Measuring Currents with Railway Class Accuracy

On-board energy measuring constitutes the system for measurement of electric energy that the traction unit takes from or returns to (during regenerative braking) the overhead contact line. Greater precision in this energy measurement allows operators to better understand their real consumption, and will enable energy management to reduce overall energy consumption, as well as monitoring total energy supplied from the external electric traction system. A new transducer for these applications will be introduced in the following.
Michel Ghilardi - R&D Project Manager, Marc Schaerrer - Development Engineer, Stéphane Rollier - Product & MarCom Manager, LEM SA, Geneva, Switzerland

In common with many other areas of business across Europe, changes in the regulatory environment are leading to more demanding standards for Railway Energy Billing. European rail-freight markets are being liberalized with privatization of the rail networks, and the separation of operating entities in terms of infrastructure and operators. Since the beginning of January 2010 passenger rail markets have been opened to cross-border competition.

Liberalization of European railway markets leads to a number of consequences, including the appearance of new competitors operating in each national market; increasing cross-border traffic and a greater number of services that operate through multiple countries; a new context of intra- and inter-modal competition; and rising demands in terms of cost transparency. This last point means that exact electricity consumption from supplies generated by every administration over which a service operates must be accurately invoiced.

Traction Units consume energy in each of the different countries they pass through; Railway Undertakings (RUs) have contractual relationships with each respective Infrastructure Manager (IM), and in order to be able to transparently bill the energy consumption, the RU must gather information regarding each border crossing, as the IM has to invoice the RU for the supply of energy. Greater precision in the energy measurement allows operators to better understand their real consumption, and will enable energy management to reduce overall energy consumption, as well as monitoring total energy supplied from the external electric traction system. The Energy Measurement Function (EMF) includes both voltage and current measurements; the relevant standard is the new EN 50463, which defines characteristics of transducers for current and voltage DC or AC measurement, as well as the energy measurement function itself.

New approach for current and voltage measurements

To comply with the required performance levels set out in the standard, LEM proposes different train solutions for current and voltage measurements. For DC voltage measurements of Class 0.5R for a single network voltage, the DV family of transducers is ideal. To carry out DC current measurement of Class 1R, a transducer from the DI family, used with a shunt of Class 0.2, will provide full compliance. For DC current measurements at the more demanding Class 0.5R, a unit from the new ITC family is the optimum solution (see Figure 1).

Measurement devices for service in the rail traction environment share a number of common features. They must measure

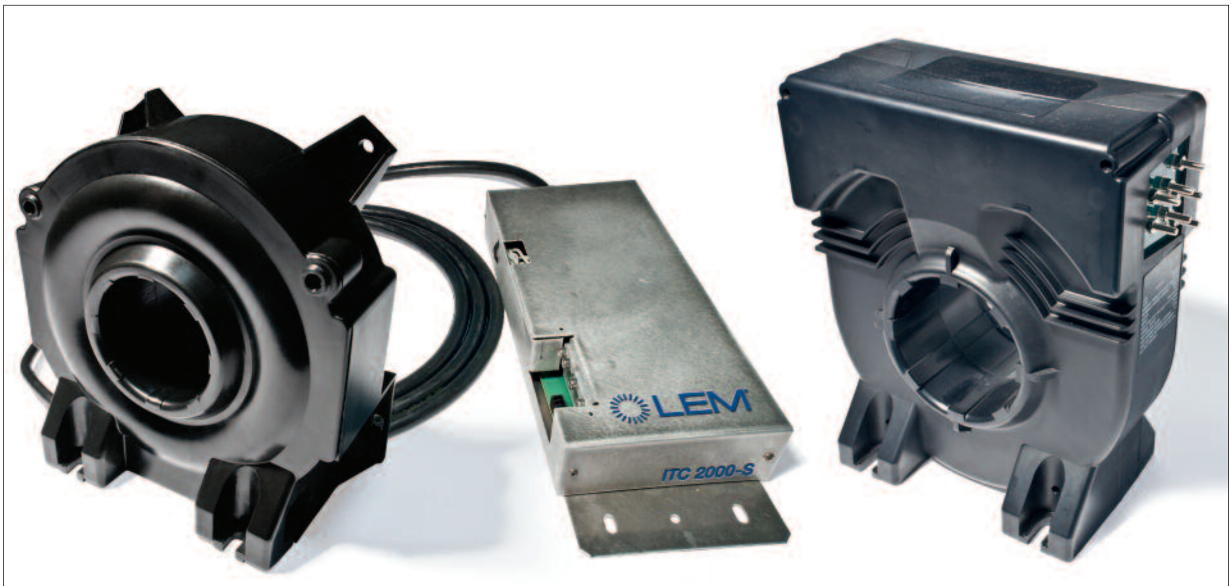


Figure 1: The ITC current transducer series; the variant with remote signal processing module (left) facilitates mounting in traction-unit roof voids

Percentage error limits — DC current transducers						
Accuracy class	± Maximum percentage current (ratio) error at percentage of rated primary current (I_{PN}) shown below, DC transducers Temperature condition: 23°C+/-2°C					
	1 %	5 %	10 %	20 %	100 %	120 %
0,2 R	2	0,4	0,2	0,2	0,2	0,2
0,5 R	5	1	0,5	0,5	0,5	0,5
0,75 R	7,5	1,5	0,75	0,75	0,75	0,75
1 R	10	2	1	1	1	1

Table 1: Permissible error limits for DC current transducers according to EN 50463

all power waveforms encountered; DC, AC, pulsed and complex. They must be of compact size for on-board deployment. They must exhibit low internal power consumption; excellent accuracy to meet the billing standards; low drift over temperature; high insulation and partial discharge levels in order to guarantee safety; and good levels of immunity against external electric, magnetic and electromagnetic fields for EMC protection. They are required to show low levels of emission; compliance to fire and smoke standards (these are mandatory in railway applications); and a range of features specific to the measurement function including immunity to common mode voltage effects, fast response time, large bandwidth, and low noise.

Desirable attributes include a modular construction approach allowing easy adaptation, with a range of connection options for the secondary side such as connectors, shielded cables, or terminals (threaded studs, M4, M5, UNC etc.). Reliability and lifetime must be designed-in and are demonstrated by an extensive series of environmental operating and ageing tests.

It is in the area of overall accuracy of the EMF (Energy Measurement Function) that EN 50463 imposes the greatest uplift in operating requirements. The EMF must have a total accuracy of 1.5% for active energy for AC, 3% for reactive energy for AC and 2% for DC, at +25°C. The accuracies of the current transducer, the voltage transducer and the Energy Meter are measured separately and combined for the overall accuracy using the following equation:

$$\varepsilon_{EMF} = \sqrt{\varepsilon_{VMF}^2 + \varepsilon_{CMF}^2 + \varepsilon_{ECF}^2}$$

where ε_{EMF} overall accuracy of EMF (system of current sensor, voltage sensor and energy meter); ε_{VMF} class accuracy of Voltage Measurement Function (voltage transducer); ε_{CMF} class accuracy of Current Measurement Function (current transducer); ε_{ECF} class accuracy of Energy Calculation Function (energy meter).

Among others, EN 50463 sets out the error limits for measurement of DC current shown in Table 1. For AC current transducers, the maximum permissible error at 1% of the rated primary current IPN is just 5% (class 1 R)! This is a significant challenge in terms of the linearity of the measurement system at the extremes of its range. Table 2 shows the permissible level of error with changes in ambient temperature, for specified ranges of DC current relative to the full-scale rated primary current. Once again, these are exacting requirements for a measurement system.

If each of the different measurement devices - voltage transducer, current transducer and energy meter - has a Class accuracy of only 1R, the overall accuracy of the EMF is 1.732%, as calculated using the square root formula above. This is sufficient to meet the specified limits for a DC system (2.0% required). However, the required overall accuracy has to be valid over the whole re-verification time - this will be a period of several years and has yet to be finally defined. To ensure that an operating margin will be maintained over time, it is therefore advisable to choose lower class accuracies than the nominal values allowed in the standard. For multi-system trains, it is permissible to use a single voltage or current sensor for two or more voltage systems. Then the following applies:

1. The voltage sensor has to fulfil the accuracy requirements for each voltage system.
2. The current sensor has to fulfil the accuracy requirements for the highest rated current. For the lower rated currents, reduced accuracy requirements are specified.
3. For the energy meter the same constraints apply as for the current sensor.

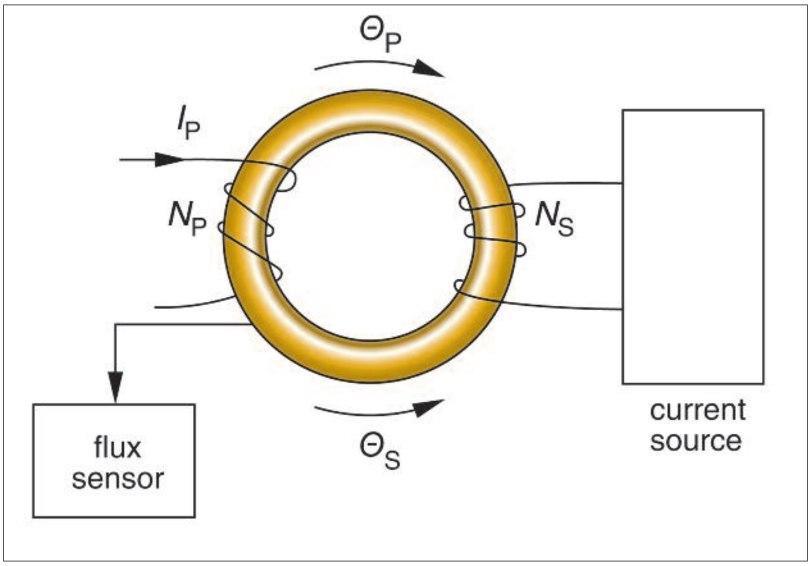
Meeting EN 50463 for current measurements

o address this developing rail-traction market and the problem of current measurement in both traction and industry applications, LEM has conceived and

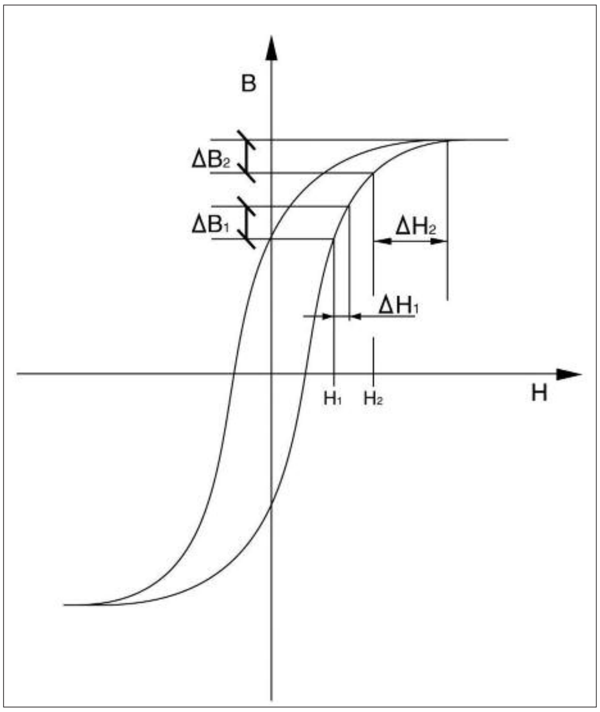
Value of current	System type	Transducer temperature coefficient [%/K]	
		Ambient temperature variation (main range) -10°C to +60°C*	Ambient temperature variation (extended range) -40°C to -10°C* and +60°C to +75°C*
$0.1\ I_{PN} \leq I \leq 1.2\ I_{PN}$	DC	0.01	0.02
$0.05\ I_{PN} \leq I \leq 0.1\ I_{PN}$	DC	0.02	0.04
$0.01\ I_{PN} \leq I \leq 0.05\ I_{PN}$	DC	0.1	0.2

* Note: reference temperature is at ±2%

Table 2: Maximum permitted deviations of DC current measurement with temperature variation



ABOVE Figure 2: **Principle of the closed loop fluxgate current transducer**



LEFT Figure 3: **Hysteresis cycle of the magnetic cores; at different points on the curve, different increments of magnetic field strength H are required to yield the same change in flux density B**

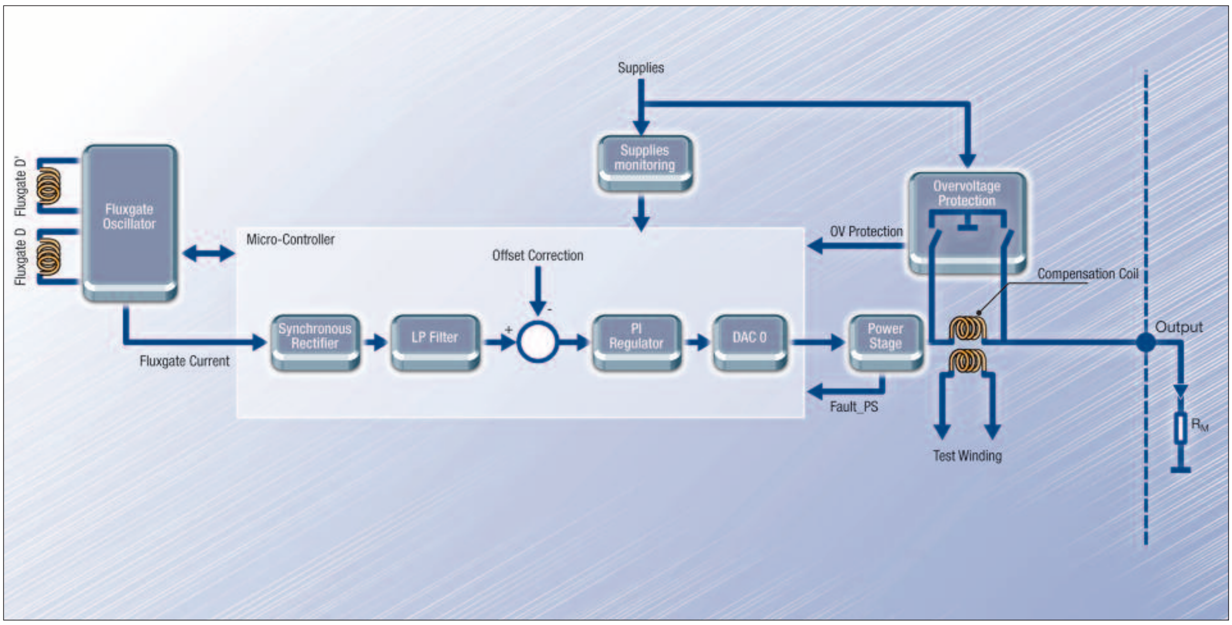
BELOW Figure 4: **Signal processing path of the ITC series transducers, showing all the major functional blocks**

designed a new series of current transducers. Three models measure a current (DC or AC) up to 4000 A_{RMS} (6000 A peak) in vehicles that are supplied with energy from networks up to 3000 V. The transducers provide extra margin on the Class 1R ("R" indicating rail-traction) specification by achieving Class 0.5R accuracy.

Initial design studies confirmed that to reach this level of performance a transducer based on closed-loop fluxgate technology would be needed. The basic principle of the closed loop fluxgate measurement technique is shown in Figure 2. The primary (load) current I_P flows in a conductor that passes through the loop or core, giving rise to a current linkage Θ_P. For accurate measurement of DC currents, the method consists of compensating (balancing or nulling) Θ_P by an opposing current linkage Θ_S created by a current I_S.

To obtain an accurate measurement, it is necessary to have a highly accurate device to measure the condition $\Theta = 0$ precisely. Fluxgate detectors rely on the non-linear behavior of magnetic materials between the magnetic field strength H and the flux density B,as per Figure 3. The fluxgate detector employs a winding around the toroidal core in which an oscillating waveform continuously drives the core round its B-H hysteresis loop.

When applying this square wave voltage to a saturable inductor until its magnetic core starts to saturate, a current is created. Without primary current, $I_P=0$, this current is symmetric. When a DC current flows through the aperture of the core, the curve of the hysteresis cycle is then shifted, causing asymmetry of the current produced by the square wave voltage. This current is then measured using an



accurate resistor and the asymmetry is used to adjust the secondary current in the compensation winding so that it exactly compensates the primary current (see Figure 4).

To this basic principle, LEM adds numerous refinements to yield a transducer that exceeds the demands of EN 50463 by a generous margin. For example, there is in fact not one fluxgate detector but two, to7 cancel out certain error terms in the measurement; a sophisticated microcontroller manages the measurement process, including a staged recovery from transient overload conditions supported up to 100 kA for 100 ms; measurement processing takes place in the digital domain, while a digital-to-analogue converter generates an analogue output signal that gives the reference to the PWM generator for the output stage; and a patented Class-D output amplifier design both reduces the power dissipation of the transducer but also decreases and balances the load currents from its power supply lines.

The ITC series meets the rail-traction industry sector's needs by reaching the Class accuracy 0.5R defined in the prEN 50463 standard for on-board energy monitoring operating over the temperature range -40 to +85°C. They are equally applicable to any situation in which kA-level current measurement accuracy of 0.5 % from 5 % to 120 % of the nominal current is required.

Standards governing rail traction measurements

A number of standards apply to any equipment used for rail traction applications. The EN 50155 standard that relates to "Electronic Equipment used on Rolling stock" in railway applications is the base standard of reference for electrical, environmental and mechanical parameters: it guarantees the overall performances of products in railway environments.

The new EN 50463 is specific to the energy measurement demand. It is worth noting that the transducers mentioned previously (DV, DI and ITC series) may be used for bi-voltage applications (that is, when switching from a network to another one when crossing from one supply domain to another) with only slightly derated accuracy. These transducers have a very low sensitivity to external magnetic DC or AC fields.

EMC (Electro-Magnetic Compatibility) is governed by EN 50121-3-2 standard for emission and susceptibility (the railway EMC standard) in its latest update, with EMC constraints higher than those of the typical industrial application standards. The DV, DI and ITC devices fully meet the higher specifications.

For Insulation and Safety, EN 50124-1 ("Basic requirements - clearances and creepage distances for all electrical and electronic equipment") has been used as a reference to design the creepage and clearance distances for the DV, DI, ITC products.

Similarly, the materials used in the construction of the units comply with the NFF 16101/2 standards for fire and smoke classification (tests report for materials available on request).

DV, DI, ITC models are produced in LEM facilities that are IRIS certified and the products are CE marked under European EMC directive 2004/108/EEC and the Low Voltage directive; LEM is able to contribute to energy savings and is certified ISO 14001 for environmental management standards.