

Low Consumption Flux-Gate Transducer

Both AC and DC High-Current Measurement is achieved

This article presents the design and implementation of a transducer system for the measurement of AC and DC high-current using the flux compensation technique in the measurement transformer, also called Flux-gate technology. The system can measure currents greater than 700 A (peak value) with a 100 kHz bandwidth measured at -3 dB.

By Manuel Román, Guillermo Velasco*, Alfonso Conesa * and Felipe Jeréz ***

**EUETIB – CEIB and **Grupo PREMO S.A.*

**Technical University of Catalonia (UPC) - Department of Electronic Engineering (DEE)*

**Compte d'Urgell 187, 08036 – Barcelona SPAIN*

Throughout time different methods of measurement of the electrical current have been developed. The different methods are based on purely electrical, magnetic or optical principles, or making use of the behaviour that some materials have in presence of a magnetic field [1].

The more suitable method in each case depends on the characteristics of the current to be measured: DC, AC or both simultaneously, frequency, peak value, accuracy, isolation, etc. Among the different methods we find: shunts, current transformers, Hall-effect and Rogowski effect transducers, Flux-gate effect transformers, and other alternative methods of less common use.

A brief summary of the main methods is presented.

Shunt

The method is based on the measure of voltage that appears on a resistance (shunt) due to electric current, according to Ohm's law.

The method is extremely simple and suitable for measurement of DC and AC accurately, but its major drawback is the absence of isolation between the power and measure circuits and the high power consumption in case of high current measurement.

Current Transformer

Based on electromagnetic principles, is an AC transformer where the secondary current is related to the primary according to the transformer turns ratio.



Picture 1: fluxgate currents transducer range

It consists of a toroidal core, where the secondary winding is wrapped. The conductor through which the current to be measured circulates become the primary winding.

The transformer is carefully conceived in order that the leakage current and the losses in the core are very small, so that no significant errors are introduced in the measure.

The main advantage of this method is its simplicity and robustness, while the main drawback is that it is only suitable for AC measures.

Hall Effect Transformer

The Hall sensor measures the voltage that appears in a semiconductor in the presence of a magnetic field perpendicular to the plane of the material when a current circulates along this material (Hall effect).

The transformer consists of a toroidal magnetic core with a gap for the Hall probe placement. The magnetic core is used to direct the magnetic field originated by the current to be measured. An additional electronic circuit processes the signal generated by the Hall probe.

The principal advantage of this system is the ability to measure DC and AC currents, up to frequencies of 100 kHz, with an acceptable precision and a galvanic isolation.

Rogowski Transformer

The Rogowski transformer has a toroidal structure, but with a coil wrapped on a non-magnetic core (named Rogowski coil) and its structure can be either rigid or flexible.

The current to be measured crosses the Rogowski coil and generates a voltage proportional to the rate of change of this current and the mutual inductance between the coil and the conductor. The value of the current to be measured is proportional to the integral of this voltage.

The advantage of this transducer is the impossibility of saturation of the magnetic core (i.e. air or plastic), but is not appropriate for DC measures and its accuracy and bandwidth are conditioned by the integrator circuit.

Flux-gate Transformer

This transformer, with physical structure similar to the Hall transformer, is based on the detection of the saturation state of a magnetic circuit. The magnetic core is built using a high permeability material, which is immersed in the magnetic field to be measured.

The magnetic material is excited by a signal that, in absence of external magnetic field, leads the magnetic material to the symmetrical saturation. This symmetry is lost with the existence of an external magnetic field.

The injection of current in an auxiliary winding creates a compensating magnetic field that restores the symmetry of the hysteresis cycle. The injected current compensates the magnetic field created by the current to be measured, and its value is proportional to this current.

This system is suitable for the measurement of DC and AC currents, with high accuracy, high frequency and high current range.

Other Methods of Measurement

So far the most important methods used for the measurement of the electrical current have been reported.

All of them are based on the detection of the magnetic field created by this current, with the exception of the direct measurement by means of a shunt.

Other methods for current measurement are based on the properties of materials sensitive to magnetic field, like those based on the magneto-resistive and magneto-optical principles or those based on the magnetodiode, magneto-transistor and superconductors components, etc... [2 - 3].

Comparison Between the Presented Methods

Table 1 presents a comparison between different methods of current measurement described above using some parameters that determine their main characteristics and usual applications.

Parameter	Shunt	Current transformer	Hall transformer	Rogowski transformer	Flux-gate transformer
AC/DC measure	AC/DC	AC	AC/DC	AC	AC/DC
Band Width	Low	Low	Middle	Middle	High
Isolation	No	Yes	Yes	Yes	Yes
Linearity	High	High	Middle	High	Very High
Precision	Middle	Middle	Middle	Middle	Very High
Offset	Yes	No	Yes	No	No
High current	Bad	Middle	Middle	Good	Very Good
Saturation effect	No	Yes	Yes	No	No
Temperature dependence	Middle	Low	High	Very Low	Low
Power Consumption	High	Low	Low	Low	Middle
Size	Very Low	Low	Low	Middle	Middle

Table1: Comparison of methods for current measurement

Flux-gate transducers

These transducers have similar physical structure to Hall transformers. They are based on the detection of the saturation state of a magnetic circuit. The ferromagnetic material used presents high permeability and is immersed in the magnetic field to measure. This system is appropriate in a large range of DC and AC current measurement with high accuracy, until maximum frequencies around 100 kHz.

The "Flux-gate" term makes reference to the principle of operation on which some transducers are based for the measurement of current with isolation. In this type of transducers the magnetic field generated by the current to measure is detected by means of a sensor.

In a similar way to the transducers based on the Hall-effect, the usually called standard Flux-gate transducers use a toroidal magnetic circuit which includes an air gap with the field measuring element and a secondary winding. The main difference between the transducers Hall and standard Flux-gates consists on the element to measure the field that crosses the magnetic circuit, as shows Figure 1. Hall cells and saturable inductors are used respectively.

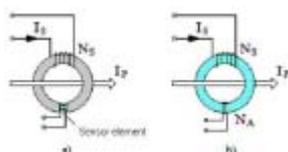


Figure 1: Structure of a Flux-gate transducer: a) standard and b) without gap in the magnetic path

The current transducer proposed in this work is based on non-standard Flux-gate transducer. The non-standard transducer developed uses its own toroidal core as field detector, and does not include any gap in the magnetic path. An auxiliary winding is added to the core and that results in a core-wound set, which is used as a saturable inductor flow detector.

In order to detect a null field in the magnetic circuit, the secondary winding is excited with the necessary current. In this circumstance, the transducer works with zero field condition, as shown in Figure 2. This condition verifies that the current imposed, by the secondary winding, is directly proportional to the primary current to be measured (Ip).

The relationship between the primary and secondary current is (1), being N_S the number of turns of the secondary winding.

$$I_P = N_S \cdot I_S \quad (1)$$

The detection of the zero flux condition in the magnetic path of the transducer is based on the change of the inductance value of the saturable inductor formed by the ferromagnetic core and the auxiliary winding. In absence of current to be measured (Ip), the net flux through the saturable inductor core is zero.

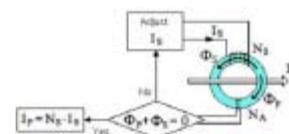


Figure: 2 Basic principle of behaviour of Flux-gate transducers

Under these conditions, if a squared voltage waveform is applied to the auxiliary winding (NA), the current waveform in auxiliary winding will be as shown Figure: 3.

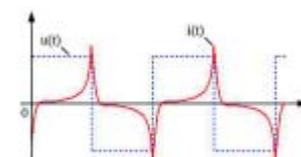


Figure 3: Voltage waveforms of excitation and current by the auxiliary winding under zero flux conditions

The effect of the current to be measured (Ip) on the auxiliary winding current (NA), when a square voltage waveform is applied, leads to an average current value different from zero, as shows Figure 4.

The average value obtained and its sign will depend on the specific value and direction of the current Ip.

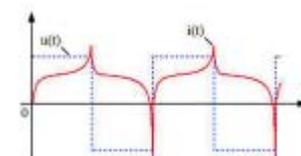


Figure 4: Voltage waveforms of excitation and current by the auxiliary winding under non zero flux conditions

Flux-gate transducer designed

The designed transducer operates in a closed-loop, according to the general scheme shown in Fig. 2. The null average value condition in the current by the auxiliary winding (NA) is used to determine the condition of zero flux in the core. The basic operating principle of the designed transducer is in Figure 4.

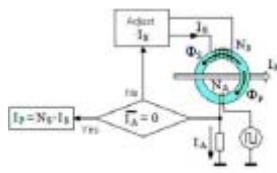


Figure 5: Principle of operation of the Flux-gate transducer designed

A disadvantage presented by this structure is the possible injection of noise on the primary current measure (IP). This noise comes from the auxiliary current (IA), and can be coupled in the primary current due to the transformer effect in the magnetic core of the transducer. The solution usually adopted to avoid this phenomenon is the use of a second core with a new auxiliary winding. These two cores with their auxiliary windings must be identical under ideal conditions [4].

Now the secondary winding (NS) in which the compensation current of flux in the transducer is applied will be common to both auxiliary cores.

The purpose of this second auxiliary core (also a second saturable inductor) is to compensate the injected noise in the primary current by the first saturable inductor. If the second auxiliary core (NA2) is excited with an equal current but in reverse direction to the current used for exciting the first auxiliary core (NA1), the currents induced on the primary current conductor (IP) will be equal and in opposite direction, cancelling its effect.

The block diagram that represents the designed measurement system is shown in Figure 6.

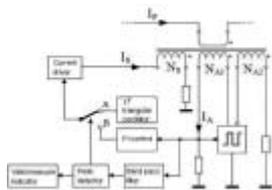


Figure 6: Block diagram of the designed Flux-gate transducer

Signal Generator for the Excitation of Auxiliary Windings

It is based on a comparator circuit with hysteresis (or Schmitt trigger). This circuit will change the value of its output voltage when the circulating current on the main winding excitation (IA) exceeds a threshold value.

The magnetic component of measure is included in the oscillator circuit, and the electrical characteristics of this component

will influence the frequency of oscillation of the squared signal generator circuit. For the transducer built, this frequency is around 300Hz.

Symmetry Detector of the Auxiliary Current (IA)

In absence of primary current (IP) the average value of the current of excitation (IA) is zero. The effect produced by the existence of a primary current is the appearance of an average value different from zero and sign dependent of the sense of of this current.

For the automatic adjustment of the value of the secondary current winding (IS), the use of a PI controller is proposed, in order to ensure that the primary current excitation winding has zero mean value.

This controller cannot guarantee the proper functioning of the measurement system at the start-up process if a primary current (IP) even of moderate value is already circulating, because under these conditions the two inductors will be saturated.

A primary current through the measurement system in non zero flux conditions, produce a high frequency current (some tens of kHz) in the main excitation winding (IA) and non zero average value, with independent sign of the primary current circulating sense (IP).

To overcome this drawback, an additional controller is included which ensures that the zero flux condition is reached regardless the value that the primary current (IP) could take at the start-up time.

The operation of this controller is based on the property mentioned previously, where the frequency of the current of the main excitation winding (IA) is high frequency when the system is not balanced and low frequency when the system is operating in the vicinity of the point of zero flux. The presence of this additional controller increases the robustness against possible situations, as sporadic transients, ensuring the accomplishment of the equilibrium conditions.

As Figure 6 shows, this controller includes a triangular low-frequency oscillator, a frequency detector for the excitation current (IA) and an analog switch controlled by the frequency detector.

While the measurement system does not operate in zero flux conditions, the input of the current compensation driver (IS) will be connected to the triangular low-frequency signal generator. This waveform guarantees

that, in some moment, a value of the winding current compensation (IS) next to the necessary condition of zero flux will be reached. When this happens, the frequency of the current of the main excitation winding (IA) decreases. This situation is detected and the originally proposed PI controller then is connected to the input of the current compensation driver.

Valid Measure Indicator

The output of the low-frequency detector circuit is connected to the indicator of valid measure. This indicator is only activated when it detects that the current of the primary winding excitation is of low frequency, effect that will occur when the system works in zero flux conditions.

An LED indicator and a relay are the output elements to indicate the condition of zero flux valid measure.

Driver to Generate the Compensation Current

This circuit is used to generate the current that will flow through the secondary winding compensation (NS).

A class D amplifier has been used for the implementation. These amplifiers present the advantage of high efficiency compared to linear amplifiers, but add harmonics of the same switching frequency and higher.

Is based on a pulse width modulator (PWM), which generates a squared voltage waveform with a duty cycle proportional to the PI controller output signal.

The output PWM squared waveform of the modulator is applied to the compensation winding (NS) through a current driver implemented with a half-bridge inverter.

The own inductance of the NS winding filters the current that circulates along it. So, the output voltage of the system measured in a shunt resistance connected in series with this winding is proportional to the primary current to be measured.

Measure of High Frequency Currents

The system of measure proposed, based on the Flux-gate principle, is only suitable for the measurement of current in DC or in AC at low frequencies. The maximum frequency for the AC measurement is fixed by the working frequency of the zero flux detection system.

For the measure of high frequency AC currents and to obtain a suitable dynamic behaviour in case of fast variations of current, a third core is included. This new core is embraced only by the compensation winding (NS) and it works exclusively as a conventional current transformer.

Power Supply

Voltage power supply of the transducer is obtained from a flyback DC / DC converter. In this way, two stable output voltages (+12V positive and the other negative -12V) are derived from a single input voltage which can be between 10V and 30V.

Experimental results

Figure 7 shows the final look of the constructed prototype. It displays the transformer of measurement, the PCB with the used electronics components and the designed box to contain the measurement system.

This prototype has been successfully tested and here we present some of the results obtained for four different types of measurements.

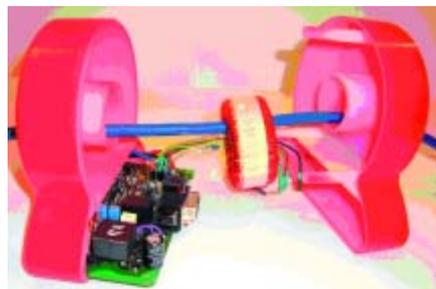


Figure 7: The designed Flux-gate transducer

In the first two experiments 35 times the main conductor has been coiled on the measurement transformer. Hence, the current measured by the transducer will be 35 times greater than the real value of the IP.

The I_p current is measured in a 3 mV/A shunt, and the IS current, generated by the designed transducer, is measured on a 1 Ω resistance. Since 1000 turns for NS have been used, the output voltage of our transducer will be of 1 mV/A.

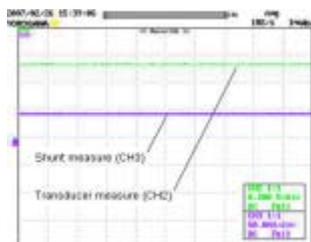


Figure 8: Measurement of a DC current

Figure 8 shows the result of a 525A DC current measurement performed with the described shunt (CH3) and with the designed transducer (CH2).

Figure 9 shows the result of the measurement of a 350 A of amplitude squared current and 1 kHz of frequency performed with the described shunt (CH3), and with the designed transducer (CH2).

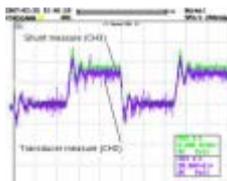


Figure 9: Measurement of a 1kHz squared waveform current

Figure 10: shows the result of the measurement of a sinusoidal current of 400 A amplitude and European network frequency (50 Hz), performed by the designed transducer.

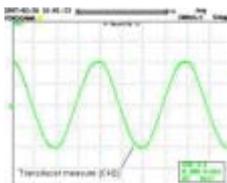


Figure 10: Measurement of a 50Hz sinusoidal current

Finally, Fig.11 shows the result of a 100 kHz sinusoidal current of 133 A amplitude measurement, performed by the described shunt (CH3), the designed transducer (CH1) and another industrial Flux-gate transducer (CH2).

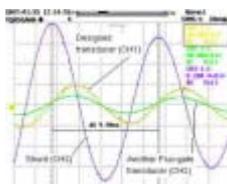


Figure 11: Measurement of a 100kHz sinusoidal current

Conclusions

A transducer based on the Flux-gate technology for the measurement of DC and AC current has been designed and tested.

The power supply of the transducer and the driver for generating the compensation current (IS) are based on high-efficiency DC/DC power converters. This choice guarantees the low consumption of the designed system compared to the existing solutions in the market.

The main characteristics of the designed system are the following ones:

- Maximum peak current: 1000 A
- Primary rated current (IN): 700 A
- Small signal bandwidth (5% of IN): DC to 100 kHz
- Conversion Ratio: 1:1000
- Supply voltage: from 10 to 30 VDC

In order to obtain a more detailed characterization of the described transducer, the reference DCT-700A can be consulted at the products general datasheet of Group PREMO S.A. [5]. This datasheet is accessible online.

www.grupopremo.com

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