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Digital Measurement of Line Current with the Use of Virtual Short Circuit Method

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***Abstract* – The paper describes a method of very accurate measurement of line current using a current transformer (CT) in a virtual short circuit. The key systematic error, amplified error due to offset of operational amplifier that leads CT in a virtual short circuit, is easily calculated using a stochastic digital measurement method and eliminated from measured RMS value of line current. Since the 2-bit stochastic digital measurement method is defined using a very simple hardware which has a small number of sources of systematic error, sources are easily identified and it is described how to eliminate these errors. A complete measurement scheme of line current is presented and applied in quadruple three-phase power analyser with MM4 type designation. MM4 is a key component of the redundant measuring system in the Electric Power Grid of Serbia.**

Keywords* – *digital stochastic measurement, line current, current transformer

I. INTRODUCTION

Measurement of the line current has been always a demanding task. The precision and the accuracy of this mass-measurement of current had definitive impact on precision and accuracy of all other measurements in the grid. In most previous studies [1-5], the input signal is digitized by using a high-resolution A/D converter. Two-bit stochastic digital measurement method (SDMM) [6-9] is relatively seldom approach to this problem. The main intention of this work is to demonstrate the fact that two-bit SDMM can measure very precisely and accurately the line current. Since the problem is very non-linear and stochastic, due to low resolution of applied AD converter and strong additive uniform random dither, it is exactly analyzed near upper limit of measurement range and in the case of sinusoidal current. The method is applied in MM4 – quadruple three-phase power analyzer – which is used in redundant monitoring measurements in Serbian power grid [7]. An investigation of application of this method near zero value, in fact near lower limit of measurement range, was recently done [8] and results were very attractive.

Such solution is not only simpler to implement, but also more robust to changes in the speeds of processors. Thanks to these features, the proposed method is applied in the device called MM4 (it is about a quadruple three-phase power analyzer who measures 12 phase currents and 4 zero currents). In addition, in this paper, we investigate the performance of a two-bit SDMM near the upper limit of the measuring range. For ease of reading, a list of notations is given in Table 1.

Table 1. Notations used in this paper.

Symbol	Meaning
$I(t)$	Line current
CT	Current transformer
N	Number of secondary windings of CT
r	Secondary winding resistance
D_1, D_2	Protective diodes
$i(t)$	Current through the secondary winding (N times reduced current $I(t)$)
R	Reaction resistor
U_0	Operational amplifier offset voltage
$e_i(\mathrm{t})$	Output voltage proportional to current $I(t)$
Δ	Quantum of the 2-bit flash A/D converter
g	Threshold voltage

II. THE PROPOSED METHOD

Fig. 1 shows the scheme of current transducer with CMT in a virtual short circuit. From this figure it can be concluded that:

$$i(t) = \frac{I(t)}{N} - \frac{U_0}{r} \tag{1}$$

i.e. that

$$e_i(t) = -R \cdot i(t) = -\frac{R}{N} I(t) + \frac{R}{t} U_0 \tag{2}$$

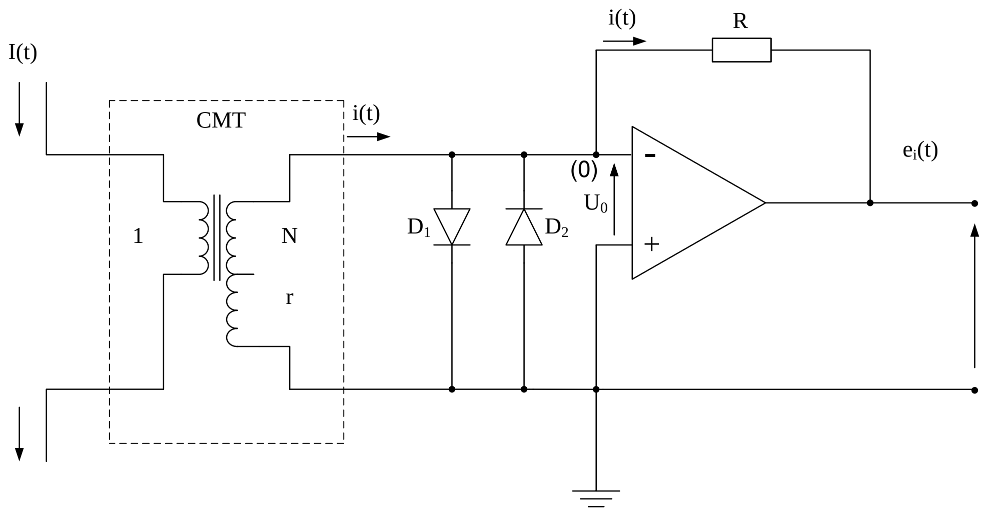

Fig. 1. Scheme of current transducer with CT in a virtual short circuit

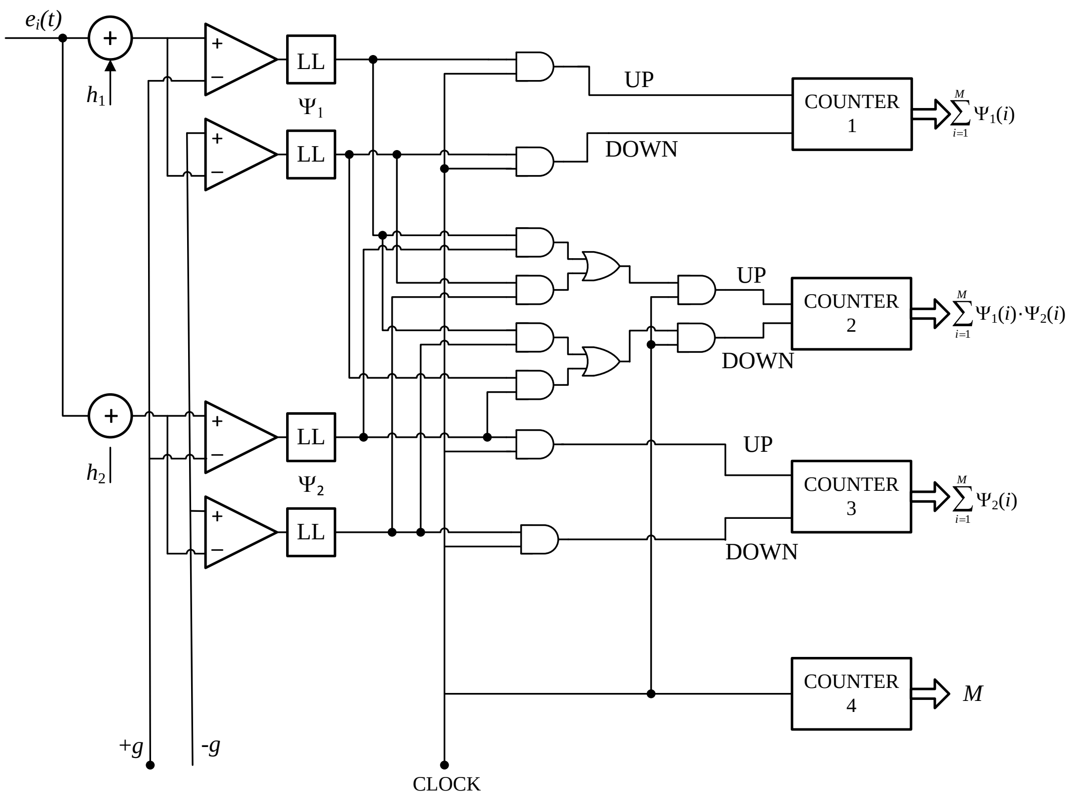

Fig. 2. Scheme of $\overline{e_i^2(\mathrm{t})}$ *and* $\overline{e_i(\mathrm{t})}^2$ *measurement*

The relation (2) shows that the offset voltage is amplified *R/r* times. U_0 is an unknown very slowly changing (practically DC) value and it causes a measurement error with the effective value (RMS) of line current $I(\mathrm{t})$ in the relative form

$$\Gamma_I = \frac{1}{2}\frac{(\frac{R}{r}\mathrm{U}_0)^2}{(\frac{R}{N}\mathrm{I})^2} = \frac{1}{2}\frac{N^2 U_0{}^2}{r^2 I^2} \qquad (3)$$

In equation (3) I represents the RMS value of the line current $I(\mathrm{t})$. On the other hand, r also depends on temperature so, in general, Γ_I represents a slowly changing and unknown value. On the basis of the relation (2), if $\overline{e_i(\mathrm{t})}$ is measured in a period or an even integer of periods of line voltage, then: $\overline{e_i(\mathrm{t})} = \frac{R}{r}U_0$ and the relation (3) becomes:

$$\Gamma_I = \frac{1}{2}\frac{\overline{e_i(\mathrm{t})}^2}{(\frac{R}{N}\mathrm{I})^2} \quad (4)$$

A supporting microprocessor calculates $\overline{e_i(\mathrm{t})}^2$ at the end of each two periods (or an even integer number of periods), which has M two-bit samples $\psi_1(\mathrm{i})$ and $\psi_2(\mathrm{i})$ as:

$$\overline{e_i(\mathrm{t})}^2 = \frac{\left(\sum_{i=1}^{M}\psi_1(\mathrm{i})\right)\cdot\left(\sum_{i=1}^{M}\psi_2(\mathrm{i})\right)}{M^2} = \frac{\langle Counter1\rangle\cdot\langle Counter3\rangle}{\langle Counter4\rangle^2} \quad (5)$$

and corrects the measured value:

$$\overline{e_i^{\,2}(\mathrm{t})} = \frac{\langle Counter2\rangle}{M} = \frac{\sum_{i=1}^{M}\psi_1(\mathrm{i})\cdot\psi_2(\mathrm{i})}{M} \quad (6)$$

Then it is:

$$I = \frac{N}{R}\sqrt{\overline{e_i^{\,2}(\mathrm{t})} - \overline{e_i(\mathrm{t})}^2} \quad (7)$$

In relation (7) for RMS of line current, I represents value with (an eliminated) error due to amplified offset of operational amplifier from Fig. 1, but also due to offsets of analog adders from Fig. 2 (these components are the building elements of the MM4 - Fig. 3). The error due to offset of high-speed analog comparators from Fig. 2 is eliminated with a cross-switching method [9].

Fig. 3. The MM4 instrument: quadruple threephase power analyzer

III. ESTIMATION OF THE MEASUREMENT PRECISION

From [8] it is known that

$$\overline{e_i} = \frac{1}{M}\cdot\sum_{i=1}^{M}\psi_1(\mathrm{i}) \quad (8)$$

$$\sigma_{\bar{e}}(\overline{e_i}) = \sqrt{\frac{1}{M}\cdot\left(\frac{2g}{2T}\cdot\int_0^{2T}|e_i(t)|dt - \frac{1}{2T}\cdot\int_0^{2T}e_i^2(t)dt\right)} = \frac{2g}{\sqrt{6\cdot M}} = 0.0144\,V \quad (9)$$

where $\sigma_{\bar{e}}(\overline{e_i})$ denotes the standard deviation of the average error e_i. In addition, from the above it is easy to show that

$$\overline{e_i^2} = \frac{1}{M}\cdot\sum_{i=1}^{M}\psi_1(\mathrm{i})\cdot\psi_2(\mathrm{i}) \quad (10)$$

$$\sigma_{\bar{e}}(\overline{e_i^2}) = \sqrt{\frac{1}{M}\cdot\left[\frac{(2g)^2}{2T}\cdot\int_0^{2T}\left|e_i^2(t)\right|dt - \frac{1}{2T}\cdot\int_0^{2T}e_i^4(t)dt\right]} = \frac{(2g)^2}{\sqrt{8\cdot M}} = 0.0625\,V^2 \quad (11)$$

In addition, considering that $i(t) = I_1 \cdot sin\omega t$, it holds that $e_i(t) = E_0 + E_1 \cdot sin\omega t$. Further, since $E_0 << E_1$, we can write $E_1 \approx 2g = 5$ V. In the above equalities, the E_0 denotes the error caused by the amplified offset of the operational amplifier and the offset of analog adders.

The scheme from Fig. 2 measures the $\overline{e_i^2}$, i.e. $E_1^2/2$. Hence, the value of the absolute error is equal to

$$G(\frac{E_1^2}{2}) = \left|\frac{E_{1m}^2}{2} - \frac{E_1^2}{2}\right| = \left|(E_0^2 + \frac{E_1^2}{2} + G_S) - \frac{E_1^2}{2}\right| \le \le \sigma_{\bar{e}}(\overline{e_i^2}) + 2\cdot|E_0|\cdot\sigma_{\bar{e}}(\overline{e_i}) \quad (12)$$

where

$$G_S = \sigma_{\bar{e}}(\overline{e_i^2}) - E_0^2 - 2\cdot E_0\cdot\sigma_{\bar{e}}(\overline{e_i}) - \sigma_{\bar{e}}^2(\overline{e_i}) \quad (13)$$

Now, suppose that U_0 = 5 mV. In addition, let us assume that is this value is subsequently amplified 20 times by measurement scheme, i.e. that $|E_0|$ = 0.1 V. In that case, it follows that

$$G(\frac{E_1^2}{2}) = (0.00625 + 0.00288)\,V^2 = 0.0654\,V^2 \quad (14)$$

Within the measurement interval T = 20 ms the relative imprecision of measurement of the RMS value of $E_1^2/2$ is equal to

$$\Gamma_{20}(\frac{E_1}{\sqrt{2}}) = \frac{1}{2}\cdot\frac{G(\frac{E_1^2}{2})}{\frac{E_1^2}{2}} = \frac{0.0654}{25} = 0.0262\,\% \quad (15)$$

Within the measurement interval T = 1000 ms the relative imprecision of measurement of the RMS is $\sqrt{25}$ times lower, i.e. it is equal to

$$\Gamma_{1000}(\frac{E_1}{\sqrt{2}}) = \frac{\Gamma_{20}(\frac{E_1}{\sqrt{2}})}{5} \approx 0.05\,\% \quad (16)$$

It can be seen that the $\Gamma_{1000}(E_1/\sqrt{2})$ is four times lower than 0.2 % of the full scale (FS) (obtained by calibration). Hence, 0.2 % of the FS represents the measurement accuracy defined by the various components: the quality of the ferromagnetic material (used in CT), the quality of the resistors, the quality of a D/A converter (to generate a random uniform dither) and so on. The accuracy of 0.2 % of the FS is not corrupted at all by the imprecision of 0.006 % which corresponds to the covering factor $k = 4$ (i.e. 4σ).

IV. CONCLUSION

The paper focuses on the accuracy of measurement of the line current in the power distribution system. Current transformer operates in ideal conditions - practically in a short circuit. Hence, the amplified error due to offset of applied operational amplifier can be a serious problem. In the paper it is shown how to measure and computationally eliminate the aforementioned error. A complete scheme of measuring of line current which was applied on serial device MM4, quadruple threephase power analyzer is presented. This device is a key measurement device in a redundant measurement system in the Electric Power Grid of Serbia. Laboratory calibration has confirmed the accuracy of measurement of 0.2% FS.

V. ACKNOWLEDGMENT

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REFERENCES

[1] V. Vujicic, *Generalized Low-Frequency Stochastic True RMS Instrument*, IEEE Trans. Instrumentation and Measurement, vol. 50, no. 5, pp. 1089-1092, Oct. 2001.

[2] B. Santrac et al., *A Novel Method for Stochastic Measurement of Harmonics at Low Signal-to-Noise Ratio*, IEEE Trans. Instrumentation and Measurement, vol. 58, no. 10, pp. 3434–3441, Oct. 2009.

[3] V. Vujicic et al., *STOCHASTIC DIGITAL MEASUREMENT METHOD – A STRATEGIC ADVANTAGE IN ELECTRICAL POWER DISTRIBUTION SYSTEM MEASUREMENTS*, CD Proceedings of XXI IMEKO World Congress “Measurement in Research and Industry”, August 30 - September 4, 2015, Prague, Czech Republic, pp.659-662.

[4] V. Pjevalica and V. Vujicic, *Further Generalization of the Low-Frequency True-RMS Instrument*, IEEE Trans. Instrumentation and Measurement, vol. 59, no. 3, pp. 736-744, Mar. 2010.

[5] P. Sovilj, S. Milovancev and V. Vujicic, *Digital Stochastic Measurement of a Nonstationary Signal with an Example of EEG Signal Measurement*, IEEE Trans. Instrumentation and Measurement, vol. 60, no. 9, pp. 3230-3232, Sep. 2010.

[6] A. Radonjic, P. Sovilj and V.Vujicic, *Stochastic Measurement of Power Grid Frequency using a Two-bit A/D Converter*, IEEE Trans. Instrumentation and Measurement, vol. 63, no. 1, pp. 56-62, Jan. 2014.

[7] P. Sovilj et al., *Stochastic Measurement of Reactive Power Using a Two-bit A/D Converter*, Proc. IMEKO TC-4 Int. Symp. on Understanding the World through Electrical and Electronic Measurement, pp. 176-179, Sept. 2016.

[8] B. Vujicic, *Null Detection Using a Low Resolution A/D Converter* (in Serbian), PhD thesis, Dept. of Power, Electronic and Telecommun. Engineering, University of Novi Sad, 2017.

[9] M. Urekar et al., *Accuracy Improvement of the Stochastic Digital Electrical Energy Meter*, Measurement, vol. 98, pp. 139-150, Feb. 2017.