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Bodo´s Power Systems®

Electronics in Motion and Conversion

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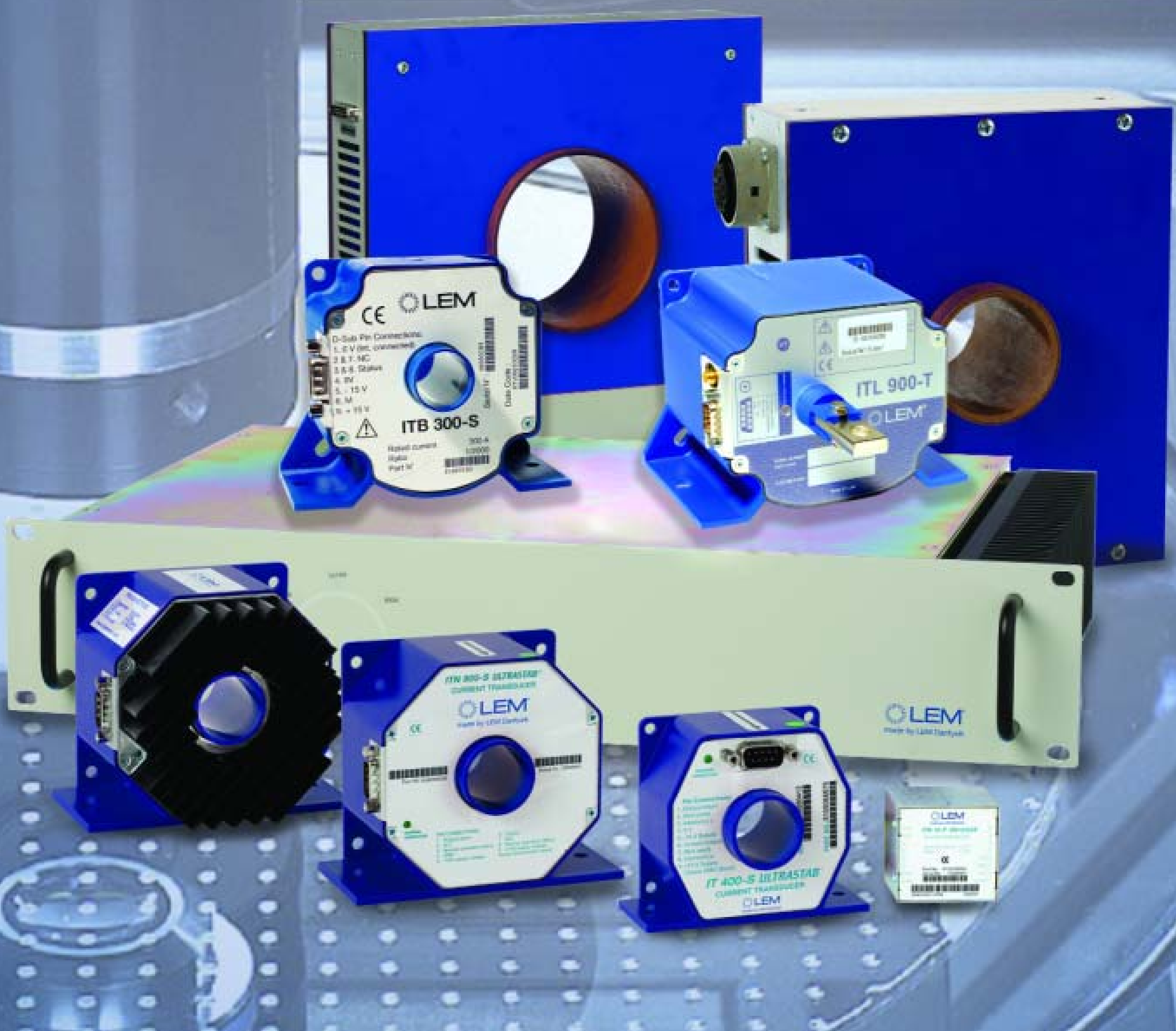

Setting the Benchmark for Accurate Current Measurement

ITxx Current Transducers, setting the benchmark for accuracy!

Certain Power Electronics applications require such extraordinary performance in accuracy, drift or response time that it is necessary to switch to advanced technologies to achieve them. The validation of equipment is often made through recognized laboratories using highly accurate performance test benches supported by high-tech subassemblies, including extremely accurate current transducers. These transducers are still in need for these traditional applications, but are also becoming part of high performance industrial applications, namely: medical equipment (scanners, MRI…), precision industrial motor controls, metering or accessories for test & measuring equipment.

By Morten Bruun-Larsen, LEM , Stephane Rollier, LEM and Horst Bezold, Signaltech GmbH

High Precision Current Transducers for the Test & Measurement Market

The world has to become more efficient and power electronics have played a crucial role to reach this goal. Hybrid- and electric vehicles, wind turbines and solar systems, industrial inverters and motors of higher efficiency. All these components must be optimized according to their losses. Efficiency measurement for power electronics and drives components needs a power measurement system of highest accuracy. During the past 10 years the LEM IT and DANFYSIK ULTRASTAB high precision current transducers became the standard for current range extension in power analysis and efficiency calculation.

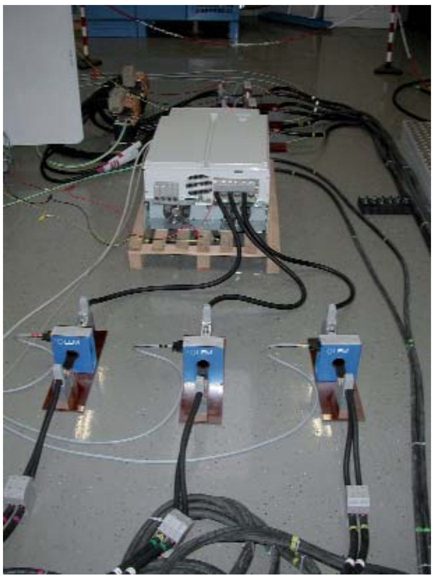

Figure 1: Six channel power measurement at KEB inverter

Demands of a Power Measurement System

Active electric power is defined in the following formula:

$$P = 1/T \cdot \int_0^T p(t)\,dt \quad \text{with} \quad p(t) = u(t) \cdot i(t)$$

The multiplication of voltage and current integrated over one signal period gives you active power. Besides a precise synchronization on the fundamental signal period the power accuracy depends on two items:

1) Amplitude error
   How precise is voltage u (t) and current i (t) measured
2) Phase error
   How long is the time (phase shift) between the sampling of voltage u (t) and current i (t)

Voltages up to 1000 V can be measured with a power meter directly. For current signals above some amps associated current transducers of highest precision are needed.

The influence of a phase error caused by an instrument or transducer increases with the decreasing of the power factor. Figure 3 shows this problem. At power factor 1, there is no phase shift between voltage and current and even an additional phase shift of 1° caused by a current transducer would result in a small power error of 0.2 %. At power factor 0.1, the phase shift between voltage and current is already 84°. An additional transducer phase error of 1° would lead to a huge power error of 17.4 %.

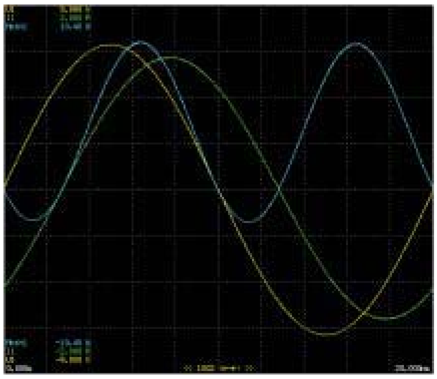

Figure 2: Power signal (blue) calculated from u (t) (yellow) and i (t) (green)

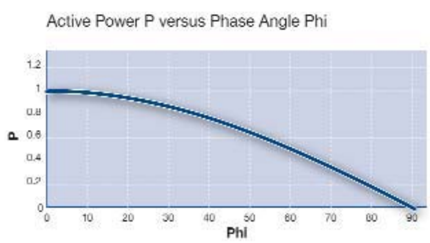

Figure 3: Influence of power factor

Problem of Differential Measurement and high Efficiencies

The biggest problem in efficiency calculation is that losses cannot be measured directly with a high enough accuracy. The most precise power meters offer a basic accuracy of 0.02 to 0.1 %. The problem is that the losses cannot be measured directly but only input- and output power. The losses must be calculated from both power values. In the worst case, the errors of both measurements are opposite. This problem increases with the efficiency of the load. Electric drives have an efficiency of around 95 %, inverters even up to 99 %. Only instruments and current transducers of highest precision are able to deliver reliable results.

Figure 4: Deviations of input- and output power measured with a power system of 0.1 % accuracy

Result: Total power error of 0.195 W (worst case) compared to actual losses of 5 W is equal to an error of 3.9 % for the losses

Optimal Current Sensors for Power Measurement

LEM Danfysik ULTRASTAB current transducers combine all the requirements for a power measurement current transducer. Offset and linearity are in the ppm range. 1 ppm is equal to 0.0001 %. Since the offset is so small one sensor can be used from a few A up to the kA-range. The transducers measure from DC up to several kHz large signals and some hundred kHz small signal bandwidths. The phase error of all transducer types is far below 1 minute, which is 1/60 degree. The sensor is galvanically isolated. The analysis of medium voltage inverters and drives is fully sustainable. Due to the galvanic isolation, there is no common mode signal, which influences the result.

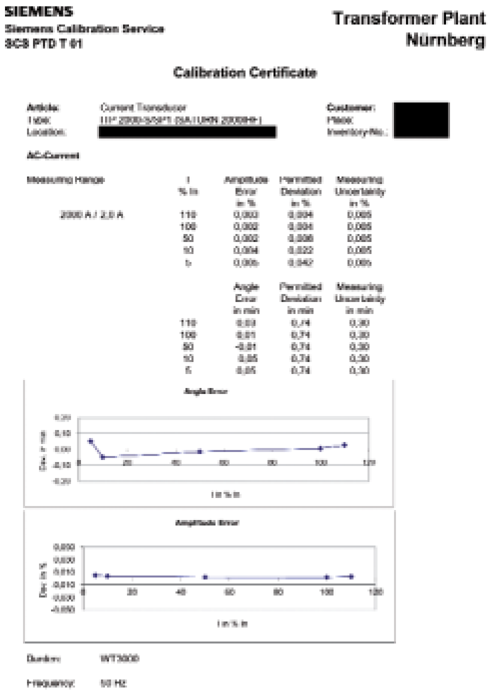

Figure 5: Calibration protocol of a 2000 A transducer. Even at low range of 50 A the accuracy is better than 0.005 % and the phase error below 0.05 min

Special Solutions for Power Analyzers
Most power measurement applications are 3-, 4- or even six channel applications. For an easy installation, wiring and use of our transducers, we provide complete multi channel solutions (Figure 6) including power supply and transducer connection cables. Thus a power measurement setup consisting of power meter and transducers is done within minutes.

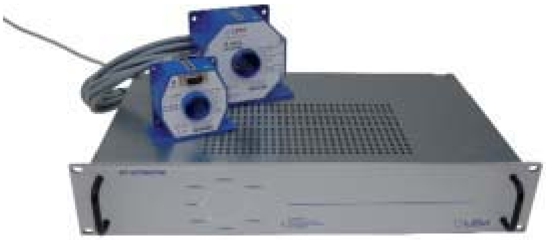

Figure 6: LEM multi channel system

Applications
You can find LEM current transducers everywhere inverters or drives need to be developed or tested.

The ITZ 2000 and ITZ 5000 range of products are normally used for final test of large low voltage and medium voltage motors and generators. Even if the machine is a pure 50 or 60 Hz drive, LEM transducers are a very economic way to measure. Other current transducer technologies demand to switch between different transducers to cover the entire current range. This increases the price of the test system remarkably. The large ITZ transducers for 2 kA and 5 kA are used for development of wind generators and solar inverters.

The IT and ITN transducers families can be used from 60 A to 1000 A for development and test of lower current applications such as small solar inverters, small and medium motors and industrial inverters and power electronics components for automotive applications. Most of the transducers are used for power and signal analysis but since this technology is so precise some of the transducers are used in calibration labs for DC and AC current calibration.

Precision Motion Control for Photolithographic Scanning Steppers

Semiconductor manufacturing relies on complex photolithographic processes, to image and create the nanoscale structures that form the integrated circuit components on the chip. The basics are to a large extent comparable to a standard photographic process, wherein an illuminated object is imaged onto a light-sensitive surface such as a film emulsion or a CCD array through the use of a lens. Speaking in terms of wafer illumination, the object is a mask containing a (large-scale) geometrical "model" of the structure to be formed and the film/CCD is a silicon wafer with a so-called photoresist spun onto its surface. Illumination is not made by visible light, but by use of deep UV (ultra-violet) light-sources like an excimer laser operating at 193nm. The use of a very short wavelength is crucial since the resolution of the process is directly proportional to the wavelength – so by using a shorter wavelength for the illumination, smaller geometries can be created – and in the end a higher integration level ("transistors/area") can be achieved.

The kind of machinery that illuminates a wafer by shining UV light through a photomask is called a wafer stepper. The term "stepper" stems from the fact that the machine steps the wafer through a series of positions in order to produce a number of "dies" (identical circuits or "chips") on each wafer. When illuminating one specific die, mask, wafer and light-source are kept stationary relative to each other.

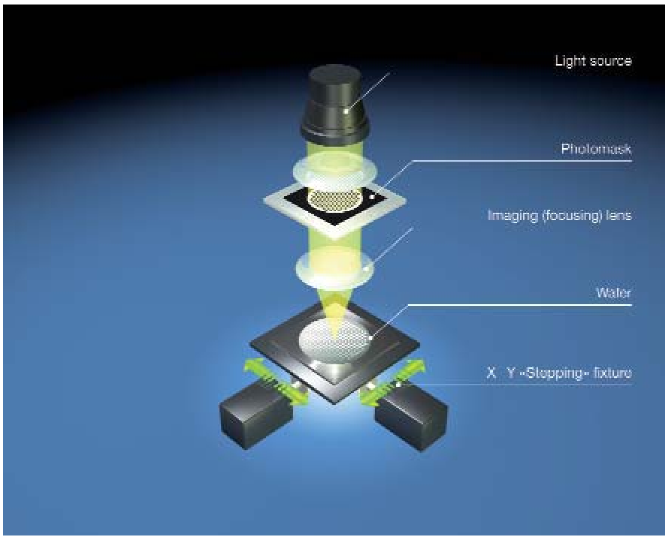

Figure 7: The basic principle of photolithography

Because the full die is exposed in one process during each step, aberrations (imaging flaws) in the optics sets an upper limit to the die area and to the achievable detail of geometry. To overcome this, the method of scan-stepping the photomask pattern onto the die has been developed. Using this method each die is exposed in a process where mask and wafer are moved opposite each other during the illumination. In this way, the photomask pattern effectively "sweeps" the wafer only by use of the center portion of the lens system and a relatively large area can be covered, yet keeping the beam at the center of the optics to keep resolution and detail at max.

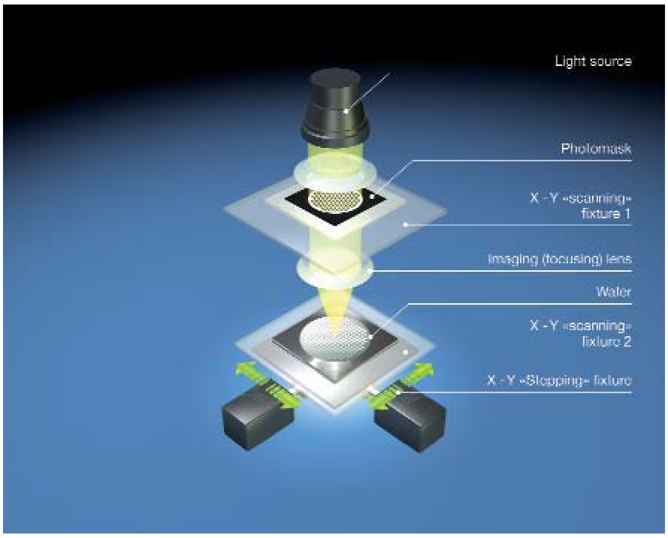

Figure 8: The photolithographic scanning stepper

Since the core technique in the scanning stepper is to move "object" and "film" while exposing, and still hoping to reproduce nanometer scale geometries, it seems evident that position and motion control is vital in this scheme. Positioning is split over two mechanisms: stepping positioning, wherein the wafer is positioned to a specific die position, and the challenging scanning positioning, where the scanning positioning mechanism controls movement of wafer and photomask in opposite directions.

The scanning positioning mechanism has limited travel (on the order of 10-20 mm) and is typically laid out using a linear ("voice coil") actuator. Motion control of this kind of mechanism can be implemented by measuring the drive current in the actuating coil; however,

since it is of highest importance that near-perfect synchronization between the two movements is achieved, a high precision current measurement with extremely high differential linearity is crucial. Ultra-high precision DC Current Transducers like the PCB mounted LEM ITN 12-P offers the required precision and differential linearity for use in this type of application. The only valid alternative offering the same level of linearity is a simple shunt resistor, but since the drive currents typically are several amperes (5-15A) this method is on the edge in terms of power loss and consequential temperature induced drift. Furthermore, the output from a shunt resistor intrinsically carries a common-mode contribution – this is not present using a DCCT where primary and secondary are galvanically isolated.
In conclusion, despite the higher cost of an ultra-high precision DCCT, the advantages offered by this technology outperform the simpler alternative of a shunt resistor for applications in scanning steppers for semiconductor manufacturing.

LEM has been producing high performance transducers for years at costs that appeal to the target market The acquisition of the Danish company Danfysik ACP A/S in 2009, the world's leading company in the development and manufacturing of highest precision current transducers reinforced this position.
To achieve the required accuracy performance, LEM's ITxx current transducers do not use Hall generators but are based on Fluxgate technology, an established technology LEM has used for many years. This is a proven high technology at the heart of several LEM current and voltage transducer families. LEM uses various versions of Fluxgate technologies, each version providing different levels of performances and costs matching depending on the customer's requirements. For the ITxx range, the Fluxgate closed Loop technology applied is certainly the most efficient. That is why we can achieve an accuracy by using ppm (part per million) of the nominal value which is quite representative of the performances reached by this product.

ITxx - Fluxgate Technology Principle

For accurate measurement of DC currents, the methods used since the beginning of the 20th century consist in compensating the current linkage Θ_P created by the current I_P to be measured by an opposing current linkage Θ_S created by a current I_S flowing through a known number of turns N_S, to obtain (Figure 9):

$\Theta_P - \Theta_S = 0$
or $N_P \cdot I_P - N_S \cdot I_S = 0$
N_P: Number of primary turns
N_S: Number of secondary turns

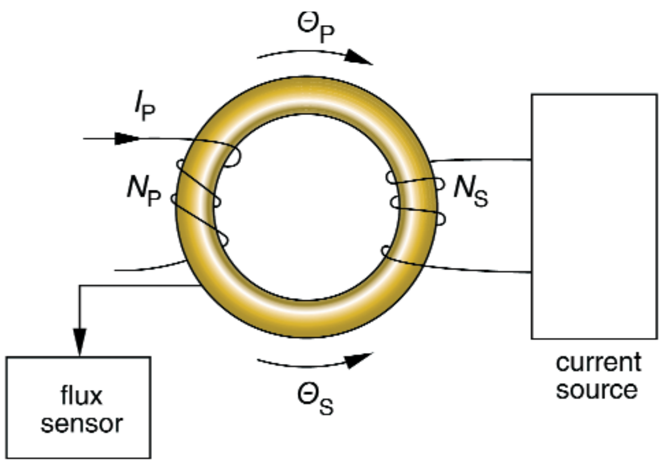

Figure 9: ITxx Fluxgate Technology Principle

To obtain an accurate measurement, it is necessary to have a highly accurate device to measure the condition $\Theta = 0$ precisely. The aim is to obtain a current transducer with the following characteristics:

- Excellent linearity
- Outstanding long-term stability
- Low residual noise
- High frequency response
- High reliability

Operation principle

To achieve really accurate compensation of the two opposing current linkages (Θ_P, Θ_S), a detector capable of accurately measuring $\Theta = 0$ must be available, which means that the detector must be very sensitive to small values of a residual magnetic flux ψ (created by the current linkage Θ) in order to achieve the greatest possible detector output signal.

Fluxgate detectors rely on the property of many magnetic materials to exhibit a non-linear relationship between the magnetic field strength *H* and the flux density *B*.

The hysteresis cycles of the magnetic cores have a form comparable to the one represented in figure 10 (more or less square according to the type of material used).

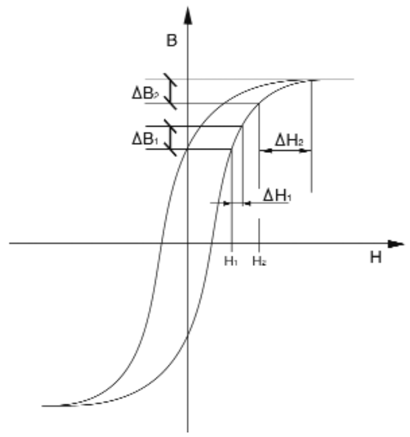

Figure 10: Hysteresis cycles of the magnetic cores

Observing $B = f(H)$ on the magnetization curve, notice that for a given field strength H_1 a flux density variation ΔB_1 corresponds to ΔH_1. But, also observe that further along the cycle, for another given field strength H_2, for the same variation $\Delta B_2 = \Delta B_1$, the ΔH_2 variation must be much greater.

The detection of the zero flux condition ($\psi = 0$) is based on this phenomenon.

When applying a square wave voltage (Figure 11a) to a saturable inductor until its magnetic core starts to saturate, a current (Figure 11b) is created. This current flowing through a measuring resistor will provide a symmetric voltage relative to zero with peak values $+\hat{V} = -\hat{V}$.

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 (Figure 11c) and leading to a measured voltage at the terminals of the resistor where $|+\hat{V}| > |-\hat{V}|$. By using peak detection to measure $+\hat{V}$ and $-\hat{V}$ and by comparing the two peak values, the deviation of the flux in the core is thus detected. As soon as the flux ψ is not zero, an error voltage $|+\hat{V}| - |-\hat{V}|$ is supplied to a power amplifier that drives a current into a compensation winding until $\psi = 0$, thus $|+\hat{V}| = |-\hat{V}|$.

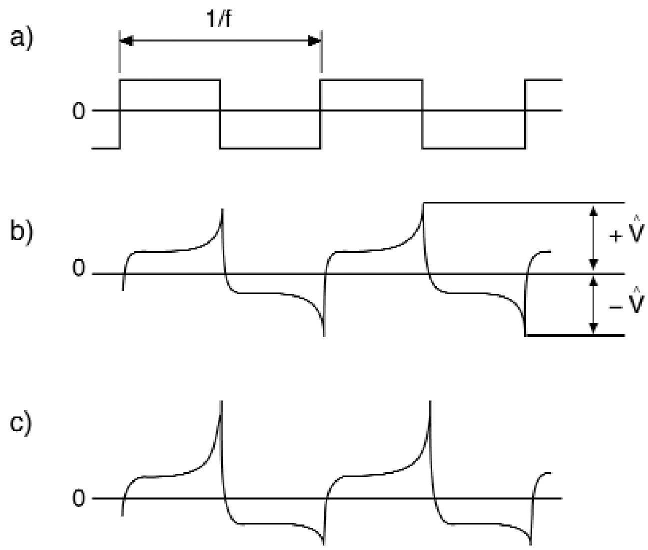

Figure 11: Square wave voltage (11a); Current created (11b); Asymmetry of the created current (11c)

Figure 12 shows a very simplified base circuit for the compensation of a DC current.

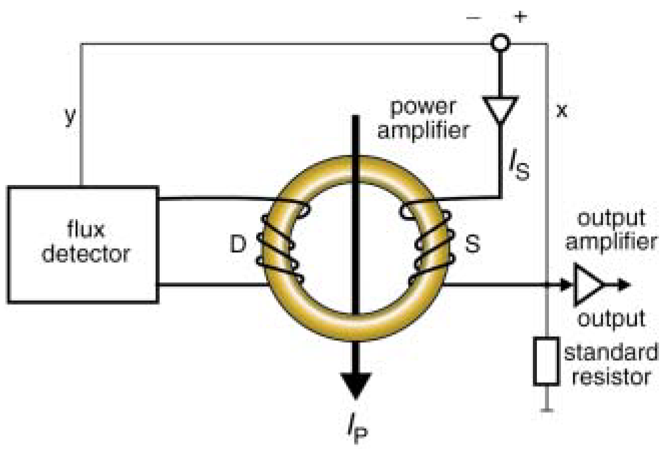

Figure 12: Simplified base circuit for DC current compensation

If the primary current $I_P = 0$, the compensation current I_S will be equal to 0. When I_P varies, the flux varies. Therefore, we detect an error $|+\hat{V}| - |-\hat{V}|$ which controls the power amplifier to supply a compensation current I_S until $\psi = 0$, thus:

$$N_S \cdot I_S = N_P \cdot I_P$$

The current I_S flows through a measuring resistor, transforming the current into a proportional voltage.

The accuracy of the measurement will not only depend on the accuracy of the measuring resistor but also strongly on the sensitivity of the flux detector. However, in spite of the DC measurement function accuracy, there are some drawbacks to this DC measurement system (Figure 13):

As the winding "D" of the flux detector is coupled with the compensation winding "S", the applied square wave voltage is re-injected into the compensation winding and creates a parasitic current in the measurement resistor.

However, the square wave voltage induced in the S winding by this flux may be practically cancelled out when a second D' winding is mounted on a second detector core (identical to D) inside the compensation winding S. The residual flux (the sum of the opposed fluxes in D and D') will create very small voltage peaks that cause the remaining signal correlated with the fluxgate excitation (Figures 13 and 14).

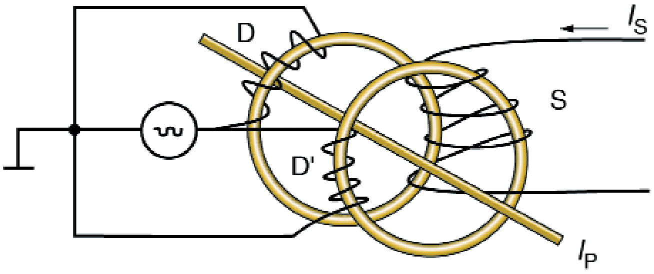

Figure 13: Solution against voltage peaks re-injection

If the application does not need a large bandwidth, the system's cut-off frequency can be designed to be lower than the excitation frequency of the fluxgates. LEM offers transducers that allow a synchronization of the fluxgate excitation with a user supplied clock to provide a workaround.

We recommend only applying primary current to the transducer after powering up the current transducer. Failing to do so will result in oscillation on the output, and a delayed lock-on to the primary current. It will further more result in an additional offset.

The magnetic part of the transducer is realized as schematically represented in figure 14:

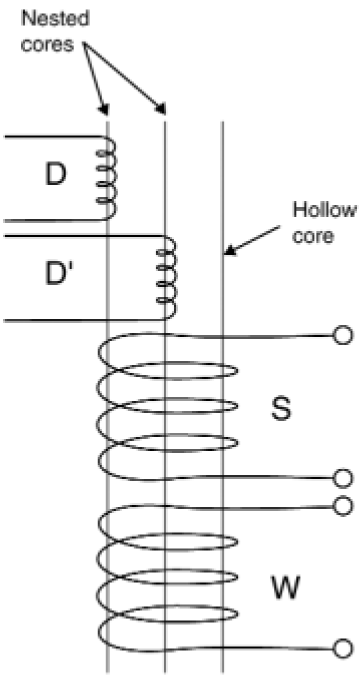

Figure 14: The various windings used and their arrangements

A fourth winding W is wound before the compensation winding S on the main core to extend the frequency range of the transformer effect to lower frequencies. It is connected to a circuit that adds some voltage via the power amplifier to compensate the too small induced voltage in a frequency range too high for the fluxgate detector.

The diagram of the compensation loop is shown in figure 15.

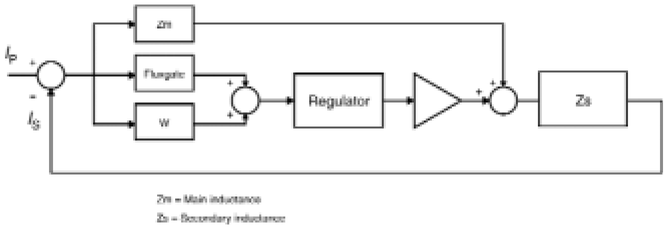

Figure 15: Compensation loop diagram

The simplified overall diagram is shown in figure 16 and can be directly deduced from the diagram, figure 15. The saturation detector is activated when the output voltage exceeds its specified range.

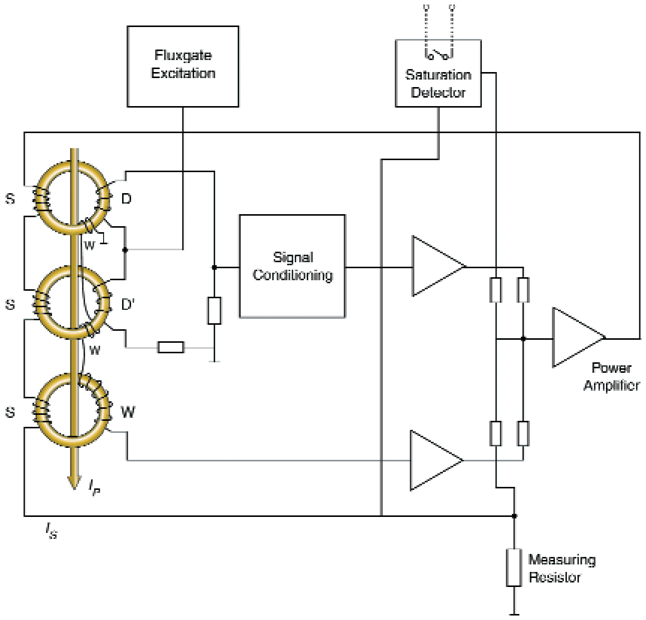

Figure 16: ITxx operation principle: simplified overall diagram

ITL 4000 model does not integrate W winding and uses a lower oscillation frequency for the fluxgate excitation.

The design of the measuring head is simplified in comparison with the other ITxx models.

Figure 17: LEM Danfysik current transducers range

Based on this technology, the LEM transducers range covers high accurate nominal current measurements from 12.5 A to 24 kA providing overall accuracy at +25°C from few ppm. Thermal offset drifts are extremely low, from only 0.1 to 6.7 ppm/K. Models from 12.5 A to 60 A nominal can be used for PCB mounting, models from 60 A to 24 kA are for panel or rack mounting.

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