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THE ZERO-FLUX CURRENT TRANSFORMER FOR IMPROVING ACCURACY, WITH APPLICATIONS FOR DISTORTED WAVEFORMS AND DC BIAS

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Abstract - Current measurements on electrical power systems very often concern nonsinusoidal conditions, due to the presence of distorting loads connected to the network (typically because of the presence of power electronic components) and the consequent harmonic pollution. In addition the presence of DC components, superimposed to alternating ones can make it impossible to correctly use the current transformers (CT's) and gives rise to the burden and composed (namely due to the distorted waveforms) errors, that are arising from the presence of the core flux in CT. Moreover saturation, hysteresis, and polarization are supported by the core flux. The presence of the core flux is the difference between a real CT and an ideal one.

A method for compensating the core flux makes a real CT operating as an ideal one. Imperious to the, burden and composed error and to the presence of DC components, superimposed to alternating ones.

A compensation method (CM) using as processing unit (PU) an operational amplifier (OA) that processes the analog compensating signal as been investigated in developing the denoted, "zero-flux current transformer" (ZFCT). The compensating analog signal is the voltage drop at the terminals of the secondary of CT. PU applies the compensating signal in series opposition with the burden's voltage drop. The compensation may be performed on every CT.

An experimental CM-compensated ZFCT has shown, the reduction of the ratio error to at least one fifth and its imperiousness to the burden up to 10 ppm.

Keywords: ampere-turns, burden and composed error, core flux

Glossary of Symbols*:* CM– compensation method, CT–current transformer, CU – compensation unit, OA – operational amplifier, ZFCT – zero-flux current transformer.

1. INTRODUCTION

In a perfect CT, the primary and secondary ampere-turns would exactly be equal in magnitude and precisely opposite in phase position for all conditions of service. In practice, the ideal is never attained because a voltage must be induced in the secondary winding to overcome the impedance of the circuit. This gives rise to a corresponding magnetic flux in the core, and it is the ampere-turns needed to maintain the flux, which constitute the *external burden error* of the CT. Moreover the resistance of the secondary winding adds to the burden error the *internal burden error*.

The presence of this core flux is the difference between a real CT and an ideal one.

A method for compensating the core flux makes a real CT operating as an ideal one.

Current measurements on electrical power systems very often concern nonsinusoidal conditions, due to the presence of distorting loads connected to the network and the consequent harmonic pollution.

In a CT the so-called *composed error* that represents, in addition to amplitude differences and time shifts, deviations caused by the different harmonic contents of the output signal compared with the input one is higher at low frequencies, and the phase error decreases for increasing frequency. This is due [1] in practice to the magnetizing current, which comes down as the frequency goes up.

In traditional CT's the effects of *saturation and hysteresis*, more or less evident, but always present with the flux in the magnetic core, causes distortions in the secondary wave form, thus limiting the above-observed advantages on phase error.

In addition the presence of DC components, superimposed to alternating ones can make it impossible to correctly use the transformer, due to the polarization of its magnetic core.

Saturation, hysteresis, and polarization are supported by the core flux, thus enhancing the usefulness of a CM to performing ZFCT.

When *distorted waveforms* are dealt with CT's (typically because of the presence of power electronic components) these devices seem to be inadequate if uncompensated by this frequency dependence arising from the core flux.

Each application should be evaluated regarding CT burden and saturation to ensure proper operation in ground-differential protection [2].

There are a number of *methods to reduce the external burden error*. These can be divided generally into a passive and an active method [3].

- In the *passive method,* an additional or compensator CT is used [4].
- In the *active method,* the output voltage of an amplifier is used to offset the voltage of the burden.

These methods are briefly surveyed in [5]. Various proposals [6] have been made over the past years. Earlier techniques involved the use of two separated cores and nested cores and the two-stage principle have been used. By these methods a sensing device of the core flux is used, namely, [5] a Hall generator, or a third winding, or even a third and a fourth winding.

The compensation methods at present available may be used for the design of very sophisticated ZFCT. On the contrary CM may perform a ZFCT by any CT. The used PU simply is an OA, A, with a rated output current in accordance with the secondary one of the compensated CT. The input voltage of OA is the voltage drop at the secondary terminals of CT.

2. BASIC PRINCIPLE OF CM

CM [7] has been devised to compensate the effect of unwanted elements, which are present in the equivalent series circuit of electrical instrumentation. This effect is usually a voltage, voltage drop, and e.m.f. induced by linked fluxes, etc. In the following the quantity in question will be indicated as $\overline{E}$. CM consists in processing a voltage $-\overline{E}$, which is equal and opposite to $\overline{E}$. This $-\overline{E}$ is applied in series with the circuit to be compensated, $-\overline{E}$ is obtained by means of a processing unit (PU). The schematic diagram of PU, illustrated in Fig, 1, consists in detecting on the instrumentation to be compensated either an e.m.f. or a voltage drop $k\overline{E}$ in phase with $\overline{E}$ to be compensated. PU is also made of an inverting OA, A that receives, as its input $k\overline{E}$, and produces, by its adjustable gain, as its output $-\overline{E}$. Moreover PU applies $-\overline{E}$ in series with the circuit to be compensated. Therefore the new terminals 2 and 2' of the compensated circuit, in which $\overline{E}$ has in series $-\overline{E}$ substitute the terminals 1 and 2 of the circuit to be compensated.

The gain of A is adjusted to zeroing the voltage between the terminals 2 and 2′. On the compensated circuit at the terminals 2 and 2′, the unwanted effects, due to $\overline{E}$ are thus cancelled.

- ***Forms of PU*** (PU always implies the use of an inverting OA (A) with adjustable gain).

- **A.** ***First Form of PU*** - It applies when the terminals of $\overline{E}$ are accessible and PU simply is A having $\overline{E}$ as its input.

- **B.** ***Second Form of PU*** - It applies when the terminals of $\overline{E}$ are not accessible and $\overline{E}$ is the voltage drop on an unwanted impedance Z_0 only present in the equivalent series circuit of the instru-

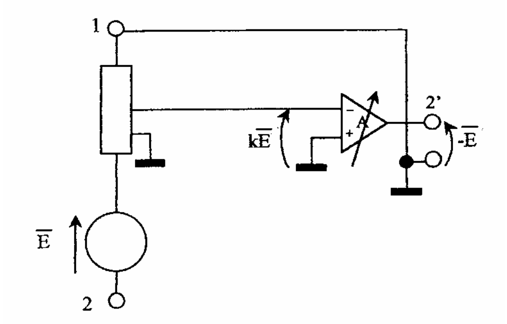

Fig. 1. Schematic diagram of CM. A is an electronic amplifier. $\overline{E'}$, k$\overline{E'}$, and -$\overline{E'}$ are the, e.m.f. or voltage drop to be compensated, the one in phase with $\overline{E'}$ and the compensating one. 1 and 2 are the terminals of the circuit to be compensated. 2 and 2′ are the terminals of the compensated circuit

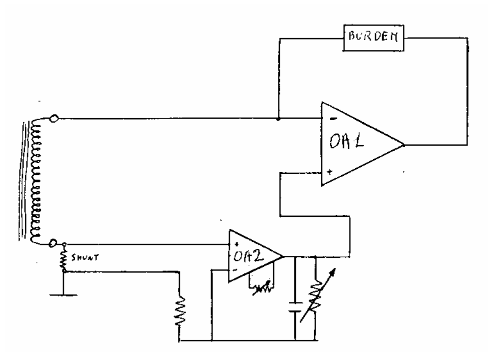

Fig. 2. Schematic diagram of ZFCT by the second form of PU. OA1 and OA2 are OA's

mentation to be compensated. The pick-up impedance Z_m similar to Z_0 is series connected with the instrumentation to be compensated and its voltage drop is the input $k\overline{E}$ of A. When two separate adjustments have to be performed the voltage drop on Z_m may be entered in a second OA, OA2, and controlled by its gain. See in Fig. 2 an application to ZFCT.

CM differs from the classical ones because of the use of PU, which processes the compensating analog signal.

3. APPLICATION OF CM FO ZFCT

To zeroing the flux of CT by CM $\overline{E}$ at the secondary terminals of CT is the chief quantity to be compensated. *The first form of PU* may then be used namely, simply an OA, A. The burden due to the output resistance, R_o of OA and secondary series copper winding resistance (which gives rise to the internal burden error), usually, may be disregarded.

And, if it is the case, *the second form of PU* may apply a proper compensation. A shunt resistor, see Fig. 2, is series connected with the secondary current (I_2) of CT and its voltage drop is summed, trough the second insulating OA OA2, to $\overline{E}$ at the secondary terminals of CT. Namely to the input voltage of OA1.

4. DESIGN of OA of CU

CU of CM for ZFCT requires an OA having its output series connected with the secondary current I_2 of CT to be compensated. A two stage OA has to be used with as output a power stage in the configuration, currently denoted “hybrid integrated”. See, in Fig. 3, the schematic diagram of the system used in our prototype of a CM-compensated ZFCT. The inverting OA operates in the potential mode and the current flows in the output power transistors, T_1 of the type PNP and T_2 of the type NPN. The error by the offset voltage has been compensated; see in Fig. 4 the two stages OA including this compensation system.

5. TEST RESULTS

A prototype of a CM-compensated ZFCT has been designed and constructed. See in Fig. 5 a photograph of the prototype connected with the set used for its test (namely, a Hartman & Brown Type MEWK CT relative test set).

Prototype rated data:

- *CT class* 0.5%, *burden*=5 VA, *ratio* 5 to 1 A.
- *OA* The Burr Brown OPA/AM integrated circuit has been used. Input bias currents are of a few tens nanoampere, the input offset voltage of a few millivolt. The power derating curve and the safe operating area has been settled. The circuit has been implemented by compensation’s system of the error by the offset voltage. The offset voltage control device, included in Fig. 4, equipped with

B = 470 kΩ, C=2,2 μF, and D=820 Ω, E= 100 kΩ, is proper for an offset voltage control range of
± 16 mV.

Fig. 6 and 7 respectively illustrate the characteristics of the ratio error (η%) and phase angle (ε ′),of CT, as a function of I_2 in percent. The uncompensated CT characteristics are denoted by the value of the burden, ranging from about 20% (0.85 VA) to 110% (5.46 VA) of the rated 5 W, at cosφ= 0.8, burden. The curve A summarizes the corresponding characteristics of compensated CT that, with the resolution of 10 ppm of the detecting set, are indistinguishable.

6. CONCLUSIONS

From the earlier illustrated test results is clearly appears that the widespread response of CT, with the burden, in the experimental ZFCT is fully compensated so that CM-compensated ZFCT is imperious to burden’s variations.

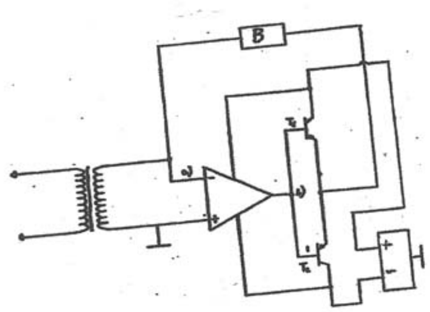

Fig. 3. Schematic diagram of the two stages OA. a) Is the first stage of OA. b) Is the second power stage

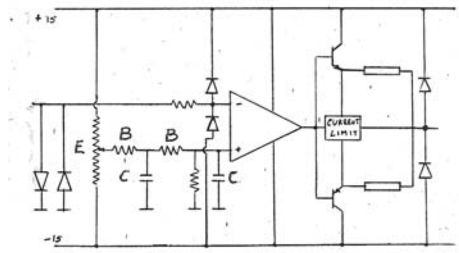

Fig. 4. The two stages OA including the compensation’s system of the error by the offset voltage

Fig. 5. Photograph of an experimental CM-compensated ZFCT connected with the test’s set

The resolution of 10 ppm of the detecting set makes credible the test of the effectiveness’ of CM in compensating the flux of CT’s for a ZFCT imperious to the burden’s influence. Moreover, see Fig. 6, the class of CT is improved from the rated 0.5% to ± 0.1%.

The benefit of CM may further on be enhanced by *the use of the second form of the PU* (see Section 3 and Fig. 2) by which the compensation of the output resistance R_0 of OA and secondary series copper winding resistance may be achieved.

Test results have demonstrated the effectiveness of CM in improving the accuracy of CT’s and its utility in the compensation of the flux of CT’s for high precision ZFCT’s and validates its utility in factory use especially with distorted waveforms and DC bias.

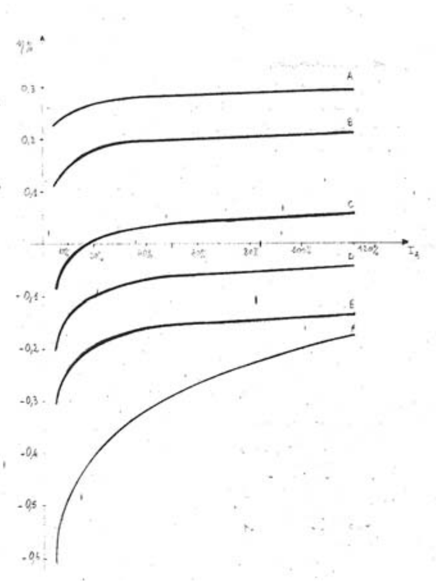

Fig. 6. Test results. The characteristics of the ratio error (η%). A is the characteristic of ZFCT. B, C, and D, E, F are the characteristics of the uncompensated CT with the burden respectively of: 20%, 40%,and 60%, 80%, 110% of the rated one

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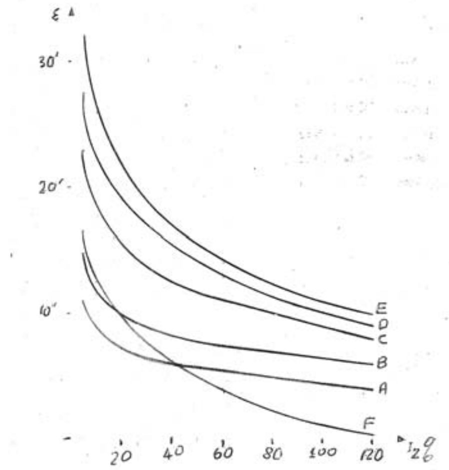

Fig. 7. Test results. The characteristics of the phase angle (ε ′). A is the characteristic of ZFCT. B, C, and D, E, F are the characteristics of the uncompensated CT with the burden respectively of: 20%, 40%,and 60%, 80%, 110% of the rated one

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