply voltages to the output or common pins. If this is a concern, LEM advises the user to insert a diode on each power supply line, both positive and negative, or to look for a specific LEM transducer that incorporates these protection diodes.

8.2 Capacitive dv/dt noise

Any electrical component with galvanic isolation has capacitive coupling between the isolated potentials. Applications with fast switching speeds, and consequently fast voltage changes (dv/dt), across this capacitance experience some coupling of the primary transient to the secondary side creating undesirable interferences.
For example, a voltage change of 10 kV/µs in combination with a 10 pF coupling capacitance generates a parasitic current of i = C • dv/dt = 100mA. This represents an error of two times the nominal output current for a transducer with a 50 mA nominal output.

This issue typically occurs with power converters where a power component, such as a MOSFET (Metal Oxide Semiconductor Field Effect Transistor) or IGBT (Insulated Gate Bipolar Transistor), switch the voltage at frequencies in the 10 kHz to 1 MHz range, generating dv/dt values in the 5 to 50 kV/µs range.

Figure 53 is an example of a primary dv/dt and the resulting output noise:

- the time scale is 200 ns/div;
- CH1 is the primary voltage of 250 V/div, a 1 kV excursion creating a 6 kV/µs transient (800 V in 133 ns);
- CH2 is the output of an LAS 50-TP representing a primary current of 16 A/div;
- CH3 is the output of an LAH 50-P representing a primary current of 4 A/div.

For these two transducers, the settling time is close to 800 ns and the peak disturbance is 50% and 7% of the nominal current, for the LAS 50-TP and LAH 50-P respectively.

dv/dt disturbances can be minimized at two different levels:

- at the transducer level the design is optimized to limit the primary-secondary capacitive coupling and to minimize the settling time after a dv/dt disturbance
- at the user level care must be taken in the application of the transducer into the system

For the latter, good EMI control practices must be observed.

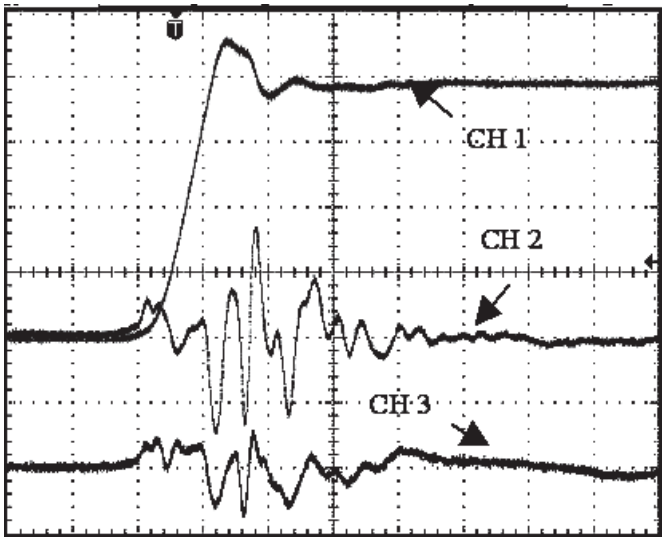


Figure 53: dv/dt disturbance and transducer signal

The following points can be highlighted:

- when long cables are used for the secondary connections of the transducer, it is advisable to use a shielded cable connecting the shield to a driven common at the measurement end of the cable
- when possible, it is recommended to desynchronize the measurement from the dv/dt occurrence, never performing a measurement during the dv/dt disturbance and settling time
- it is possible to attenuate the dv/dt disturbances using a low pass filter; while this is detrimental to the transducer bandwidth, in many cases it is a reasonable and desirable solution
- during printed wiring board (PWB) layout it is important to keep secondary traces and primary traces, wires, or bus bars separated and avoid long parallel runs to minimize capacitive coupling; the best scenario has the secondary traces running perpendicular to the primary providing immediate separation; it is also advantageous to include a screening trace or plane, connected to a star ground point, between the primary and secondary to shunt the disturbance to the screen rather than the secondary

8.3 Magnetic disturbances

Because the majority of transducers use magnetic coupling, it is important to be concerned with external magnetic fields likely to disturb a measurement. Potential sources include transformers, inductors, wires, busbars, as well as other transducers. Typical power electronics equipment has multiple conductors, oftentimes in close proximity to each other. A transducer may be disturbed by the magnetic fields from adjacent conductors, with the disturbance being the largest with short distances and high currents. A key parameter in this case is the relative position between the field sensing element (e.g. Hall or Fluxgate cell) and the conductor creating the disturbance.

To minimize the disturbance please try:

- to increase the distance between the transducer and the external conductor as much as possible
- to modify the transducer and/or conductor layout to optimize the conductor position with regard to the field sensing element of the transducer
- to twist, layer or parallel, if possible, the source and return conductors to minimize the external field
- to divide the external conductors into equal parts and place them symmetrically on each side of the transducer, canceling or minimizing the external magnetic influence
- to magnetically shield the transducer

Typically, tests are performed by LEM to record external field influences. The results of these tests and further advise are available on request.

8.4 Typical misapplication of a transducer parameter

The incorrect use of a transducer may impact the performance or reliability of the design. Here are a few classical cases of misapplication, although an analysis at a specific operating condition may lead to these results.

Measurement resistance

- $R_M < R_{Mmin}$ Risk of overheating (current output) or measurement range reduction (voltage output)
- $R_M > R_{Mmax}$ Measurement range reduction and electronic saturation (current output)

Current

- $I_N > I_P$ Magnetic saturation and permanent offset
- $I_N < I_{PN}$ Reduced accuracy

Secondary supply voltage

- $V_C < V_{Cmin}$ Reduced accuracy and/or limited output signal range
- $V_C > V_{Cmax}$ Risk of overheating or permanent damage

Temperature range

- Excessive measurement error
- Mechanical damage to components

8.5 LEM ASIC based transducers

One of LEM's answers to the market need for size and cost reduction, along with accuracy and reliability improvement, has been the move toward Application Specific Integrated Circuits (ASICs) which replace all the discrete circuitry in a transducer with an „all in one" chip solution.

While the impact of an ASIC in terms of size reduction is obvious, the challenge is to make the best use of ASIC capabilities to improve accuracy. LEM uses state-of-the-art techniques to minimize offset and other parameters affecting the transducer accuracy. The transducer environment is also taken into account, in particular the presence of very high di/dt and dv/dt, which could impact measurement quality if not appropriately considered.

LEM today employs ASIC technology in a number of products including Hall effect based open loop, closed loop and Eta transducers as well as various Fluxgate technologies. This puts LEM in the position to produce a wide range of ASIC based transducers and to better address customer specific requirements, providing a continuous improvement path into the future.

9 LEM – the leader in electrical parameter measurement

With over 30 years of research, design, development, and production, LEM is your source for electrical parameter measurement components. LEM commitment to quality and its customers has made it the leader in its market for over 20 years in a row. We work towards continuous improvement of our products and processes.

Let us show you our wide array of products, developed specifically for customers like you. If you can't find the product you are looking for, we have R&D resources in every area of the world to address your needs.

Please take this opportunity to contact the LEM regional office nearest you to learn more about how LEM can help you solve your problems and improve your products, making you more competitive.

It is the objective of all LEM employees to adhere to the **LEM Quality Policy:**
The key to success for our company is the customer's satisfaction regarding respect for their demands as well as their expectations.

In a continuous effort to fulfill the **LEM Mission Statement:**
To Help optimize the Utilization of World Energy and Natural Resources, LEM contributes to the Mastery of Electricity by providing innovative and cost effective Components, Instruments, Systems and Services.

10 Glossary A-Z

Ampere-turns
The ability of a coil to generate a magnetic field. This is given by the product of the coil current and the number of coil turns.

Bandwidth, small signal
The range of low level sine-wave frequencies that can be reproduced with a specified reduction in signal amplitude, typically -1 or -3dB. Typically, the bandwidth of most transducers given in the data sheet are assuming a current derating with frequency increase.

Bandwidth, power
The range of nominal amplitude sine-wave frequencies that can be reproduced, typically limited by internal heating.

Closed loop current transducer
A current transducer in which the magnetic field created by the primary (measured) current is cancelled by a magnetic field with an opposite direction, created by a secondary (output) current. The secondary current is a true image of the primary current scaled based on the primary to secondary turns ratio.(§3.2; §3.5)

C-type transducer (§ 4.4)
Highly accurate Fluxgate transducers operating on the closed loop principle. Very good frequency behavior. Sensitivity to temperature changes is minimized. C-type transducer portfolio includes CT (current: § 4.4.2), CD (differential: § 4.4.3) and CV (voltage: § 4.4.4) transducers.

Current transformer
A transformer used to measure AC current while also providing isolation. Current is scaled based on primary to secondary turns ratio.

Degauss cycle
Applying a decaying AC field to return a magnetic material to a zero remanence (B_R) condition (§ 3.1.6.1). See also *Demagnetization, Magnetic offset* and *Remanence*.

Demagnetization
Returning a magnetic material to a zero remanence (B_R) condition (§ 3.1.6.1). See also *Degauss cycle, Magnetic offset and Remanence.*

di/dt following
The ability of a transducer to accurately reproduce a step in primary current with a controlled rate of change (di/dt).

Differential current transducer
A transducer used to measure the difference between two opposing currents. These are often used to measure leakage current.

EMC
Electro-Magnetic Compatibility, implying conformance with defined standards.

Eta
Eta technology is a combination of open loop and current transformer technologies. In general, Eta transducers have open loop performance at low frequencies and current transformer performance at high frequencies (§ 3.3).

Fluxgate
Fluxgate technology implies driving a magnetic core material through its complete B-H loop. The field from a primary current causes a shift in this behavior that is measurable. See also *C-type, IT-type, Low frequency Fluxgate, Standard Fluxgate and § 4.*

Global error
The worst-case error considering all possible factors. This is not necessarily the addition of all error factors as some factors are multiplicative while others cannot be simultaneously in their worst-case conditions. This is an absolute limit used in worst-case design scenarios. In practice errors should be considered statistically, with the probability and distribution of deviations leading to a much smaller actual total error.

Hall effect / Hall generator
The Hall effect is the force applied to charge carriers in a magnetic field causing an imbalance in voltage.
The device referred as Hall generators or Hall cells are designed to take advantage of the Hall effect by providing a usable output for measurement of magnetic fields.

Hysteresis
The hystereses curve of a magnetic material described his overall magnetic performances, advantages and drawbacks included (Figure 4).
Because a Hall generator measures the magnetic field, transducer Hysteresis has typically an impact on the transducer accuracy (magnetic offset), gain (possible saturation effects in open loop), behavior after a current overload (eventual need of demagnetization), heating at high frequency (hysteresis losses), influence of external magnetic field (local saturation).

IT-type transducer
One of the most accurate transducer technologies available, based on a closed loop Fluxgate principle (§ 4.5). See also *C-type, Fluxgate, Low frequency Fluxgate, Standard Fluxgate and § 4.*

Low-frequency Fluxgate
A low cost product from the Fluxgate transducer portfolio with a limited bandwidth. See also *C-type, IT-type, Fluxgate, Standard Fluxgate and § 4.*

Magnetic offset
The output offset resulting from the remanence of the magnetic material being used. See also *Degauss cycle, Demagnetization and Remanence.*

Measurement resistor
When a device provides an output current a resistor is typically used to convert the output current into a voltage for measurement. This „measurement resistor“ is also commonly referred to as a „burden“ or „load“ resistor.

Measurement voltage
The voltage created across a „measurement resistor“ is referred to as the „measurement voltage“.

Nominal (current or voltage)
The maximum rated continuous RMS value of input signal. Sometimes called „continuous“ or „rated“ current or voltage.

Offset drift
The drift of offset current or voltage versus temperature at the transducer output, specified in mA/K or mV/K.

Offset error / voltage
Output signal of the transducer when subject to no primary excitation (e.g. $I_P = 0$). It is mostly due to electrical parameters but also depends on magnetic influences.

Open loop current transducers (§ 3.1)
Current transducers where the output signal is an image of the magnetic field created by the primary current to be measured. It generally uses a magnetic circuit which focuses the field on a field sensing element, e.g. made of a Hall generator. The output signal is a direct amplification of the Hall signal, giving a true image of the measured current if the system is designed for a linear behavior.

Primary
The input, driving or measured side of a circuit and the components related to that side of the circuit. Galvanic isolation is provided between the primary and the secondary side. For example, the primary winding carries the primary current. See also *Secondary*.

PWB (printed wiring board)
Often referred to as a „PCB" or printed circuit, or PWB depending on the geographic location.

Ratiometric
The output (offset and/or transfer function) is directly proportional to the supply or a reference voltage. See also Offset and Transfer function.

Reaction time
The delay between the measured signal reaching 10% of final value and the output signal reaching 10% of final value. See also *Response time*, and *Rise time* (Figure 8).

Recovery time
The time required to 'recover' and resume normal operation after an event that interrupts operation, such as saturation. Not to be confused with *Settling time.*

Remanence
After traversing a hysteresis loop the output will not return to zero when the input is at zero. The amount remaining at the output is the remanence and, in essence, creates an additional output offset. See also *Magnetic offset and Hysteresis.*
It is minimized by design in LEM transducers and is often resulting from a non-expected primary current overload. The magnetic offset defines the offset on the transducer output signal, positive or negative depending on the direction of the current overload.

Response time
The time difference between the driving signal reaching 90% of its final value and the measured signal reaching 90% of its final value. This is a combination of delay time, driving signal rise time, and measured signal rise time. See also *Reaction time and Rise time* (Figure 8).

Rise time
The time difference between a signal reaching 10% and 90% of its final value. See also *Delay time, Reaction time, and Response time difference* (Figure 8).

Saturable inductor
An inductor designed to operate into its saturation region. The inductance value varies from a high value at low currents (based on the permeability of the core) to a low value at high currents (the core permeability becomes unity when saturated). (Figure 25).

Secondary
The output, driven or measurement side of an isolated circuit and the components related to that side of the circuit. Isolation is provided between primary and secondary side components. For example, the secondary supply provides secondary compensation current. See also *Primary*.

Settling time
The amount of time required to 'settle' to within a defined tolerance after a disturbance, such as dv/dt. Not to be confused with **Recovery time.**

Standard Fluxgate
A LEM definition, Standard Fluxgate transducers operate on the closed loop principle and provide the most „standard" performance in term of accuracy or bandwidth. Non-standard Fluxgate transducers include the more efficient IT or C-types, or the less dynamic „low frequency" Fluxgates. See also *C-type, IT-type, Fluxgate, Low frequency Fluxgate and § 4.*

Transfer function
The ratio of output signal to input signal. For example, if a 100A input creates a 1V output the transfer function is 1V / 100A or 1mV / 100mA. The output of a ratiometric device is dependent on the supply voltage, so V_S will be part of the transfer function.

Turns ratio
The ratio of primary turns to secondary turns in a transformer. With closed loop current transducers, the turns ratio typically assumes a single primary turn. For example, 1:1000 implies 1000 secondary turns and a secondary current of 1mA with a single primary turn carrying 1A.

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