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Wide Band Current Transformer with Sensitivity Depending on the Measuring Signal Frequency

Andrei Marinescu[1], Ionel Dumbravă[1], Lucian Mandache[2]

[1]*R&D National Institute ICMET Craiova, Romania, amarin@icmet.ro, iodum@icmet.ro*
[2]*University of Craiova, Romania, lmandache@elth.ucv.ro*

***Abstract* – In many electrical engineering applications it is necessary to measure some complex current signals containing high frequency periodic components (MHz) or short duration pulses (ns) superimposed on a low frequency carrier signal (usually power line frequency). For the overall measurement of such complex signals, wide band current transformers (WBCT) are currently used. The paper refers to the achievement of a wide band current transformer whose sensitivity changes automatically with the frequency of the measuring current, so as it does not reach saturation at low frequency large signals.**

Keywords* – *current transformer, wide frequency band, frequency-dependent sensitivity

I. INTRODUCTION

In power electronics applications, particle accelerators technique, electrical testing technique, electromagnetic compatibility a.s.o., it is necessary to measure some periodic currents with different shapes or frequencies and some bipolar or unipolar current pulses with ns duration. Many times, high frequency signals (or short duration pulses), which are important for establishing the operating regime of static switches or for determining the life time of the equipment used in distribution or transmission networks by detecting the partial discharges, are superimposed on a power line frequency carrier signal. For the overall determination of these complex signals, wide band current transformers (WBCT) are currently used. WBCTs are inductive sensors of current to voltage type, with ferri- or ferromagnetic core, which by an adequate sizing are able to cover a wide frequency band having three up to at least six decades. They behave like a pass-band filter, and their present performances are given both by the magnetic materials used and by the methods utilized for extending the frequency band in which their sensitivity is constant [1,2,3].

In the current engineering practice, there are encountered many situations in which the low frequency component of the complex signal has a magnitude as high as that it leads to the saturation of WBCT magnetic coreand to measurement errors within the entire frequency band. A general method to avoid the saturation caused by low frequency signals, maintaining the nominal sensitivity of WBCT at high frequencies, is shown in this paper.

II. WBCT SENSOR

WBCT is usually achieved on a toroidal magnetic core where the single-turn primary is the cable through which the measuring current flows, located on the toroid axis, and the secondary is a distributed winding, closed on a built-in fixed resistor.

A WBCT is mainly characterized by its sensitivity (S) instead of the transformation ratio Nused for the low frequency current transformers (CTs). S is defined as the ratio between the output voltage across the built-in load resistor (R_2) and the primary current and it is expressed in V/A or its equivalent in Ohms. At a high quality WBCT, S has a constant value within the entire measuring frequency band given in catalog. It is determined at the middle of the frequency band, where the phase error is zero. After simple calculations, for a single-turn primary one reaches the relationship:

$$S = R_2/n \qquad (1)$$

where the number of turns of the secondary winding is was denoted by n.

A schematic diagram of a classical WBCT, built with four constructive elements, is shown in Fig. 1: magnetic circuit 1, secondary winding 2, built-in load resistor 3 and electromagnetic screen (not shown) used for decreasing the capacitive coupling with the circuit in which the current represented by the primary winding is measured 4.

The measuring current is a usually a combination of low and high frequencies components with different shapes and magnitudes, which when are within the WBCT frequency band, should be accurately measured.

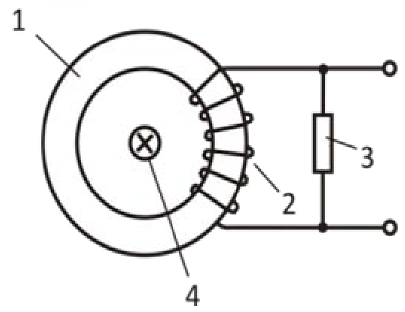

Fig. 1. Schematic diagram of a classical WBCT, with toroidal core and secondary winding closed on a load resistor of small value.

Besides *S*, two important parameters related to the limitation of the magnetic saturation effect are defined at WBCT: ratio I/f expressed in A_{peak}/Hz for the entire operating frequency range when sinusoidal and non-sinusoidal periodic currents are measured and product I x t expressed in A·s, defined for the case in which unipolar current pulses are measured.

Faraday's law leads to an inversely proportional relationship between the maximum value of magnetic flux density in the core and the frequency of the measuring signal:

$$B_{max} = K \cdot R_2 / f = K \cdot S \cdot n / f \qquad (2)$$

where *K* is a constant parameter for a given magnetic circuit.

The relationship shows that at low frequencies the magnetic flux density is much higher than at high frequencies and consequently, at a given WBCT with closed magnetic core, the amplitude ratio between pulse current and low frequency current may be between 100 and 1000. For example, a WBCT could measure high frequency pulses of 100 kA and low frequency currents having amplitude of only 100 A. Therefore, the limits for linear non-saturation operation of a WBCT at low frequency are rather tight. By reducing the sensitivity, the magnetic flux density in core decreases and the ratio I/f increases, but at the same time the possibility to measure simultaneously high frequency, relatively small currents in numerous other applications, decreases.

With the development and widespread use of nanocrystalline magnetic materials intended for utilization within a wide frequency band with low losses, high permeability, lowremanent induction and linear magnetization characteristic, it is possible to obtain a constant sensitivity *S* of WBCT up to frequencies of a few Hz [4]. In this case, due to the technology issues in achieving an air gap [5], it becomes more important to find a solution for decreasing selectively the sensitivity only at low frequencies.

III. WBCT WITH FREQUENCY-DEPENDENT SENSITIVITY

Wide band current transformer with a sensitivity that changes automatically with the frequency of the measuring signal [6] ensures increasing the value of the ratio I/f at low frequencies, using a circuit with variable impedance depending on the signal frequency, connected in parallel on one of the WBCT voltage outputs. Thus, its sensitivity is reduced for a pre-set low frequency range, so as its nominal sensitivity at the high frequencies from the transformer measuring range remains unchanged.

This solution is shown in Fig. 2: WBCT with its main components from Fig. 1 has a dipolar circuit 6 connected in parallel to the load resistor 3, circuit achieved so as it represents an impedance *Z* (*f*), which depends on the measuring current frequency.

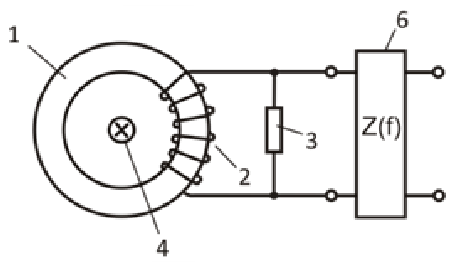

Fig. 2. WBCT achieved with frequency-variable impedance, connected in parallel to the load resistor.

In its simplest form, the impedance *Z* (*f)* is a passive, R-L series circuit, according to Fig. 3.

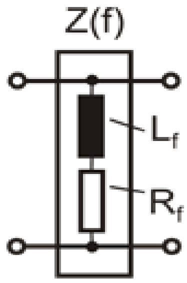

Fig. 3. Diagram of frequency-variable impedance.

Impedance *Z* (*f*) is designed so as, at low frequencies, the circuit behaves like a resistor R_f connected in parallel to the WBCT load resistor R_2,and this leads to the decrease of magnetic flux density into the magnetic circuit. It follows an increase of the equivalent impedance by 20 dB/decade, up to the cutoff frequency f_t, when the inductive reactance ωL_f becomes so high that it affects no more the WBCT load resistor R_2, and therefore WBCT sensitivity remains the original one. Therefore the eq. (1) becomes:

$$S(f) = [R_2 \| Z(f)]/n \tag{3}$$

and eq. (2) becomes:

$$B_{max}(f) = K \cdot [R_2 \| Z(f)]/f \tag{4}$$

In particular, if $Z(f) = R_f + j\omega L_f$, at low frequencies it results that $|Z(f)| \approx R_f$ and the corresponding sensitivity is:

$$S_1 = [R_2 \| R_f]/n < S$$

and

$$B_{max1} = K \cdot [R_2 \| R_f]/f < B_{max} \tag{5}$$

At high frequencies it results $|Z(f)| \approx \omega L_f \to \infty$

$S_2 = R_2/n = S$
and

$$B_{max2} = K \cdot R_2/n = B_{max} \tag{6}$$

With this simple topology R-L from Fig. 3 and on the basis ofeq. (3) and (4), it can be automatically obtained a controlled decrease of the magnetic flux density and sensitivity at low frequencies, equivalent to a similar increase of the WBCT ratio I/f, without changing the nominal sensitivity at high frequencies.

IV. MATHEMATICAL MODEL

In order to perform an optimized design of the WBCT, a time-domain mathematical model of the system is compulsory. Starting from the classical configuration shown in Fig. 1, the KVL for the primary and the secondary loops leads to:

$$u_1(t) = R_{w1} i_1(t) + N_1 \frac{\mathrm{d}\varphi}{\mathrm{d}t} \tag{7}$$

$$N_2 \frac{\mathrm{d}\varphi}{\mathrm{d}t} = (R_2 + R_{w2}) i_2(t) \tag{8}$$

where: u_1 is the voltage drop across the primary winding of N_1 turns (usually $N_1 = 1$) and resistance R_{w1}; i_1, i_2 are the primary and the secondary currents respectively; the secondary winding has N_2 turns and resistance R_{w2}; φ is the magnetic flux through the cross section of the ferromagnetic core.The Ampere's law expressed for the ferromagnetic core of length l_{Fe}, assumed in a first instance as linear,is:

$$H_{Fe} l_{Fe} = N_1 i_1 - N_2 i_2 \tag{9}$$

and it leads to:

$$R_m \; (t) + N_2 i_2(t) = N_1 i_1(t) \tag{10}$$

where H_{Fe} is the strength of the magnetic field and R_m is the magnetic reluctance of the core of cross section S_{Fe} and relative permeability μ_r:

$$R_m = \frac{l_{Fe}}{\mu_0 \mu_r S_{Fe}} \tag{11}$$

By gluing eq. (7), (8) and (10) together, one obtains the mathematical time-domain model:

$$\begin{cases} N_1 \dfrac{\mathrm{d}\varphi}{\mathrm{d}t} - u_1(t) = R_{w1} i_1(t) \\ N_2 \dfrac{\mathrm{d}\varphi}{\mathrm{d}t} - (R_2 + R_{w2}) i_2(t) = 0 \\ R_m \varphi(t) + N_2 i_2(t) = N_1 i_1(t) \end{cases} \tag{12}$$

This algebraic-differential equation system has as input quantity the primary current and asmain variables the secondary current beside the magnetic flux (the variable u_1 is of lower interest).The initial value of the magnetic flux is also needed to obtaina well-posed problem.

Since the system was assumed as linear, the frequency-domain model can be easily obtained as an algebraic equation system:

$$\begin{cases} j\omega N_1 \underline{\Phi} - \underline{U}_1 = R_{w1} \underline{I}_1 \\ j\omega N_2 \underline{\Phi} - (R_2 + R_{w2}) \underline{I}_2 = 0 \\ R_m \underline{\Phi} + N_2 \underline{I}_2 = N_1 \underline{I}_1 \end{cases} \tag{13}$$

This latter allows simulating frequency characteristics.

V. RESULTS AND DISCUSSIONS

An analysis in the frequency range was done by a vector network analyzer (Anritsu MS4630B). The frequency characteristics from Fig. 4 were measured for a WBCT achieved on a nanocrystalline toroidal core with $R_2 = 9.97\ \Omega$ and $n = 40$ turns, according to the diagram from Fig. 1.

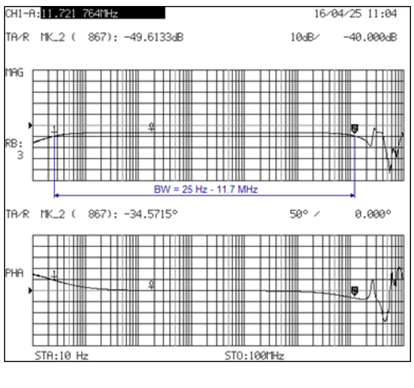

Fig. 4. Frequency characteristics of the studied WBCT.

As result, a sensitivity $S = 0.23$ V/A in the pass band defined at ± 3 dB from 25 Hz up to 11.7 MHz was obtained.

The frequency characteristics obtained through numerical simulation using the mathematical model (13) reveals a cutoff frequency of 29 Hz, very close to the experimental one (see Fig. 5, where the magnitude of the output voltage was represented in green and its phase in red). The cutoff point at high frequencies has not been fund through simulation because of the assumption regarding the linearity of the ferromagnetic core (see section IV).

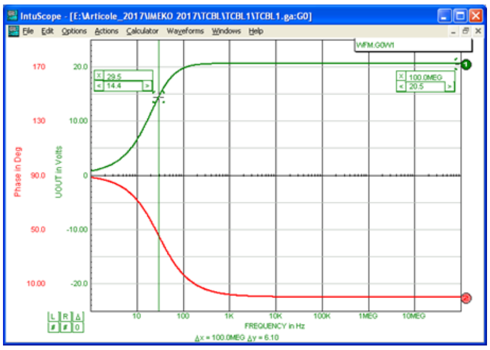

Fig. 5. Simulated frequency characteristic of the WBCT from Fig. 1.

After connecting the frequency-variable impedance *Z(f)* with *R* = 0.438 Ohm and *L* = 110.1 µH to the WBCT output, according to Fig. 2, the new frequency characteristicsare that from Fig. 6, showing that at low frequencies the sensitivity decreased to the value *S* = 0.026 V/A, almost 10 times lower than the sensitivity at the same frequency in case of WBCT without *Z(f)*.

Instead, at the frequencies from the upper side of the pass band, the sensitivity remained actually constant (0.21 V/A) within a frequency range from 15 kHz up to 12.7 MHz.

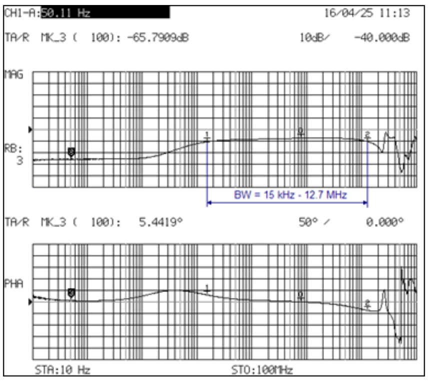

Fig. 6. Frequency characteristics of WBCT with Z(f).

The phenomenon of saturation produced by a 50 Hz sinusoidal current at the studied WBCT was analyzed.

It was experimentally determined that WBCT without *Z(f)* saturates at a current of 4 A in primary.

The signal at the output from WBCT (signal 2) for a current of 11 A (signal 1), maximum value that could be obtained experimentally, is shown in Fig. 7. Signal 1 is 10 times smaller because a shunt of 0.1 Ω was used at the current measurement.

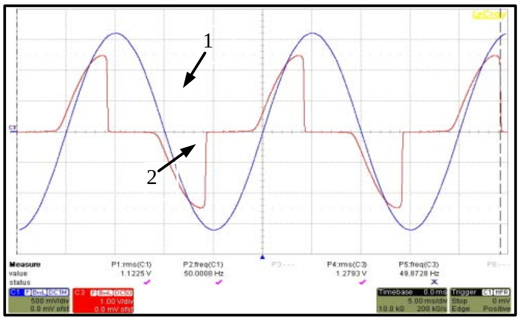

Fig. 7. WBCT without Z(f) is saturated at a current of 11 A.

The same current was measured with WBCT fitted out with *Z (f)* and the measurement result is given in Fig. 8. In this way, saturation does not appear at 11 A current.

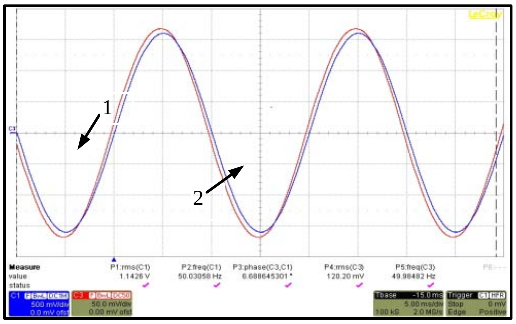

Fig. 8. Measurement of 11 A current at WBCT with impedance Z(f).

In Fig. 9, there are measured pulses with the rising slope lower than 10 ns from a PD calibrator, proving the WBCT frequency band, and in Fig. 10 it is shown the diagram for simultaneous measurement of two currents with very different frequencies: 50 Hz and 5 kHz.

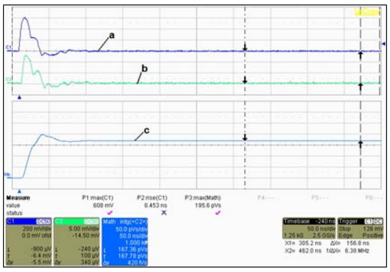

Fig. 9. Results of the measurements of PD pulse. a – current pulse measured with a shunt 50 Ohm (Ipeak = 12.2 mA), b – current pulse measured by WBCT, c – integral of the current pulse b (qm = 0.167 nC), time base 50 ns/div.

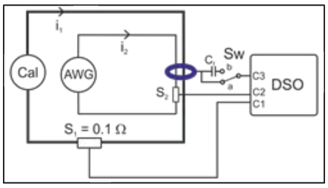

Fig. 10. Diagram for simultaneousmeasurement of a current AC (i_1) and high frequency signal (i_2). Cal - calibrator Fluke 5500A, AWG – signal generator, C_f- part of high pass filter, S_1*,* S_2 *- shunts, DSO – oscilloscope, Sw - switch.*

Fig. 11 shows the measurement results for *Sw* in position a, and Fig. 12 shows those ones for *Sw* in position b.

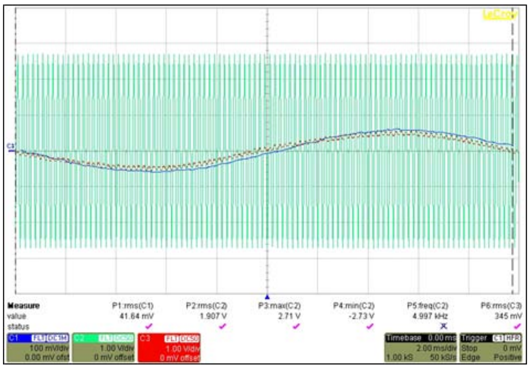

Fig. 11. Sw in position a. C1 – voltage across the shunt S_1, C2 – voltage across the shunt S_2,C3 – signal at the output from WBCT.

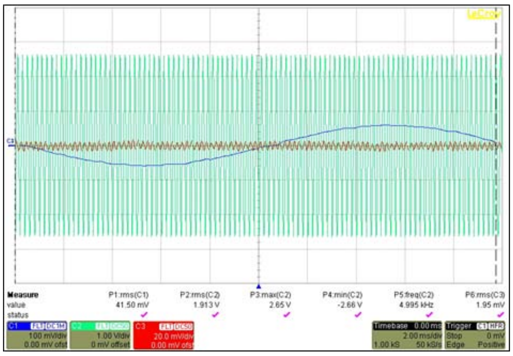

Fig. 12. Sw in position b. C1 – voltage across the shunt S_1*, C2 – voltage across the shunt* S_2*, C3 – signal at the output from WBCT.*

VI. CONCLUSIONS

The paper deals with a wide band current transformer (WBCT) with sensitivity depending on the measuring current frequency, characterized by the fact that, for making possible the measurement of currents in primary circuit without saturating it when these currents have large components at low frequencies, it has a frequency variable impedance connected at the output. In this way, its sensitivity changes against the constant initial value within the entire frequency band, so that the sensitivity at low frequency decreases and the sensitivity at high frequencies remains unchanged.

The frequency-variable impedance is a dipolar, passive circuit with an R-L series topology, through which the two different sensitivities, S_1 and $S_2 = S$ separated by a transition zone S_0 with a slope of 20 dB/decade variation, are achieved.

The impedance $Z(f)$ may change so as the transition zone S_0 is restrained in the frequency range without affecting the two **levels** of the frequency characteristic, by adopting a passive, more complex topology of RLC type, for which the sensitivity transition in the zone S_0 is done by 40 – 60 dB/decade.

The change of WBCTs sensitivity may be achieved both at the commercial and at experimentally developed ones by inserting, between the WBCT output and the viewing device, a coaxial T adapter to which the impedance $Z(f)$ is connected.

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