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OPTOELECTRONIC CURRENT TRANSFORMER FOR MEDIUM VOLTAGE NETWORKS

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Abstract – **The paper presents an optoelectronic hybrid current transformer which allows current measurement in medium voltage networks and provides remote measuring signal transmission with high immunity against disturbances.**

An electromagnetic instrument transformer is connected to measuring chain including an optical data link between two electronic units: one unit which operates at medium voltage in measuring point and other which operates at low voltage in monitoring and control point.

The first unit achieves both the voltage-to-frequency and electro-optic conversions of measuring signal from secondary coil of current transformer.

The second unit achieves the optic-to-electric and frequency-to-voltage conversions to obtain the analogous measuring signal in condition of reference document, the standard IEC 60044-8.

The first unit generates the variable reference signal (measuring signal) for the second unit which operates as closed loop system based on PLL structure with very good static and dynamic performances.

The structure of optoelectronic hybrid current transformer, the function of each structural block, the testing procedures, experimental results and conclusions are presented in the body of paper.

Also, a few steps for mathematical model used in dynamic behavior analysis and the main parameters of step response are presented.

Mr. Prof. Dr. Eng. Andrei Marinescu, is project manager, coordinating specialist in electromagnetic compatibility and high power/high voltage measurement. Mr. Eng. Nicolae Paduraru is the designer of electromagnetic transformers with insulator support and metal case. Mr. Eng. Alexandru Manta and Mr. Eng. Marinel Popescu are the designers of electronic modules and optical data link.

Keywords: *nonconventional, instrument, transformer, optical, link*

1. INTRODUCTION

Electric quantity monitoring in medium voltage networks imposes the achievement of some special technical conditions related to: transformer or sensor manufacturing, accurate signal transmission between the measuring point and the monitoring point, achievement of a safe insulation between the two points one at high potential and the other at low potential adjacent to human operators.

In the last years, fiber optics (FO) are more and more used to transmit the TV broadcasting signals, to achieve phone calls between fixed posts, to achieve internet communications, etc.

In comparison with the copper cables used for data transmission the fiber optics offer some important advantages leading to their intensive use in the domain of analogic and digital signal transmission.

In FO, the information is transmitted under the form of optical signals having a high immunity to electromagnetic interferences and induction phenomena in strong electric and magnetic fields. They can be mounted adjacent to cables passed by high currents or being at high potential.

At the same time, being made of glass or plastic their operation is safe and removes electrocution risk. They have high resistance to corrosive agent action.

At the same time, the common mode disturbances are withdrawn due to using FO.

They have a high efficiency, low attenuation per length unit and enable accurate transmission of the signals even at high frequencies.

FO are more and more used to transmit the transducer generated signals as well as the monitoring or control signals for HV and MV three phase medium voltage installations.

The paper presents an optoelectronic hybrid current transformer which makes the above conditions easier to fulfil by using an appropriate technical solution: an electronic processing unit named optoelectronic emitter (EOE) converts the electric signal generated by an electromagnetic current transformer into optical signal.

The signal is transmitted by FO to the optoelectronic receiver (ROE) which converts it in a measurable electric signal.

The structural diagram of the transformer is presented and the main diagram blocks are described. Then it is a brief presentation of the signal transmission path behaviour in dynamic regime and the physical model of the transformer is presented.

Finally, the paper contains the experimental results obtained during the tests and the conclusions resulted from experimental result analysis.

Also, the next steps for future development of current transformer are defined.

2. THE STRUCTURE OF TRANSFORMER

The transformer was designed using as reference document the standard IEC 60044-8. When the primary rated current passes through the medium voltage busbar (BMT) the electromagnetic transformer generates at its terminals the voltage U_1=150 mV. When U_1 is applied at optoelectronic emitter (EOE) input, the voltage U_e=4 V is obtained at optoelectronic receiver (ROE) output.

The optical connection between the two optoelectronic modules is achieved by multimode FO with a diameter of 62.5/125 µm. The optical wavelength of the signal transmitted through FO is 850 nm. Signal U_1 generated by the electromagnetic transformer – TCM (current instrument transformer) is frequency modulated inside EOE and transformed in logical signal with variable frequency. The instantaneous frequency of the FO transmitted impulses is proportional with the instantaneous value of the alternating signal with the effective value U_1.

In ROE, the optical signal impulses are converted in electrical impulses by receiver photodiode - FD. A phase locked loop monitoring system [1], [2] restores the initial electric signal which is then amplified to a value U_e. An expansion factor of the primary rated current equal to 1.2 was chosen from the standard. So at a value 1.2xIn the electromagnetic transformer generates U_1=180 mV.

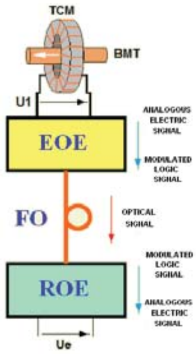


Figure 1: Principle diagram of the hybrid electronic transformer.

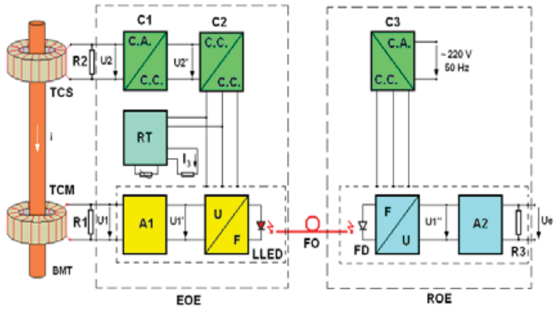


Figure 2: Block diagram of hybrid optoelectronic transformer.

Fig.2. presents the structure of the optoelectronic hybrid transformer where the measuring signal transmission path can be seen: the current instrument transformer with the load resistance, amplifier A1, voltage-frequency converter U/F, laser LED, FO, photodiode, a transconductance amplifier, frequency-voltage converter F/U and amplifier A2.

In EOE, the frequency modulation of the measuring signal U_1 takes place. The frequency modulation consists in modifying the frequency of a carrier signal (amplitude is constant) depending on the instantaneous value of a modulating signal. In other words, the instantaneous frequency f_i varies around the value f_p reaching the extreme values $f_{max}=f_p+\Delta f$ *and* $f_{min}=f_p-\Delta f$, corresponding to amplitude $+U_{1'max}$ *and* $-U_{1'max}$.

Since the frequency modulated signal amplitude is not information carrier (it is constant), the signal is insensitive to atmospheric disturbances and other noise types that may influence signal amplitude. That is why the frequency modulated transmitted signals are very “clean”.

U/F converter is a voltage controlled oscillator (OCT) generating a rectangular signal with a frequency of 168.5 kHz when U_1=0 V. When $U_{1'}$=12V, the frequency of the signal generated by OTC is 300 kHz.

The transformations of the measuring signal U_1 along the transmission path are presented in a logical succession in fig.1 and are graphically represented in Fig. 3. At the same time, fig.2 presents a saturated current transformer (TCS) and converters C1 and C2 which supply the optoelectronic emitter. The two transformers are placed under the same medium voltage busbar passed by the current to measure. Converter C3 supplies the optoelectronic receiver placed in the monitoring point.

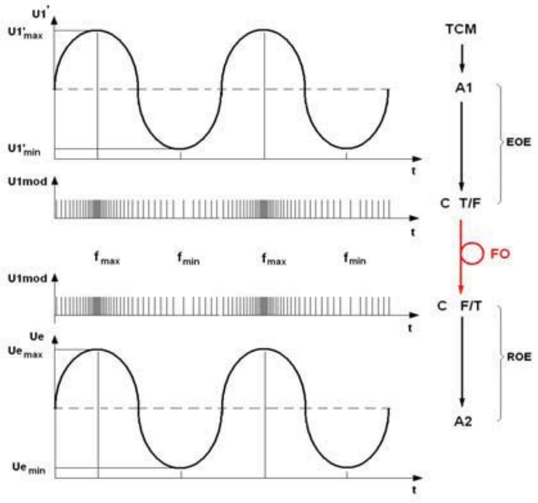


Figure 3: Continuous signal transformation for frequency modulation transmission.

3. DYNAMIC REGIME OF SIGNALS

For the variation range of the measured current it is considered that TCM, A1 and OCT are elements with linear static characteristics. Output quantity/ input quantity relationship is expressed by a transfer factor with constant value.

TCM transfer factor is K_{TCM}=0.75 mV/A, amplifier A1 transfer factor is K_{A1}=26.6 mV/mV, and OCT transfer factor is k_{OCT}=137706 rad/s/V.

According to the system theory, the transmission path between TCM and photodiode FD together with the associated amplifier can be considered as representing a prescription element (EP) for the closed loop tracking system (fig. 4). This should be clever enough to monitor the evolution of the measuring signal U_1 and of the measured quantity – current passing through BMT.

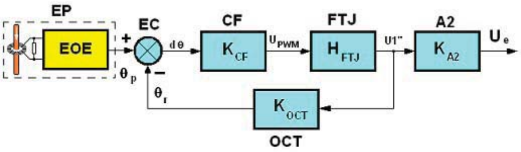


Figure 4: Structural diagram of the transmission system of TCM generated measuring signal.

The closed loop tracking system is known and represents a phase locked loop or with locked phase. The following component blocks can be distinguished in its structure:

- a voltage controlled oscillator (OCT) identical with the one from EOE;
- a phase comparator CF achieved under the form of a logical circuit OR-EXCLUSIVE;
- low-pass filter achieved with passive components.

The EP generated signal (with phase θ_p) and OCT generated signal (with phase θ_r) are applied at the inputs of the comparison element EC which determines the phase error dθ. The phase comparator CF supplies at its output a width modulated signal U_{PWM} the filling factor of which is proportional with the value dθ. The low-pass filter FTJ supplies at its output the signal $U_{1''}$ that represents the mean value of U_{PWM}. The voltage controlled oscillator changes the frequency of its oscillations depending on the value $U_{1''}$ and tries to follow the prescribed signal bringing close θ_r of θ_p so that to obtain $d\theta \cong 0$.

Amplifier A2 amplifies signal $U_{1''}$ so that the effective value of signal U_e to be 4V when the measured current has the rated value.

As in EOE case, it is considered that the above mentioned blocks have linear static characteristics and can be marked in the block diagram with transfer factors: k_{CF}=12V/π=3.82 V/rad, k_{OCT}=137706/s rad/s/V. For the low-pass filter, the following transfer function is considered:

$$H_{FTJ}(s) = \frac{1}{1+sRC} \tag{1}$$

where R and C are the parameters of the passive components the filter consists of [3].

For the closed loop tracking system the transfer function is defined:

$$G(s) = \frac{U_1''(s)}{\theta_p(s)} \tag{2}$$

where the functions and transfer factors of the elements from the direct path and the reaction path are replaced obtaining:

$$G(s) = \frac{k_{CF}\dfrac{1}{1+sRC}}{1+k_{CF}\dfrac{k_{OCT}}{s}\dfrac{1}{1+sRC}} \tag{3}$$

The final form:

$$G(s) = \frac{\dfrac{k_{CF}}{RC}\dfrac{k_{OCT}}{s}}{s^2+\dfrac{1}{RC}s+\dfrac{k_{CF}k_{OCT}}{RC}} \tag{4}$$

That is similar to the general form of the transfer function of a second degree element:

$$G(s) = \frac{\omega_n^2/s}{s^2+2\xi\omega_n s+\omega_n^2} \tag{5}$$

where the damping factor and natural frequency result from the relations:

$$\xi = \frac{1}{2\sqrt{k_{CF}k_{OCT}RC}} \tag{6}$$

$$\omega_n = \sqrt{\frac{k_{CF}k_{OCT}}{RC}} \tag{7}$$

From condition:

$$\xi = 0{,}707 = \frac{\sqrt{2}}{2} \tag{8}$$

$$RC = \frac{1}{2k_{CF}k_{OCT}} \tag{9}$$

It is got:

$$\omega_c = k_{CF}k_{OCT}\sqrt{2} \tag{10}$$

Real frequency and stabilization time are obtained from the relations:

$$\omega = \omega_n\sqrt{1-\xi^2} \tag{11}$$

$$t_s = \frac{4}{\xi\omega_n} \qquad (12)$$

while the coordinates of the first maximum have the expressions:

$$t_{\max} = \frac{\pi}{\omega_n\sqrt{1-\xi^2}} \qquad (13)$$

$$M = 1 + e^{\frac{-\pi\xi}{\sqrt{1-\xi^2}}} \qquad (14)$$

These are parameters characterising the dynamic regime behaviour of the phase locked loop. By their means an analysis of the output signal U_e evolution when the input signal U_1 amplitude has a step variation can be made.

4. PRESENTATION OF TRANSFORMER PHYSICAL MODEL

The modular structure presented in fig.1. and fig.2. was the basis for achieving the transformer physical model under the form of two units: one optoelectronic measuring and emission (EOE) unit intended to operate close to the measuring point and an optoelectronic receiver unit (ROE) intended to operate in the monitoring point.

Fig.5. represents the EOE unit together with the main constituent elements: the two toroidal transformers, the electronic module and the laser LED. They are enclosed in a metal box placed on a 24 kV insulator made of composite materials.

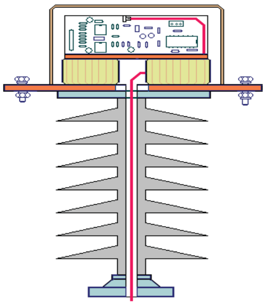


Figure 5: EOE supported by the post insulator.

The FO comes through the insulator body and joins the laser LED with the optical connector placed at insulator base.

Fig.6 presents an image of both transformer units interconnected by 20 m long FO placed outside the insulator.

The optoelectronic receiver unit is enclosed in a metallic box and is supplied from the low voltage network.

When the current through the medium voltage line decreases excessively or interruptions of the current through BMT appears, EOE supply is provided by few miniature accumulators with 500 mAh capability and operation in series connection.

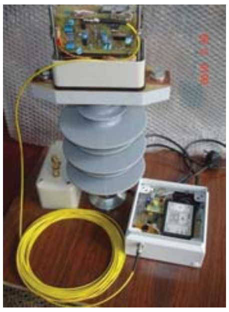


Figure 6: Assembly of the two transformer units optically connected by a 20 m long FO.

5. EXPERIMENTS

Initially, the experiments consisted in checking the constituent elements of the measuring signal transmission.

The data necessary to plot the experimental static characteristic U_1= f(I) were collected and it was compared to the theoretical one obtained considering the transfer factor k_{TCM} (fig. 7.)

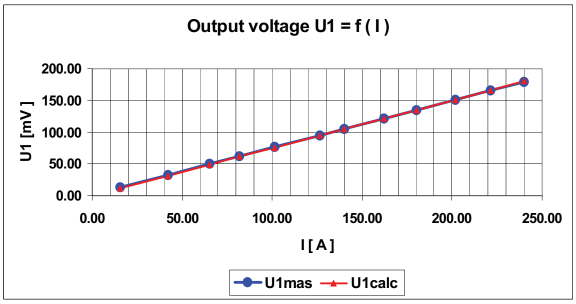


Figure 7: Static characteristics U_1=f(I) of TCM.

The optical transmission chain of the measuring signal consisting of EOE, FO and ROE was checked using the diagram from the figure below.

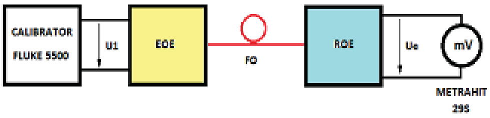
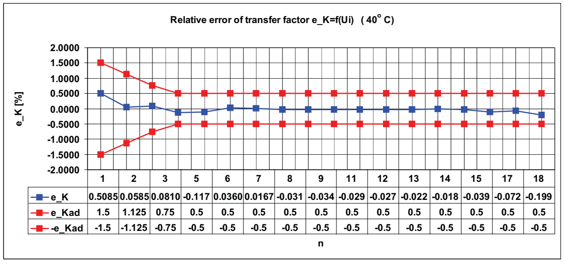


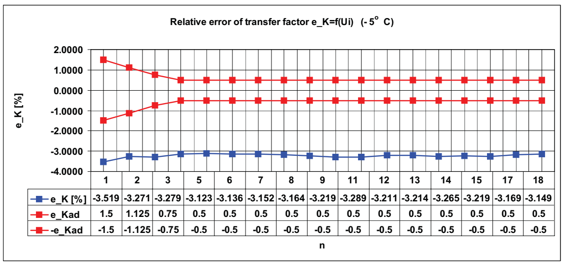
Figure 8: Checking set-up for measuring signal transmission path.

This set-up was used to determine experimentally the static characteristics U_e=f(U_i) at different temperatures (+25° C, +40° C, -5° C), using FO with a length of 100 m, 200 m, 400 m and 600 m.



	1	2	3	5	6	7	8	9	11	12	13	14	15	17	18
e_K	0.5085	0.0585	0.0810	-0.117	0.0360	0.0167	-0.031	-0.034	-0.029	-0.027	-0.022	-0.018	-0.039	-0.072	-0.199
e_Kad	1.5	1.125	0.75	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
-e_Kad	-1.5	-1.125	-0.75	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5

Figure 9: Relative error of the transfer factor of the measuring signal transmission path and its limits provided by standard when operating at +40° C.



	1	2	3	5	6	7	8	9	11	12	13	14	15	17	18
e_K [%]	-3.519	-3.271	-3.279	-3.123	-3.136	-3.152	-3.164	-3.219	-3.289	-3.211	-3.214	-3.265	-3.219	-3.169	-3.149
e_Kad	1.5	1.125	0.75	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
-e_Kad	-1.5	-1.125	-0.75	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5

Figure 10: Relative error of the transfer factor of the measuring signal transmission path and its limits provided by standard when operating at -5° C.

The measurements performed at -5° C lead to important deviations from the standard allowed limits. That is why it was necessary to identify the element having temperature variation sensitive operation.

This is the CMOS 4046 itself used as phase locking loop. In order to withdraw this influence factor, the local temperature control of this circuit was adopted.

A temperature regulating system based on a PWM generator was used. The filling factor of the generated signal is low at high temperatures.

Records of the waveshapes for signals U_i (got from a signal generator) and U_e were made using an Genesis acquisition system.

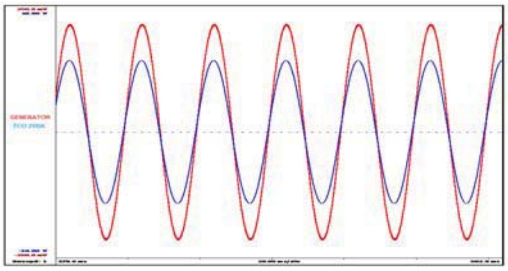


Figure 11: Waveshapes of signals U_1 (sine signal) and Ue recorded with an acquisition system.

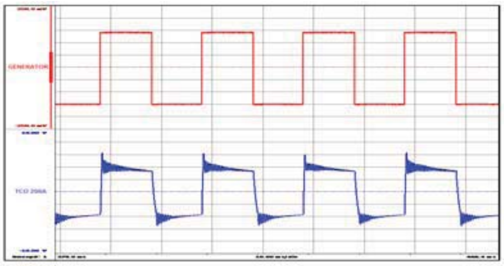


Figure 12: Waveshapes of signals U_1 and U_e recorded with an acquisition system.

In the end, tests for transformer amplitude and phase error determination were performed using the comparison method with a standard transformer.

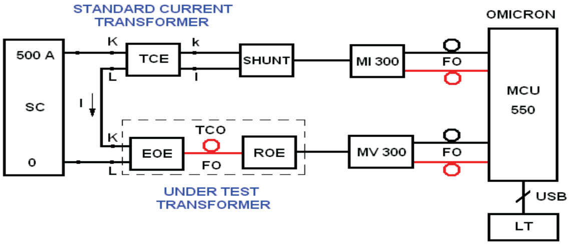


Figure 13: Diagram of the set-up used to determine the amplitude and phase errors.

The waveshape of output signal obtained for square input signal shows an about 6.5 ms time response for transmission chain.

Also, the static errors obtained by comparing with a standard transformer are between standard limits.

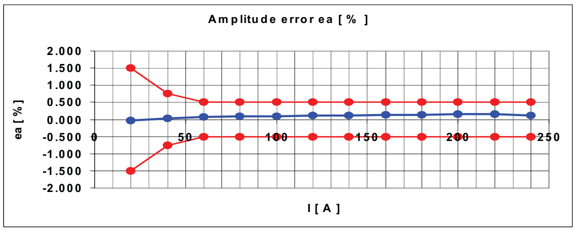


Figure 14: Experimental amplitude error and the standard imposed limits for accuracy class 0.5.

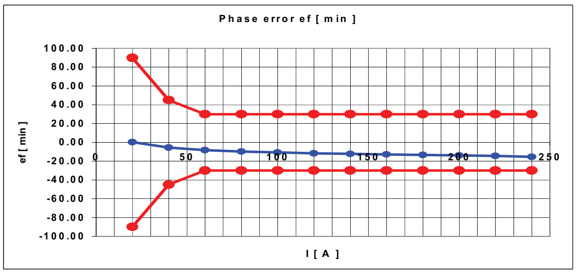


Figure 15: Experimental phase error and the standard imposed limits for accuracy class 0.5.

The following conclusions are presented in connection with [9], [10] and [11].

6. CONCLUSIONS

The current transformer is based on ICMET two decades acquired experience related to high potential data transmission by optoelectronic means.

The achieved current transformer is a fully functional product compliant with IEC 60044-8. It is achieved according to the modular principle and it is the first from the series of optoelectronic current transformers with rated voltage up to 420 kV. The only element that is different from one module to another is the post insulator with the integrated FO that has a different length.

The measurement uncertainty (amplitude, phase errors, repeatability, temperature) determines the framing of this current transformer in class 0.5.

Data transmission from the station to the control room is achieved digitalally using FO.

According to the agreement with C.N. Transelectrica, the current transformer will be mounted in the very next period in an electric power station and will operated beside a classical current transformer with a view to comparing objectively the results.

ICMET concerns in FO digital data transmission domain will be continued to obtain the accuracy class 0.2 and for using some professional integrated circuits with low energy consumption.

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